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Scientific Analysis/Calculation Administrative Change Notice

QA: QA

Complete only applicable items.

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4. Title:	Screening Analysis of Criticality Features, Events, and Processes for License Application				
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6. Approvals:

	Print Name and Sign	Date
Preparer:	John A. McClure [signature]	3/10/2008
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7. Affected Pages	8. Description of Change:
1-5	Added subtitle rows to Table 1.2-1 identifying the initiating events.
4-14	Deleted the statement that accumulation of fissile mass in the far-field environment cannot exceed the near-field accumulation. Revised the first sentence in the last paragraph to read "The criticality potential of waste forms in either the external near-field or far-field locations depends on whether the fissile mass that can be accumulated in these locations over 10,000 years after closure can exceed the minimum critical mass for the waste form in that environment."
6-11, 6-24, 6-25	Change "breech" to "breach".
6-20	Change dimension in last sentence of paragraph 1 from 50 in to 50.37 in.
6-24	Change reference to degradation products from boron carbide to chromium boride.
4-11	Added a citation of (SNL 2007 [DIRS 178851], Section 6.2.1) in Section 4.1.13 as source for considering a damaged area as a network of SCCs. Text revised in first sentence of Section 4.1.13 to clarify the connection between SCC development and RST value.
4-13	Revised the third sentence in the first paragraph of Section 4.1.14 to read "The waste package outer barrier is constructed of Alloy 22, which has a corrosion rate that ranges from 0 to 15 nm/yr (SNL 2007 [DIRS 178519], Figure 6-10) and the probability of the waste package OCB breaching in the first 10,000 years after repository closure due to general corrosion is low (SNL 2007 [DIRS 178519], Section 8.1)." Identified SCC propagation rate as a mean value from Table 6-6 of SNL 2007 [DIRS 181953].
6-11	Change sentence citing Figure 6-6 in paragraph 1 to read "In addition, the intact configuration (base case) is designed to remain subcritical when fully flooded (SNL 2008 [DIRS 182788], Section 7) and the design basis configuration accounts for corrosion loss of the neutron absorber over the first 10,000-year period following repository closure.
6-1	Revised Section 6.2, sentence 3 to read "The loading curve for commercial fuel is established…". Added a statement concerning conditions for maintaining DOE SNF below the respective critical limits.
6-11	Revised first paragraph, fourth sentence to read "In addition, the intact configuration for commercial fuel is designed…". Added a statement concerning criticality evaluations for DOE SNF.

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6-25	Revised last paragraph, fourth sentence to read "In addition, the intact configuration for commercial fuel is designed…". Added a statement concerning criticality evaluations for DOE SNF.
6-4 and 6-25	Change citation of (SNL 2008 [DIRS 182788], Figure 6-6) to (SNL 2008 [DIRS 182788], Section 7).
6-14 and 6-15	Added summation to probability Equation 6.3-1 and 6.3-2.
1-4, 4-8, 4-13, 6-9, 6-11, 6-24, 6-32, 6-37, I-1	Correct citation of [DIRS 179476] to show date as 2008. Change title to include *": Methods"* as appropriate.
8-5	Added MOL number to DIRS 179476, corrected title, and changed date to 2008.
8-8	Added MOL number to DIRS 182788.

to determine the scenario(s) that must be included in the TSPA-LA or the design changed to meet the screening criterion.

An overview of the YMP FEP scenario and analysis development process in *Features, Events, and Processes for the Total System Performance Assessment: Methods* (SNL 2008 [DIRS 179476], Section 6.3 and 6.4) describes the TSPA-LA FEP identification and screening process that led to the development of FY 2007 LA FEP List and Screening (DTN: MO0706SPAFEPLA.001 [DIRS 181613]). Changes in FEP list, FEP names, and FEP descriptions can be traced through that report. The criticality FEPs addressed in this report form a subset of the FY 2007 LA FEP List and Screening (DTN: MO0706SPAFEPLA.001 [DIRS 181613]). These FEPs are listed in Table 1.2-1 by number in column 1, name in column 2, and description in column 3. Note that an "intact" waste package in this FEPs analysis includes "loss of containment but internal structures and waste form not degraded" as well as the package being sealed as at the time of repository closure. A loss of containment for waste packages includes any breach of the outer corrosion barrier (OCB) (e.g., from stress corrosion cracking (SCC), localized corrosion, or shearing). The sixteen criticality FEPs address scenarios derived from four initiating events (early failure of engineered barriers, seismic, rockfall, and igneous) in four environments (i.e., in-package intact, in-package degraded, external near-field, and external far-field). (The four environments cover only three locations as the in-package intact and degraded configurations for current designs differ primarily in the waste form composition.) While the engineered barrier system (EBS) components and neutron absorber materials are designed to maintain their function in nominal repository environments over the first 10,000-year period after repository closure by specifying a corrosion allowance or minimum thickness (SNL 2007 [DIRS 179394], Table 4-1, Items 03-07 and 03-10), disruptive environments must be considered as well as uncertainty in the corrosion rates, thus degraded states must also be considered.

Table 1.2-1. Criticality FEPs List Utilized in Screening Analysis

FEP Number	FEP Name	FEP Description
FEPs Associated with Nominal (Early Failure) Event Sequence Initiators		
2.1.14.15.0A	In-package criticality (intact configuration)	The waste package internal structures and the waste form remain intact. If there is a breach (or are breaches) in the waste package that allows water to either accumulate or flow-through the waste package, then criticality could occur in situ. In-package criticality resulting from disruptive events is addressed in separate FEPs.
2.1.14.16.0A	In-package criticality (degraded configurations)	The waste package internal structures and the waste form may degrade. If a potentially critical configuration (sufficient fissile material and neutron moderator present with a lack of neutron absorbers) develops, a criticality event could occur in situ. Potential in situ critical configurations are defined in Figures 3-2a and 3-2b of *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505]). In-package criticality resulting from disruptive events is addressed in separate FEPs.
2.1.14.17.0A	Near-field criticality	Near-field criticality could occur if a fissile material-bearing solution from the waste package is transported into the drift and the fissile material is precipitated into a critical configuration. Potential near-field critical configurations are defined in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505], Figure 3-3a). Near-field criticality resulting from disruptive events is addressed in separate FEPs.

Table 1.2-1. Criticality FEPs List Utilized in Screening Analysis (Continued)

FEP Number	FEP Name	FEP Description
FEPs Associated with Nominal (Early Failure) Event Sequence Initiators		
2.2.14.09.0A	Far-field criticality	Far-field criticality could occur if a fissile material-bearing solution from the waste package is transported beyond the drift and the fissile material is precipitated into a critical configuration. Potential far-field critical configurations are defined in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505], Figure 3-3b). Far-field criticality resulting from disruptive events is addressed in separate FEPs.
FEPs Associated with Seismic Event Sequence Initiators		
2.1.14.18.0A	In-package criticality resulting from a seismic event (intact configuration)	The waste package internal structures and the waste form remain intact either during or after a seismic disruptive event. If there is a breach (or are breaches) in the waste package that allows water to either accumulate or flow-through the waste package, then criticality could occur in situ.
2.1.14.19.0A	In-package criticality resulting from a seismic event (degraded configurations)	Either during or as a result of a seismic disruptive event, the waste package internal structures and the waste form may degrade. If a critical configuration develops, criticality could occur in situ. Potential in situ critical configurations are defined in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505], Figures 3-2a and 3-2b).
2.1.14.20.0A	Near-field criticality resulting from a seismic event	Either during or as a result of a seismic disruptive event, near-field criticality could occur if fissile material-bearing solution from the waste package is transported into the drift and the fissile material is precipitated into a critical configuration. Potential near-field critical configurations are defined in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505], Figure 3-3a).
2.2.14.10.0A	Far-field criticality resulting from a seismic event	Either during or as a result of a seismic disruptive event, far-field criticality could occur if fissile material-bearing solution from the waste package is transported beyond the drift and the fissile material is precipitated into a critical configuration. Potential far-field critical configurations are defined in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505], Figure 3-3b).
FEP Number	**FEP Name**	**FEP Description**
FEPs Associated with Rockfall Event Sequence Initiators		
2.1.14.21.0A	In-package criticality resulting from rockfall (intact configuration)	The waste package internal structures and the waste form remain intact either during or after a rockfall event. If there is a breach (or are breaches) in the waste package that allows water to either accumulate or flow-through the waste package then criticality could occur in situ.
2.1.14.22.0A	In-package criticality resulting from rockfall (degraded configurations)	Either during or as a result of a rockfall event, the waste package internal structures and the waste form may degrade. If a critical configuration develops, criticality could occur in situ. Potential in situ critical configurations are defined in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505], Figures 3-2a and 3-2b).
2.1.14.23.0A	Near-field criticality resulting from rockfall	Either during or as a result of a rockfall event, near-field criticality could occur if fissile material-bearing solution from the waste package is transported into the drift and the fissile material is precipitated into a critical configuration. Potential near-field critical configurations are defined in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505], Figure 3-3a).
2.2.14.11.0A	Far-field criticality resulting from rockfall	Either during or as a result of a rockfall event, far-field criticality could occur if fissile material-bearing solution from the waste package is transported beyond the drift and the fissile material is precipitated into a critical configuration. Potential near-field critical configurations are defined in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505], Figure 3-3a).

Table 4.1-3. Maximum Allowable Displacement with Drift Collapse for an Intact Drip Shield

Package Type	Outside Diameter of OCB (mm)	Nominal Length (mm)	Clearance Without Pallet (mm)
Commercial SNF TAD Canister	1,881.6	5,850.1	836
Codisposal Short	2,044.7	3,697.4	673
Codisposal Long	2,044.7	5,303.9	673
Codisposal-MCO	1,749.3	5,278.6	969

Sources: SNL 2007 [DIRS 179394], Table 4-3, for outside diameter of OCB and for nominal length of the TAD waste package; SNL 2007 [DIRS 179567], Tables 4-8 through 4-10, for the outside diameter of OCB and nominal length of the codisposal waste package types.

NOTES: Clearance without the pallet is calculated as the interior height of the drip shield (2,717.8 mm) minus the outside diameter of the waste package OCB, rounded to three significant digits (listed in Output DTN: MO0705CRITPROB.000, file: *Fault Displacement Abstraction for Criticality Updated DTN 10-25-07.xls*, spreadsheet: "Tables by WP Type," rows 14 to 24).

MCO = multicanister overpack.

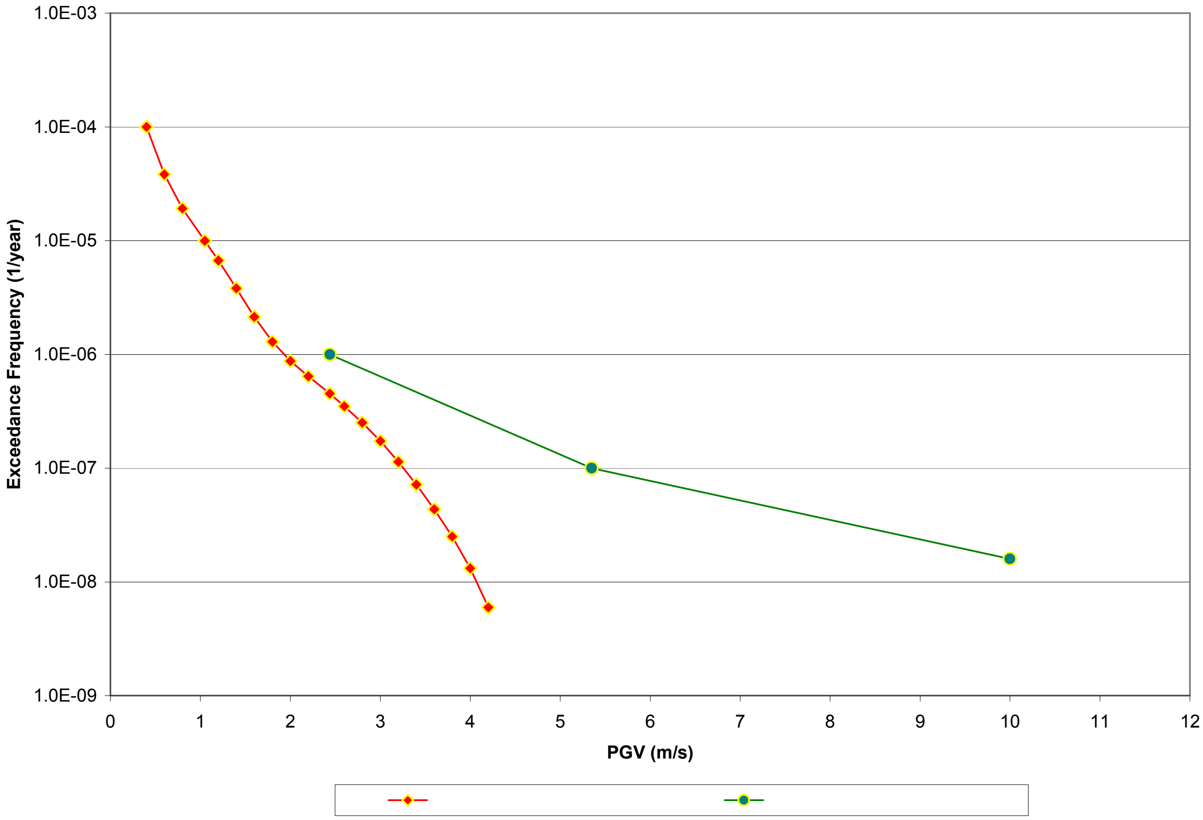
4.1.7 Waste Package and Drip Shield Interactions with Seismic Events

The number of waste packages that could be emplaced on faults in the repository is evaluated in Section 6.4.1 following the analysis method from DTN: MO0705FAULTABS.000 [DIRS 183150], file: *Fault Displacement Abstraction for Criticality.xls*, spreadsheet: "Tables by WP Type" adjusted for the inventory from Table 4.1-2 and dimensions from Table 4.1-3.

The probability of drip shield damage or failure from seismically induced rockfall is developed through fragility curves for the drip shield plates and framework that is documented in DTN: MO0703PASDSTAT.001 [DIRS 183148], file: *Plate Fragility Analysis.xls*, spreadsheet: "Summary," and file: *Frame Fragility Analysis.xls*, spreadsheet: "Summary," respectively. Significant failure probabilities were developed for the nondegraded drip shields subjected to 100% rockfall loads at exceedance frequencies of approximately 10^{-8} per year based on the bounded hazard curves. Likewise, with the exception of very large blocks, rockfall in nonlithophysal zones does not cause waste package damage (SNL 2008 [DIRS 179476], FEP 1.2.03.02.0B).

4.1.8 Emplacement Drift Information

Emplacement drift information is required to properly assign seismic information to the two geologic zones – lithophysal and nonlithophysal. The lithophysal and nonlithophysal fractional areas are calculated by dividing the emplacement drift area of both geological zones by the total drift area. The drift emplacement area by geological unit is given in Table 1 of the reference cited in *Total System Performance Assessment Data Input Package for Requirements Analysis for Subsurface Facilities* (SNL 2007 [DIRS 179466], Table 4-1, Item 01-01). This information is summarized in Table 4.1-4.



Sources: DTNs: MO0501BPVELEMP.001 [DIRS 172682]; file: *Bounded Horizontal Peak Ground Velocity Hazard at the Repository Waste Emplacement Level.xls*, spreadsheet: "Bounded Horizontal PGV Hazard;" Unbounded Hazard Curve: SNL 2007 [DIRS 176828], Section 6.4.3.

Figure 4.1-1. Seismic Exceedance Frequency versus PGV Value

4.1.12 Hydrogen Deflagration

Hydrogen concentrations of 4% or greater by volume are required for deflagration in air (Coward et al. 1952 [DIRS 182138], Figure 7, Table 3; Kuo 1986 [DIRS 170633], Table 4.5). The minimum oxygen concentration capable of supporting a flame front is approximately 4 vol % (Coward et al. 1952 [DIRS 182138], Table 44). Gas temperatures resulting from a hydrogen deflagration are approximately 350°C (Coward et al. 1952 [DIRS 182138], p. 15). Gas pressure ratios resulting from a hydrogen deflagration are approximately 1 to 4 times the initial pressure (Coward et al. 1952 [DIRS 182138], p. 12).

4.1.13 Vibratory Seismic Ground Motion

Stress corrosion cracking resulting from damage that caused stresses to exceed a high residual (tensile) stress threshold (RST) is expected to be the failure mode of waste packages subjected to impact processes due to vibratory induced ground motion events (SNL 2007 [DIRS 178851], Section 8.2). The damaged or deformed area that exceeds an RST value is conceptualized to result in a tightly spaced network of stress corrosion cracks (SNL 2007 [DIRS 178851], Section 6.2.1). The residual tensile stress threshold is often shortened to the residual stress threshold or RST, with the understanding that the principal residual stress must always be tensile to initiate SCC. The results from each calculation of structural response of the waste package seismic events are calculated for three discrete values of the RST level for Alloy 22 (i.e., 90%, Section 6.2.12.1[a]). The computational method for evaluation of the combined drip shield rupture and waste package OCB localized corrosion probability is documented in File: *Localized_Corrossion.zip* (files: *CSNF_bin[x].txt* for x = 1, 2, 3, 4, and 5; *CDSP_bin[x].tx*t for x = 1, 2, 3, 4, and 5) (DTN: MO0709TSPALOCO.000 [DIRS 182994]; SNL 2007 [DIRS 183478], Appendix O). The calculation uses input from the host-rock lithology, localized corrosion probability, waste package temperature and relative humidity, temperature effect from drift collapse, and uncertainty in the parameters that describe seepage chemistry. Note that these intermediate results are available only in separate sets for the lithophysal and nonlithophysal units, so to obtain the total probability distribution across the entire repository the analysis must be done for each set with the method and results documented in (SNL 2007 [DIRS 184078], Appendix B).

Analyses of large, single-block (28.29 metric tons) impacts of rocks in the nonlithophysal zone show that such impacts may cause the drip shield to buckle and potentially contact the waste package outer corrosion barrier. The analysis indicated that waste package damage could occur for the most severe events at a PGV level of 5.35 m/s (SNL 2007 [DIRS 178851], Table 6-153).

4.1.14 Physical Properties

Properties of various materials that may be used in the fabrication of waste packages and canisters are documented in this section. Physical properties of gases used in this analysis are listed in Table 4.1-7. The waste package outer barrier is constructed of Alloy 22, which has a corrosion rate that ranges from 0 to 15 nm/yr (SNL 2007 [DIRS 178519], Figure 6-10) and the probability of the waste package OCB breaching in the first 10,000 years after repository closure due to general corrosion is low (SNL 2007 [DIRS 178519], Section 8.1). Stress corrosion cracks can develop in Alloy 22, however, and propagate at a mean rate of 1.1×10^{-9} mm per second (SNL 2007 [DIRS 181953], Table 6-6, Section 8.1.2). This rate is essentially independent of the stress intensity factor (SNL 2007 [DIRS 181953], Figure 6-9 and Section 8.1.2).

Localized corrosion in the form of pitting and crevice corrosion can occur on exposed surfaces of the waste package OCB provided an appropriate aqueous environment is present (SNL 2008 [DIRS 179476], FEP 2.1.03.03.0A). Seepage water through ruptured drip shields can provide the basis for such an environment to develop. Once localized corrosion occurs, it propagates at a median rate of 127 µm per year with a lowest percentile of 12.7 µm per year (DTN: MO0703PAGENCOR.001 [DIRS 182029], file: *LC_Propagation.pdf*, Table 1). Thus localized corrosion, once initiated, can penetrate the waste package OCB in less than 1000 years.

The absorber material designated for the TAD canisters is borated stainless steel (Orrell 2007 [DIRS 182643]) produced by powder metallurgy that results in a near-optimal dispersion of boron throughout the material (ASTM A 887-89 Grade A [DIRS 178058], pp. 1 to 4). Corrosion rates for neutron absorber materials measured in aqueous environments simulating expected repository environments are listed in Table 4.1-8. The initial thickness specified for the borated stainless steel absorber plates in the TAD canisters is 11 mm (SNL 2007 [DIRS 179394], Table 4-1, Item 03-10). Based on the average corrosion rate of 0.0271 µm/yr (set with exposure time > 100 hr showing the highest average) from Table 4.1-8, the absorber plate thickness after 10,000 years would be approximately 10 mm.

Table 4.1-7. Physical Properties of Gases

Properties of Gases		
Property	**Value**	**Source**
Standard atmosphere pressure	0.101 MPa	Parrington 1996 [DIRS 103896], Physical Constants
Molecular weight of water	18.015×10^{-3} kg/mole	Parrington 1996 [DIRS 103896], Physical Constants
Molecular weight of helium	4.003×10^{-3} kg/mole	Parrington 1996 [DIRS 103896], Physical Constants
Density of water vapor	Function of temperature (kg/m^3)	ASME 1993 [DIRS 108050], Table 1
Density of helium	Function of temperature (kg/m^3)	Holman 1997 [DIRS 101978], Table A-6

Table 4.1-8. Corrosion Rates of Waste Package Materials

Absorber Material	Corrosion Rate	Notes
Ni–Gd Alloy [a]	Average value 0.056 μm/yr	30°C, J-13 solutions
Ni–Gd Alloy	Average value 0.307 μm/yr	60°C, J-13 solutions
Borated Stainless Steel – 400 hour test [b] ASTM 304B4 Grade A alloy [c]	Average value 0.0271 μm/yr	Range 25°C to 90°C
Stainless Steel Type 316L [d]	Median value 0.003 μm/yr	30°C fresh water

Sources: [a] DOE 2004 [DIRS 168434], Table 17.
[b] DTN: MO0706ECTBSSAR.000 [DIRS 181380], Table 5.
[c] Orrell 2007 [DIRS 182643].
[d] DTN: MO0409SPAACRWP.000 [DIRS 172059], file: *aqueous-316L.xls*, spreadsheet: "freshwater."

4.1.15 Criticality Potential of Waste Forms

As discussed in Section 1.4, a configuration class (a set of similar configurations whose composition and geometry are defined by specific parameters) is considered to have *potential for criticality* if the probability of the configuration class formation is above a specified probability screening criterion. For configurations with potential for criticality (i.e., probability of the configuration occurring is above the screening criterion), an additional evaluation of the range of configuration class parameters may be necessary to determine if the maximum effective neutron multiplication factor (k_{eff}) range could exceed the critical limit for the waste form. If such is the case, additional control measures may be required to assure that the maximum k_{eff} range is below the critical limit for the waste form.

The criticality potential of waste forms in either the external near-field or far-field locations depends on whether the fissile mass that can be accumulated in these locations over 10,000 years after closure can exceed the minimum critical mass for the waste form in that environment. Fissile mass accumulations from diffusive releases into the invert have been evaluated and documented in DTN: MO0604SPANOMIN.000 [DIRS 182944], file: *CSNF Results.xls*, spreadsheet: "Table for Report" and file: *DOE SNF Results.xls*, spreadsheet: "Table for Report" with the median values shown in Table 4.1-9 for the early

6. SCIENTIFIC ANALYSIS DISCUSSION

6.1 PROBABILITY OF CRITICALITY CALCULATIONAL APPROACH

The following sections discuss the processes used in evaluating the probability of occurrence of configurations in the repository with potential for criticality. Section 6.2 discusses the approach to organizing the processes and event scenarios. Section 6.3 provides the details for the criticality screening justifications for the early failure event FEP scenarios (all criticality FEP scenarios are listed in Table 1.2-1). Section 6.4 provides the details for the disruptive seismic event FEP scenarios, Section 6.5 for the single block rockfall disruptive event FEP scenarios, and Section 6.6 for the igneous disruptive event FEP scenarios.

6.2 SCENARIOS IMPORTANT FOR CRITICALITY

During design, criticality analyses are performed to demonstrate that the initial emplaced configuration of the waste form remains subcritical, even under flooded conditions. Several potential configurations that could occur in the repository over the 10,000-year regulatory period are selected, based on sensitivity studies, in the development of the loading curves that result in the highest k_{eff} in order to set an upper bounding limit that encompasses all other configurations. The loading curve for commercial fuel is established such that the k_{eff} of a waste package fully loaded with assemblies selected from the curve will be less than a certain critical limit under all postulated postclosure conditions (SNL 2008 [DIRS 182788], Section 1). The design basis configuration developed in *CSNF Loading Curve Sensitivity Analysis* (SNL 2008 [DIRS 182788], Section 6.2.4.1) is considered to bound the various limiting configurations that would result for each of the criticality FEP scenarios (early failure of engineered barrier, seismic, rockfall, and igneous) for commercial SNF. Analyses have likewise shown (Radulescu et al. 2004 [DIRS 165482], Section 11.4; BSC 2004 [DIRS 168935], Section 6; BSC 2004 [DIRS 171926], Section 6) that all intact and degraded configurations of the DOE-owned SNF have a k_{eff} below the critical limit provided the neutron absorber material is present as required. The nominal FEP scenarios address non-disruptive events that can affect the probability of criticality for the repository. The seismic FEP scenarios include both vibratory and faulting events. The vibratory seismic scenarios include most rockfall events since a seismic event is the initiator for such events that can affect the probability of criticality for the repository. The rockfall FEP scenario is limited to nominal rockfall events not caused by seismic activity that could damage a waste package.

For a criticality event to occur, the appropriate combination of materials (e.g., neutron moderators, neutron absorbers, fissile materials, or isotopes) and geometric configurations favorable to criticality must exist. Therefore, for a configuration to have potential for criticality, all of the following conditions must occur: (1) sufficient mechanical or corrosive damage to the waste package OCB to cause a breach, (2) presence of a moderator (i.e., water), (3) separation of fissionable material from the neutron absorber material or an absorber material selection error during the canister fabrication process, and (4) the accumulation (external) or presence of a critical mass of fissionable material. The probability of developing a configuration with criticality potential is insignificant unless all four conditions are realized, and then is only representative of a conservative estimate since the probability values associated with the many other events required to generate a critical configuration have been conservatively set to one (1).

provide additional assurance that the probability of achieving configurations with potential for criticality in the postclosure period are sufficiently low to be screened from consideration in performance analyses.

Several of the scenario evaluations include additional unquantified conservatisms as no credit is taken for the stainless steel liner or TAD canister in the commercial SNF waste packages or for the DOE-owned SNF canister in the codisposal waste packages as a barrier to water ingress. All of the internal waste package components are considered to fail when the waste package OCB is breached.

6.2.1 In-Package Scenarios

As stated in Section 6.2, the waste package/waste form configuration must degrade or deviate in some manner from the design configuration to achieve a potentially critical configuration. This is because the as-designed intact commercial SNF waste package in a fully flooded environment is precluded from achieving criticality (SNL 2008 [DIRS 182788], Section 7). Likewise, criticality evaluations for DOE-owned SNF include flooded conditions (Radulescu et al. 2004 [DIRS 165482], Section 10). Even if a waste package is breached, the very low corrosion rates of the waste package materials (Section 4.1.14) effectively prevent potentially critical configurations from developing over the regulatory period by internal reconfigurations that separate fissile material from absorber material. Deviations from the design configuration could result from undetected operational failures (e.g., fabrication processes, waste form loading errors, and drying procedures). The only identified events that can breach a waste package in the early failure scenario during the regulatory period are: (1) stress corrosion cracking initiated from manufacturing defects, (2) misplaced drip shields allowing advective seepage onto waste packages leading to breaching from localized corrosion, or (3) a deflagration event resulting from radiolytic gas generation and ignited by metal-to-metal motions such as may occur during a non-disruptive seismic event. The TAD canisters (SNL 2007 [DIRS 179394], Table 4-1, Item 04-04) and possibly others (i.e., DOE-owned SNF canisters) are expected to be loaded in spent fuel pools. Intact TAD and DOE canisters and waste packages are expected to contain little moisture per requirements for drying (SNL 2007 [DIRS 179394], Table 4-1, Item 04-04) but retention of water in a canister waste package could possibly occur if the drying and inerting process is incomplete. The process controls for the drying and inerting process for commercial SNF canisters and waste packages are expected to be similar to NUREG-1536, *Standard Review Plan for Dry Cask Storage Systems* (SNL 2007 [DIRS 179394], Table 4-1, Item 04-04) and, thus, sufficiently rigorous to reduce the likelihood of leaving residual water in the TAD canisters to levels, which, if quantified, would not significantly increase the overall probability of criticality in the repository. The consequences of a deflagration event are discussed in Appendix I as a defense-in-depth contribution without quantitative evaluation of event sequence probabilities.

Fabrication defects in the waste package OCB that can lead to stress corrosion cracking have been analyzed in *Analysis of Mechanisms for Early Waste Package/Drip Shield Failure* (SNL 2007 [DIRS 178765], Section 6). Such events include, for example, improper material selection, improper heat treatment, and waste package OCB lid closure weld flaws. The probabilities associated with the set of fabrication defects in the waste package OCB has been evaluated individually from the respective event tree/fault tree diagrams and collectively with the exception of the weld flaws in the latter case. Thus, probability values from the collective that waste packages are fabricated and loaded according to design specifications as sensitivity studies have shown that the pressurized water reactor SNF waste form in various degraded configurations, such as saturated porous schoepite, does not result in a more reactive configuration than the design basis configuration (SNL 2007 [DIRS 181373], Table A-12; SNL 2008 [DIRS 182788], Section 6.2.5).

The only such identified events that can breach a waste package in the early failure event over the regulatory period are stress corrosion cracking initiated from either weld flaws in the waste package OCB lid or undetected fabrication defects in the waste package OCB, and improperly emplaced drip shields that allow advective flow onto the waste package OCB, which may permit localized corrosion to develop. Stress corrosion cracking of the waste package OCB is addressed as an *included* FEP in FEP 2.1.03.02.0A (SNL 2008 [DIRS 179476], Section 2.1.03.02.0A) but requires an initiator mechanism such as mechanical damage except for weld flaws in the OCB closure lid where residual tensile stresses can exist. Even if a waste package were to fail early because of a defect, only a limited amount of water could collect in the waste package. This is because most through-wall penetrations, especially cracks from stress corrosion cracking, are usually tight and of limited length based on observations of SCC morphology in Alloy 22, which is expected to be transgranular rather than intergranular, as commonly observed in high-tensile environments such as light water reactors (Herrera 2004 [DIRS 168133], Section 2.0). A typical example of transgranular type SCCs is illustrated in Figure 6.3-1 for stainless steel. (While Figure 6.3-1 does not have an embedded length scale, typical SCC opening widths range from 0.01 to 0.05 mm (SNL 2007 [DIRS 181953], Section 6.3.3).) Note that no credit is taken for the reduction in the rate of water ingress into a failed waste package due to the presence of the stainless steel inner liner or, for commercial SNF, the TAD canister and for codisposal, the DOE-owned SNF canister.

WP flow rate") and insufficient to support localized corrosion. However, an improperly emplaced drip shield could result in an advective flow that could support localized corrosion. In addition, the interior of the waste packages will be warmer than the external environment for a considerable time period (SNL 2008 [DIRS 179962], Figure 6.4.2-4b). The accumulation of water within the waste package will be limited by evaporation through the breaches because of the warmer waste package as discussed in *Waste Package Flooding Probability Due to Seismic Fault Displacement* (SNL 2008 [DIRS 184078], Section 6.2.1.4). In addition, the intact configuration (base case) for commercial fuel is designed to remain subcritical when fully flooded (SNL 2008 [DIRS 182788], Section 7) and the design basis configuration accounts for corrosion loss of the neutron absorber over the first 10,000-year period following repository closure. Likewise, criticality evaluations for DOE-owned SNF include flooded conditions (Radulescu et al. 2004 [DIRS 165482], Sections 10 and 11.4; BSC 2004 [DIRS 168935], Section 6; BSC 2004 [DIRS 171926], Section 6). Significant geometrical reconfigurations would be very improbable from waste package breaches that are limited to SCC or localized corrosion since the internal structure remains in place.

Seismic analyses (SNL 2007 [DIRS 176828], Section 6.7.3.1), however, have indicated that the drip shield will be partly surrounded by rockfall at PGV levels that are below the levels with the potential for causing separation, and this rockfall occurs within the first few seconds of the ground motion. The larger rock blocks or the lithophysal rubble provide normal and shear confinement to the sidewalls and possibly the crown of the drip shield. The horizontal acceleration imparted to the drip shield by the ground motion will be resisted by the weight of the rockfall and by the frictional forces between the rock and the drip shield plates and between the footings and the invert. The exterior bulkheads on the sidewalls of the drip shield provide an additional physical restraint or "locking" mechanism between the drip shield and rubble that will constrain axial movement. Thus, the presence of rockfall around the drip shields will restrict the relative displacements that are required to separate adjacent drip shields, so that separation is not expected to occur, even for extreme ground motions. Thus, it is very improbable that a waste package will be exposed to the maximum seepage rate associated with the drip shield loss of function except for improperly emplaced drip shields.

Therefore, stress corrosion cracking in the OCB closure lid welds of waste packages is the most credible (but not the sole) initiator for events in the early failure of engineered barrier criticality FEP scenario that, coupled with neutron absorber material misload events (Section 6.2) and, for 21-PWR TAD canisters, with waste form misload events, could lead to configurations with potential for criticality.

A waste package breach is not expected to increase the criticality potential for the near-field location, or for the far-field location, (FEPs 2.1.14.17.0A and 2.2.14.09.0A, respectively, for the early failure event, Table 1.2-1). Section 6.2.2 discusses the minimum fissile mass necessary for criticality external to the waste packages (Tables 4.1-9 and 4.1-10) where it is concluded that insufficient fissile material can collect over the first 10,000-year postclosure period to achieve a critical mass.

6.3.1 Stress Corrosion Cracking in the OCB Closure Lid Welds

Sources of corrosion of the waste package OCB have been considered in the screening of processes affecting waste package degradation in *Features, Events, and Processes for the Total*

System Performance Assessment: Methods (SNL 2008 [DIRS 179476], FEP 2.1.03.02.0A). ThisFEP identifies the propagation of incipient cracks that can occur on the waste package outer barrier closure welds (since these cannot be annealed to relieve tensile stress but stress mitigation selection of an assembly with characteristics (burnup and enrichment) in the unacceptable range of the loading curve. Thus, the probability of a loading curve violation for TAD canisters is expected to be similar in magnitude to the 21-PWR Absorber Plate Waste Package value. However, neighboring assemblies that have low reactivity values may provide partial compensation for the excess reactivity from the incorrectly loaded assembly. Given that a misloading curve violation occurs, the likelihood of the misloaded configuration having potential for criticality has been shown to be 0.014 from results of a probabilistic calculation of that potential (SNL 2008 [DIRS 182788], Section 7).

The probability of misloading assemblies in the 44-BWR TAD canister is insignificant since the entire expected BWR inventory for the repository is in the acceptable region of the loading curve map (SNL 2008 [DIRS 182788], Section 6.1.1.1.3). Misloading of waste forms in DOE-owned SNF canisters is very improbable because the shape and size of the DHLW glass canisters and the various DOE-owned SNF canisters differ significantly and can be readily distinguished by visual inspection per Section 4.1.5. Thus, the waste form misload probability for DOE-owned SNF waste packages is considered sufficiently low such that, if quantified, would not significantly increase the overall probability of criticality in the repository.

Sensitivity studies have shown that the pressurized water reactor SNF waste form in various degraded configurations such as saturated porous schoepite does not result in a more reactive configuration than the design basis configuration (SNL 2007 [DIRS 181373], Table A-12; SNL 2008 [DIRS 182788], Section 6.2.5). This result supports the assertion (Section 1) that a loading curve violation is the most likely pressurized water reactor waste form configuration with potential for criticality. The probability of a potentially critical configuration resulting from an assembly misload of a PWR TAD canister, from the above discussion, is $0.014 \times 1.18 \times 10^{-5} = 1.65 \times 10^{-7}$ per TAD canister.

The probability for the occurrence of configurations with potential for criticality is evaluated from a number of independent sets of sequences of events where all of the events in any specific sequence must happen for that configuration to occur. Since the events in any one sequence can also be considered as independent entities, the probability of the sequence is the product of the probability of each individual event. The expected probability of having a particular sequence occur in exactly *k* waste packages in the repository is a Binomial process described by the Binomial probability distribution, P_B (*n; p, N*), with probability "p" for occurrence in a waste package and "q = 1 - p" for non-occurrence. The probability of having the sequence occur in at least "*k+1*" waste packages is given by:

$$P(\textit{at least } k + 1 \textit{ waste packages}) = 1 - \sum_{l=0 \textit{ to } k} P_B(l; p, N) \qquad \text{(Eq. 6.3-1)}$$

where

k = number of items affected (e.g., waste packages, drip shields)
p = probability for occurrence of the event
N = number of possible items involved.

For large N and small "p" where N × p ≅ λ, the Binomial distribution converges to the Poisson distribution with a mean of λ = N × p. Then Equation 6.3-1 can be written as:

$$P(at\ least\ k+1\ waste\ packages) = 1 - \sum_{l=0,k} P_P(l; N \times p) = 1 - \sum_{l=0,k} \frac{\lambda^l \times \exp(-\lambda)}{l!} \qquad \text{(Eq. 6.3-2)}$$

The criterion for screening criticality scenarios from consideration in the repository is having a low probability for the occurrence of a criticality event sequence for any waste package in the repository (which can be stated as the probability of having at least one such sequence occur) is given by Equation 6.3-2 with $k = 0$. For the case where $k = 0$ and λ is small, Equation 6.3-2 can be approximated by λ. Then the probability of at least one waste package configuration with criticality potential occurring in the repository is given by λ (= $N \times p$).

The initiating event leading to a possible waste package early failure scenario is a SCC caused breach of the waste package OCB. Initiators for SCCs, discussed above, are OCB closure lid weld flaws having a per package probability of $3.84 \times 10^{-5} \times 1.25 \times 10^{-3}$, OCB fabrication flaws having a per package probability of 1.13×10^{-4}, and a misplaced drip shield coupled with localized corrosion having a per package probability of $4.36 \times 10^{-9} \times 1.0$, where the probability of localized corrosion is set to 1.0. The combined probability of the initiators for the suite of early failure scenario evaluations is given by:

$$(3.84 \times 10^{-5} \times 1.25 \times 10^{-3}) + (1.13 \times 10^{-4}) + (4.36 \times 10^{-9} \times 1.0) = 1.13 \times 10^{-4}$$

Evaluating the event sequences for commercial SNF and DOE-owned SNF with potential for criticality using the number of 21-PWR TAD canisters given in Table 4.1-3 as 4,568, the number of 44-BWR canisters as 2,915, and DOE-owned SNF canisters with criticality potential (DOE1, DOE2, and DOE7 groups) as 1,223 and setting the number of drip shields equal to the number of waste packages gives:

PWR TAD canister loading curve violation:
$\{1\text{-}P_B\ (0; ((3.84 \times 10^{-5} \times 1.25 \times 10^{-3} + 1.13 \times 10^{-4} + 4.36 \times 10^{-9} \times 1.0) \times 1.65 \times 10^{-7}), 4568)\} = 8.5 \times 10^{-8}$

PWR TAD canister absorber misload:
$\{1\text{-}P_B\ (0; ((3.84 \times 10^{-5} \times 1.25 \times 10^{-3} + 1.13 \times 10^{-4} + 4.36 \times 10^{-9} \times 1.0) \times 1.25 \times 10^{-7}), 4568)\} = 6.5 \times 10^{-8}$

44-BWR TAD canister absorber misload:
$\{1\text{-}P_B\ (0; ((3.84 \times 10^{-5} \times 1.25 \times 10^{-3} + 1.13 \times 10^{-4} + 4.36 \times 10^{-9} \times 1.0) \times 1.25 \times 10^{-7}), 2915)\} = 4.1 \times 10^{-8}$

DOE-owned SNF canister absorber misload (DOE1, DOE2, and DOE7):
$\{1\text{-}P_B\ (0; ((3.84 \times 10^{-5} \times 1.25 \times 10^{-3} + 1.13 \times 10^{-4} + 4.36 \times 10^{-9} \times 1.0) \times 1.25 \times 10^{-7}), 1223)\} = 1.7 \times 10^{-8}$

Evaluating the event sequences for DOE-owned SNF with the additional absorber loading constraint from Section 4.1.15 that the DOE1 waste form (MOX) and DOE7 waste form (aluminum-based DOE-owned SNF) include neutron absorber shot as well as plate type

6.4.1 Waste Package Failure from a Seismic Event

Analyses of damage to drip shields from fault displacements expected to be applicable to the first 10,000-year-period after repository closure considers the drip shields to be intact prior to the event for determining the clearances between EBS components (SNL 2007 [DIRS 176828], Section 6.11.1). Damage to the drip shield causing loss of function is not expected to result from seismic faulting until sufficient displacement occurs to make contact between the drip shield and the drift. The emplacement drift has a nominal diameter of 5.5 m (5,500 mm) (SNL 2007 [DIRS 179466], Table 4-1, Item 01-10). Within the drift, the steel support beams and associated ballast form a level invert with a surface height of 52 in (1,320.8 mm) above the lowest part of the drift (SNL 2007 [DIRS 179354], Figure 4-1). The drip shield is a free-standing structure that sits on the invert. The drip shield has an external height for the overlap section of 113.62 in (2,886 mm) (SNL 2007 [DIRS 179354], Table 4-2, Item 07-01), rounded up to 2,890 mm. The internal height of the drip shield, defined as the distance from the invert floor to the lowest point on the underside of the top of the drip shield, is 106.93 in (2,715.8 mm) (SNL 2007 [DIRS 179354], Table 4-2, Item 07-01), which is rounded to 107 in (2,717.8 mm). The clearance between the crown (top) of the drip shield and the drift roof is 50.37 in (SNL 2007 [DIRS 179354], Table 4-2, Item 07-01), rounded to the nearest inch or 1,270 mm.

Seismic faulting can generate a large number of possible dynamic response scenarios in a drift. A reasonable approach for simplifying the analyses was to calculate clearances excluding the pallet elevations[5] (SNL 2007 [DIRS 176828], Section 6.11.1.1). The combined clearance between the crown of the drip shield and the roof of the drift (1,270 mm) and between the top of the waste package and the bottom of the drip shield, as shown in Table 6.4-1, determines the maximum fault displacement that could occur before the waste packages are potentially damaged or breached through a shearing mechanism. This analysis selected the smaller of these clearances since drift collapse is likely in the lithophysal zone during a seismic disruptive event associated with fault displacement. Fault displacement in excess of the clearance values in Table 6.4-1 are conservatively considered to fail the waste package and the overlying drip shield.

The set of clearance values in Table 6.4-1 represents the failure criterion for waste packages and drip shields under fault displacement when the waste package OCB and drip shield are intact at

[5] The following is the rationale for neglecting the pallet elevation (SNL 2007 [DIRS 176828], Section 6.11.1.1):

> Movement along a sudden discontinuity will affect the rubble surrounding the drip shield after drift collapse in the lithophysal zone. The lithophysal rubble is a loosely packed material with porosities between 0.09 and 0.29. (The porosity of rockfall in the nonlithophysal units is similar to that for the lithophysal rubble.) With this free space, the rubble has substantial movement in the plane of discontinuity and longitudinally along the drift axis during the fault displacement. The movement of the rubble will allow the drip shield to move with the fault displacement, rather than being rigidly pinned to the invert. In this situation, the effective clearance around the drip shield is expected to be significantly larger than space between the top of the waste package and bottom of the drip shield.
>
> Simulations demonstrate that the rubble particles undergo large dynamic motion in response to displacements of the drip shield, similar to what would occur during a vertical fault displacement. It follows that the clearance between the top of the drip shield and the roof of the drift will be partly available, but the exact value is difficult to quantify. Likewise, the dynamic response of the rubble, invert and emplacement pallet during a fault displacement is difficult to predict. As a simplification, the approximation is made that the clearance between the top of the waste package and the bottom of the drip shield is determined without the pallet. This is a reasonable approximation because the clearance between the top of the drip shield and the roof of the drift, 1,270 mm, is more than four times greater than the differences in clearance with or without considering the pallet, which range from 283 to 317 mm (SNL 2007 [DIRS 176828], Table 6-57).

A rupture or tear may occur in a drip shield plate if the local strain exceeds the ultimate tensile strain due to either loading of the drip shield from drift collapse in the lithophysal zone or rock block impacts in the nonlithophysal zone on the drip shield caused by vibratory ground motion (SNL 2008 [DIRS 179476], FEP 2.1.03.03.0C, FEP 2.1.03.03.0B). Localized corrosion could potentially cause waste package failure from exposure to advective seepage flow following rupture of a drip shield (SNL 2007 [DIRS 176828], Section 6.1.4). The most likely form of localized corrosion to affect the waste package OCB is crevice corrosion (Section 4.1.14) that can attack discrete locations such as occluded regions where contact exists between the waste package OCB and pallet if environmental conditions favorable to the corrosion processes are present. A condition necessary for localized corrosion is the persistent presence of an aqueous medium on the waste package OCB surface and dissolved chemical ions. Environmental conditions conducive to localized corrosion are present only for portions of the initial 10,000-year period following repository closure. Localized corrosion, once initiated, can penetrate the waste package OCB in less than 1,000 years (Section 4.1.14).

For a criticality event to occur, the proper combination of materials (neutron moderators, neutron absorbers, fissile materials, or isotopes) and geometric configuration must exist as stated in Section 6.2. The presence of neutron absorber materials in waste package canisters is important for criticality control during the 10,000-year period following repository closure for the majority of the canisters proposed for disposal of SNF in the repository. For seismically induced vibratory events, there are no mechanisms identified that can lead to removal of neutron absorber material from a waste package. For such a situation to occur, vibratory ground motions would need to induce failure of the spent fuel canisters and fracture the fuel baskets. In addition, there are no forces identified that can systematically separate the absorber materials from the fuel material that would result in concentrating absorber in one part of a waste package and fuel in another. It has been previously demonstrated through loading curve analyses for the 21–PWR Absorber Plate and the 44–BWR Absorber Plate waste package variants that an intact, fully flooded waste package configuration as designed cannot achieve criticality (SNL 2008 [DIRS 182788], Section 6.2.2). The 21-PWR and 44-BWR TAD canisters are similarly expected to not have any criticality potential in an aqueous environment provided the borated stainless steel (or its degraded form as chromium boride) absorber proposed for use in the TAD canisters remains in the proximity of the waste form. However, neutron absorber material misloads can occur in TAD canisters as the result of various operations (or the lack thereof) during the canister fabrication and loading processes. These processes include the use of wrong materials and/or failure to install the specified neutron absorber materials into the canister, which affect the criticality potential of waste forms. Likewise, the DOE-owned SNF canisters do not have any criticality potential in an aqueous environment provided the Ni–Gd absorber proposed for use in the DOE-owned SNF canisters remains in the proximity of the waste form (BSC 2006 [DIRS 181335], Section 7.10) and Section 4.1.15.

Vibratory motions from seismic events could theoretically cause schoepite in a breached commercial SNF waste package to migrate to the ends of the fuel assembly tubes, fall to the bottom of a waste package, and thus separate from the neutron absorber material. This scenario is expected to be very improbable for reasons that include the following:

- The fuel assembly tubes extend the full length of the fuel assemblies allowing minimal clearance for material to pass

- The active fuel is centered in the fuel assemblies away from the ends where losses could occur
- Assemblies will likely have their end caps attached when loaded into the TAD canisters
- Assembly hardware (e.g., spacer grids and end fittings) will limit the magnitude of any lateral movement
- The clearance between the fuel assembly tubes and end plates is ≤ 1 inch.

Thus, for commercial SNF, the fissile material will likely remain within the fuel tubes that contain the neutron absorber material, minimizing the likelihood that a critical configuration could assemble at the bottom of a waste package from schoepite exiting the fuel assembly tubes.

The same scenario (separation of fissile and absorber material) does not exist for DOE-owned SNF since the DOE canisters have a different geometry (small (18-inch diameter, sealed container) and the canister must breach for material to leave the canister. Analyses have shown (Radulescu et al. 2004 [DIRS 165482], Section 11.4) that all intact and degraded configurations of the DOE-owned SNF have a k_{eff} below the critical limit provided the neutron absorber material is present as required. Thus, vibratory motions from seismic events that do not cause failure of the DOE canister have little likelihood of initiating events that could lead to configurations with potential for criticality.

As discussed in Section 6.3.1, the rate of water transport through cracks in both the drip shield and waste package under seepage drips indicates that the maximum volumetric flow rate through SCCs in a given waste package is very low (DTN: SN0705WFLOWSCC.001 [DIRS 184848], file: *Analysis for Water Flow through Stress Corrosion Cracking (SCC) Cracks in Waste Package and Drip Shield.xls*, spreadsheets: "Sheet flow DS flow rate" and "Sheet flow WP flow rate") and insufficient to support localized corrosion. In addition, the interior of the waste packages will be warmer than the external environment for a considerable time period (SNL 2008 [DIRS 179962], Figure 6.4.2-4b). The accumulation of water within the waste package will be limited by evaporation through the breaches because of the warmer waste package as discussed in *Waste Package Flooding Probability Due to Seismic Fault Displacement* (SNL 2008 [DIRS 184078], Section 6.2.1.4). In addition, the intact configuration for commercial fuel is designed to remain subcritical when fully flooded (SNL 2008 [DIRS 182788], Section 7) and the design basis configuration accounts for corrosion loss of the neutron absorber over the first 10,000-year period following repository closure. Likewise, criticality evaluations for DOE-owned SNF include flooded conditions (Radulescu et al. 2004 [DIRS 165482], Sections 10 and 11.4; BSC 2004 [DIRS 168935], Section 6; BSC 2004 [DIRS 171926], Section 6). However, it is very improbable that the cladding can maintain its barrier function during a vibratory ground motion event that damages the waste package OCB allowing schoepite to form after a breach develops. Thus, the set of events evaluated in Section 6.3.1 as contributors to the probability of criticality are appropriate for vibratory ground motions.

The series of events begins with the occurrence of a seismic vibratory ground motion event. Events in the various seismic vibratory scenarios requiring probability values for the calculation are listed as follows:

1. Probability of a seismic vibratory ground motion event

far-field configurations (FEPs 2.1.14.20.0A and 2.2.14.10.0A, respectively) since the probability of a waste package breach from a seismic vibratory rupture of a drip shield is already very low and external accumulation can only proceed after such an event. A discussion of the events required for external critical configurations is provided in Section 4.1.15 with the conclusion that the likelihood for the occurrence of configurations with potential for criticality was very low. Thus, the criticality potential in the near-field and far-field locations referenced by FEPs 2.1.14.20.0A and 2.2.14.10.0A from a seismic vibratory drip shield rupture and localized corrosion induced waste package breach is insignificant.

6.4.2.3 Evaluation of Waste Package Damage from Seismically Induced Large, Single Rock Block Falls

This section evaluates the probability of achieving a configuration with criticality potential in the repository resulting from large, single block impacts to the waste package (after penetration of the drip shield resulting from structural failure) in the nonlithophysal rock units. Impacts that can damage a waste package must fail the drip shield stiffeners that have different fragility characteristics than the drip shield plates (DTN: MO0703PASDSTAT.001 [DIRS 183148], file: *Frame Fragility Analysis.xls*). The large block analysis indicated that waste package damage could occur for the most severe events involving rock Block 1 (SNL 2007 [DIRS 178851], Section 6.4.7.3) characterized by a rock block mass of 28.29 metric tons at a PGV level of 5.35 m/s (SNL 2007 [DIRS 178851], Table 6-153). It is important to note that the analysis for Block 1 was based solely on the 5.35 m/s PGV level that corresponds to an exceedance frequency of 1×10^{-7} per year on the unbounded hazard curve (Table 4.1-5) but is well below the 1×10^{-8} annual exceedance frequency on the bounded hazard curve that is the basis for TSPA. The conclusion from the calculations at a PGV level of 5.35 m/s is that rock block 1 would cause the stiffeners to fail. The maximum stiffener displacement expected for drip shield stiffeners from an impact of rock Block 1 (28.29 metric tons) is 20.4 cm for a drip shield (SNL 2007 [DIRS 178851], Section 6.4.7.3). Since the impact is expected to fail the drip shield stiffeners, there is a possibility that deformation of the drip shield may continue such that contact between the rock block and waste package OCB could happen although at a substantially reduced velocity but still sufficient to be an initiator for SCCs in the waste package OCB. However, a complete failure process of the drip shield has yet to be performed for the impact of rock block 1 (which fails the drip shield stiffeners). (Note: This failure mode is screened out for TSPA (SNL 2008 [DIRS 179476], FEP 1.2.03.02.0B) on the basis that failure of the drip shield stiffeners is unrealistic.)

Failure of the drip shield plates from impacts by rock blocks 2 through 7 do not cause contact between the drip shields and the waste packages because the axial stiffeners do not tear or rupture (SNL 2007 [DIRS 176828], Table 6-51). Thus, there is no potential for damage to the waste packages from rupture of the drip shield plates due to impacts by rock blocks 2 through 7 because the framework of the drip shields remains structurally intact (i.e., the axial stiffeners remain intact) and are able to deflect rockfall debris away from the waste packages (SNL 2007 [DIRS 176828], Section 6.10.2.11).

Although a rockfall event that could fracture the drip shield stiffeners is hypothetically possible, the probability of such an event is well below the low probability limit for the bounded hazard curve (Figure 4.1-1). Thus, the contribution of such events to the probability of achieving a and accumulation in the external location. As stated above, the probabilities of these additional events are less than one. Section 6.2.2 discusses the minimum fissile mass necessary for criticality external to the waste packages and concludes that, for a subset of the waste forms, insufficient fissile material can collect over the first 10,000-year postclosure period to achieve a critical mass. A discussion of the events required for external critical configurations is provided in Section 4.1.15 with the conclusion that the likelihood for the occurrence of configurations with potential for criticality was very low. Thus, the criticality potential in the near-field and far-field locations referenced by FEPs 2.1.14.20.0A and 2.2.14.10.0A from a seismic faulting event is concluded to be insignificant.

The events in the short sequences are considered as the principal contributors to the probability of occurrence of configurations having criticality potential following a seismic initiating event. Extending the sequences to include additional events would further decrease the probability for the occurrence of configurations with potential for criticality. Conditions inherent in the use of one or two sequences of events to estimate a conservative value for the probability of achieving a configuration with potential for criticality were discussed in Section 6.3.2. When the probabilities, although not explicitly quantified, of each of these necessary events are considered, together with the probability of the initiating event, the probability of criticality resulting from this seismic scenario is considered sufficiently low such that, if evaluated, would not change the conclusion, based on low probability, that a criticality event in the repository can be screened from further consideration in analyses.

6.5 FEPS ASSOCIATED WITH ROCKFALL EVENT SEQUENCE INITIATORS

The repository horizon lies within the Topopah Spring Tuff, and essentially consists of two main types of rock: the nonlithophysal rock and the lithophysal rock (Table 4.1-4). The nonlithophysal rocks, which comprise 15% of the emplacement area, are hard, strong, jointed rock masses whereas the lithophysal rocks, which comprise 85% of the emplacement area, are relatively more deformable with lower compressive strength (BSC 2004 [DIRS 166107], p. vii). The lithophysal rocks also contain cavities in the rock (lithophysae) that are connected by intense fracturing (BSC 2004 [DIRS 166107], Sections 6.1.2 and 6.4.1.1). Rockfall has been conjectured to be an initiating event that could cause drip shield failure through rupture leading to subsequent waste package breaching through localized corrosion (SNL 2008 [DIRS 179476], FEP 2.1.07.01.0A). Such breaches may allow the influx of seepage water (either advective or diffusive) into the waste package, which, in turn, has the potential to initiate processes leading to a critical configuration.

Three mechanisms in the repository environment have been identified as potential initiators of rockfall events in the emplacement drifts: (1) seismic vibratory ground motions, (2) thermal stress (generated by the decay heat from the emplaced waste packages), and (3) static fatigue from nominal degradation of rock (BSC 2004 [DIRS 166107], p. viii). Drip shield damage from rockfall induced by thermal loading is found to be minor since the block sizes for such rockfall are small with a mean mass of less than 0.2 metric tons (BSC 2004 [DIRS 166107], p. 6-102). The nominal case for drift degradation (i.e., considering thermal and time-dependent effects, but excluding seismic effects) results in only partial collapse of the emplacement drifts at 20,000 years. The conclusion for the nominal scenario is that negligible drift degradation will occur over the initial 10,000-year postclosure period (BSC 2004 [DIRS 166107], p. x). Thus, seismically induced rockfall is the only one of the three mechanisms that has potential for

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8.2 CODES, STANDARDS, REGULATIONS, AND PROCEDURES

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APPENDIX I. HYDROGEN DEFLAGRATION EVENTS IN A WASTE PACKAGE

The consequences of hydrogen generation by radiolysis and a subsequent deflagration event in a waste package are discussed in this Appendix for potential use as a contribution to defense-in-depth for criticality purposes without an explicit probabilistic evaluation. This event is dependent on residual water being left in a TAD canister and/or waste package due to a failure of the drying and inerting process that is considered as sufficiently improbable to permit the probability to be designated as insignificant (Section 6.2).

Chemical species produced by radiolysis have been identified in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2000 [DIRS 165505], p. 2-2) as a mechanism for exacerbating corrosion of the EBS components in the repository. Radiolytic sources of corrosion have also been considered in the screening of processes affecting cladding degradation (FEP 2.1.02.15.0A) in *Features, Events, and Processes for the Total System Performance Assessment: Methods* (SNL 2008 [DIRS 179476]) and excluded on the basis of low consequences for TSPA analyses. The direct effects of radiolysis within a waste package are considered in FEP 2.1.13.01.0A (Radiolysis) and secondary effects in FEP 2.1.12.01.0A (Gas Generation) and FEP 2.1.12.08.0A (Gas Explosions in EBS) (SNL 2008 [DIRS 179476]).

The effects of radiation on fluids in either a liquid or gaseous state have been discussed by a number of authors (e.g., Green 1994 [DIRS 181678]; Shoesmith and King 1998 [DIRS 112178], p. 2). While Shoesmith and King (1998 [DIRS 112178]) address primarily the effects of gamma radiation on corrosion properties of waste package materials, such processes derive from the radiolytic effects on fluids. Such radiolytic effects on fluids may lead to formation of a variety of species such as carbon dioxide, carbon monoxide, hydrogen, oxygen, methane, and various nitrogen oxide forms. Oxidizing radicals and molecular products may be generated where oxidants include, but are not necessarily limited to, OH^+, O_2^-, H_2O_2, and O_2. Likewise, radiolysis can lead to the formation of reductants such as H^+ and H_2. In moist air environments, radiolytic processes can lead to the fixation of nitrogen as NO, NO_2, and especially HNO_3 (Reed and Van Konynenburg 1988 [DIRS 156140], pp. 393 to 404). Nitric acid is one of the principal corrosive radiolytic chemical species produced in an irradiated air-water vapor system when the hydroxyl radicals generated from the water vapor react with nitrogen dioxides, which are formed by the radiolytic reaction between nitrogen and oxygen, to form acids. The number of oxidants and reductants formed by radiolysis within intact waste packages that may contain residual moisture is limited to those that can be generated from water and/or water vapor. Since this latter group includes both hydrogen and oxygen, an analysis of the quantity and type of compounds formed, particularly potentially flammable gas mixtures such as H_2 and O_2, is necessary to evaluate an appropriate safety envelope for SNF waste packages.

Radiolytic production of particular chemical species depends upon the radiation environment, the chemical components present, and the physical environment where the radiolytic reactions are occurring. However, the yield of any given chemical species is characterized by a single parameter, "G," identified as the G-factor (Reed and Van Konynenburg 1991 [DIRS 153009], pp. 1,396 to 1,403). The "G" value represents the number of molecules of a chemical species produced per 100 eV of absorbed radiation energy in the volume containing the irradiated environment. While both gamma and neutron radiation from SNF are similarly effective with respect to radiolytic species production, the gamma dose from commercial SNF is two or more