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	Scientific Analysis/Calculation Error Resolution Document *Complete only applicable items.*	QA: QA Page 1 of 29

1. Document Number: ANL-DS0-NU-000001	2. Revision/Addendum: 00	3. ERD: 05
4. Title: Screening Analysis of Criticality Features, Events, and Processes for License Application	5. No. of Pages Attached: 28	

6. Description of and Justification for Change (Identify affected pages, applicable CRs and TBVs):

Introduction:

This document is being written as an action to resolve the following CRs:

CR-13772: Inconsistent Justification for Neutron Absorber Material Misload Probabilities

CR-13797: Formula Error in Damage Probability Calculation

Background Information Summary:

While responding to RAI 3.2.2.1.2.1-5-008, CR-13772 was initiated because the treatment of neutron absorber misload when using shot was evaluated differently than when using neutron absorber plates. While assessing the impact of including the shot absorber error consistently with the plate absorber error, the formula error which initiated CR-13797 was discovered. This ERD will correct the formula error identified in CR-13797, add additional qualitative justification for treating the neutron absorber misload between absorber plates and absorber shot differently, add a sensitivity evaluation that treats the neutron absorber misload consistently to determine the impact to total probability of criticality, and update the applicable files in Output DTN: MO0705CRITPROB.000. This ERD is written using page changes with changed lines identified with change bars. All prior ERD (ERD01 through ERD04) and ACN (ACN 01) changes have been incorporated into the pages changed due to this ERD and are also identified by change bars.

AMR Changes:

Please see attached for changed pages. Changed pages of ANL-DS0-NU-000001 REV 00 are as follows: 1-8; 4-1; 4-2; 4-12; 4-18; 4-19; 6-3; 6-8; 6-13; 6-15; 6-16; 6-27; 6-28; 6-29; 6-31; 6-36; 6-46; 7-1; 7-2; and 7-3. In addition to the changes to resolve the CRs above, an editorial correction was made on pages 6-15 and 6-27 to change the citation of Table 4.1-3 to 4.1-2. DIRS references 183006 and 183007 were added to Section 8.3.

Impact Evaluations/Results:

The following documents were evaluated for impact: : LA-SAR, ANL-EBS-PA-000014 Rev. 00, ANL-EBS-MD-000076 Rev. 00 ACN 01, ANL-WIS-MD-000024 Rev. 01 ACN 01, ANL-WIS-MD-000026 Rev. 00, and ANL-WIS-MD-000027 Rev. 00 ACN 01.

See attached for impacts.

The changes in this ERD do not impact the conclusion of ANL-DS0-NU-000001 REV 00 nor any other affected document as the probability of criticality for the DOE SNF and CSNF waste forms results in a net decrease due to the changes from this ERD.

	Printed Name	Signature	Date
7. Checker	Cliff Hansen	Clifford Hansen	8/20/09
8. QCS/QA Reviewer	Brian Mitcheltree	B Mitchtr	8/20/09
9. Originator	John Scaglione	John Scaglione	8/20/09
10. Responsible Manager	Jerry McNeish	Jerry A McNeish	8.20.09

- Fabrication activities for waste packages are to be performed in accordance with a quality control program as specified in Section 9.4 of *Waste Package Fabrication Specification* as cited in Section 4.1.2.1 of *Total System Performance Assessment Data Input Package for Requirements Analysis for Transportation Aging and Disposal Canister and Related Waste Package Physical Attributes Basis for Performance Assessment* (SNL 2007 [DIRS 179394]). Quality checks (e.g., weight measurements of loaded DOE-owned SNF canisters containing absorber material in shot form) in addition to quality control programs may be necessary to sufficiently minimize operational or process failures.

- The various surrogate processes and operations used in this analysis are typical of quality control procedures and are considered reasonable proxies for such quality control procedures. However, as the FEPs screening justification is based, in part, on the probabilities derived from these surrogates, results from analyses of the final operational and fabrication procedures must demonstrate that the overall error probabilities from the fabrication and operational processes satisfy the FEPs screening justifications.

- The overall probability of criticality estimate does not include an evaluation of Naval Nuclear Propulsion Program SNF. The overall probability for the repository will remain below the regulatory criterion provided that the value for the naval SNF is less than 6.4 $\times 10^{-5}$ for the repository over 10,000 years.

- The results of the FEP screening presented herein are specific to the repository design and processes for YMP available at the time of the TSPA-LA. Changes in direct inputs listed in Section 4.1, in license application postclosure design parameters used for this evaluation, or in other subsurface conditions will require evaluation to determine whether the changes are within the limits stated in the FEP evaluations. Engineering and design changes are subject to evaluation to determine whether there are any adverse impacts to safety, as codified at 10 CFR Part 63 ([DIRS 180319], Subpart 73 and Subparts F and G) (see also the requirements at 10 CFR Part 63 [DIRS 180319], Subpart 44).

1.4 IMPLEMENTATION OF DISPOSAL CRITICALITY ANALYSIS METHODOLOGY

The criticality FEPs screening analysis implements the risk-informed, performance-based disposal criticality analysis methodology as documented in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505]). An overview of the disposal criticality analysis methodology is presented in Figure 1.4-1 (YMP 2003 [DIRS 165505], Figure 3-1). The text in various boxes in Figure 1.4-1 has been modified from the original figure to improve the clarity of the items. The shaded boxes in Figure 1.4-1 signify the portion of the methodology associated with the FEPs screening analysis. The development of potential criticality scenarios is based on the standard configuration classes of the master scenario list (Box 1 of Figure 1.4-1) (YMP 2003 [DIRS 165505], Section 3.3). These criticality scenarios have been identified as having the most likely potential to increase the maximum k_{eff} of an in-package or external system. The criticality FEPs screening decision is based on probabilities

4. INPUTS

Technical product input usage is categorized in SCI-PRO-004, *Managing Technical Product Inputs*, as either direct input or indirect input. Direct input (addressed in this Section) is input used in a technical product that is directly relied on to support the results or conclusions. Indirect input is used to provide supporting information and is not used in the development of results or conclusions in the technical product. Supporting information for the direct input data is also provided in this section to aid in transparency and clarity.

All direct inputs used in this report are identified in Section 4.1. The direct inputs were obtained from controlled source documents and other appropriate sources in accordance with the controlling procedure SCI-PRO-004. The methods used for qualification of external data are discussed in Appendix II. The FEP screening criteria derived from 10 CFR Part 63 [DIRS 180319] and expanded in *Yucca Mountain Review Plan, Final Report* (NRC 2003 [DIRS 163274]) that are relevant to the FEP screening analysis are identified in Section 4.2 together with the method for addressing these criteria. Lastly, codes and standards applicable to the criticality FEP screening analysis are identified in Section 4.2.

4.1 DIRECT INPUTS

The following sections present the direct inputs used to perform the screening justifications for postclosure criticality FEPs which have been obtained from DTN: MO0706SPAFEPLA.001 ([DIRS 185200], folder FEPs_be.zip, file *FEPs_be.mdb*) and listed in Table 1.2-1. Supporting information for the direct input data is also provided in this section for aiding transparency and clarity. Use of these data is justified as they are extracted from qualified project sources and their application is compatible with their developed purpose and limitations.

4.1.1 Mean Annual Seismic Exceedance Frequency Range and Time of Seismic Event

The mean annual seismic exceedance frequency of concern with respect to the probability of criticality evaluation ranges from 10^{-4} to 10^{-8} per year (SNL 2007 [DIRS 176828], Table 6-61). Seismic events occur randomly in time and are considered as independent events with regard to magnitude, time, and location. These events are modeled as a Poisson process (SNL 2007 [DIRS 176828], Section 5.2) that represents a compromise between the complexity of natural processes, the availability of information, and the sensitivity of relevant results. The range of annual exceedance frequencies used for particular seismic consequence evaluations may not cover the entire range due to varying thresholds for damage (e.g., the range for seismic faulting analyses is from approximately 10^{-7} to 10^{-8} per year) (SNL 2007 [DIRS 176828], Table 6-65).

4.1.2 Waste Package Fabrication and Operational Error Probabilities

As stated in Section 1, one of the principal events that can lead to configurations with potential for criticality is the Top Event "NA-MISLOAD" (BSC 2004 [DIRS 172494], Figure I-5) representing a neutron absorber misload in a canister. The neutron absorber misload event represents the improper performance of the neutron absorber due to fabrication related errors (e.g., incorrect material installed during fabrication, absorber content outside specified range). An absorber misload event can only occur during fabrication of a canister or its components due to process or procedural errors and are similar to waste package and drip shield early failure mechanisms (SNL 2007 [DIRS 178765], Section 6.2). Errors in fabrication and operational processes are primarily due to human factors that are common to the various processes. Surrogate fabrication and operational processes with associated human factor errors have been evaluated in *Analysis of Mechanisms for Early Waste Package/Drip Shield Failure* (SNL 2007 [DIRS 178765]) and results are used for such initiating events for the waste package and drip shield early failure mechanisms. The surrogate processes are:

1. Improper performance of the neutron absorber represented as a material selection error in the waste package component fabrication processes (SNL 2007 [DIRS 178765], Section 6.3.2)

2. Failure of the waste package and canister drying/inerting process represented as an operational process error (SNL 2007 [DIRS 178765], Section 6.3.5)

3. Drip shield misplacement allowing the possibility of advective seepage flow directly on a waste package OCB (SNL 2007 [DIRS 178765], Section 6.4.4)

4. Fabrication flaws allowing increased susceptibility to SCCs (SNL 2007 [DIRS 178765], Section 6.3).

Waste package fabrication and operational process error probabilities have been obtained from DTNs: MO0701PASHIELD.000 [DIRS 186103] and MO0705EARLYEND.000 [DIRS 186104]. The probability values assigned to absorber misloads due to material selection errors, waste package and canister operational process failures, waste package SCC mitigation process failures, and the occurrence of OCB closure lid weld flaws for this analysis are listed in Table 4.1-1. The operational process failures include the drying and inerting process and OCB outer lid weld stress mitigation process. These processes are conceptually similar as each requires operator actions and the human error failure rate from the OCB outer lid weld stress mitigation process is assigned to each one in Table 4.1-1.

Table 4.1-1. Undetected Errors in Waste Package Fabrication and Operational Processes

Waste Package Operations	Probability per Canister
Absorber material selection error [a]	1.25×10^{-7} per canister
Drying and inerting process failure	3.77×10^{-5} per canister
Outer closure lid weld stress mitigation process failure [a]	3.77×10^{-5} per canister
Emplacement error for drip shield [a]	2.19×10^{-9} per drip shield
Fraction of waste package OCB lid weld flaws oriented normally to surface [b]	8.0×10^{-3}
Probability of undetected fabrication defects in a waste package OCB [c]	1.13×10^{-4} per waste package
Probability of at least one flaw in waste package OCB lid closure weld [d]	1.56×10^{-1}

Sources: [a] DTN: MO0705EARLYEND.000 [DIRS 186104], file: *Table 6-8 and 6-12.doc*.
[b] DTN: MO0701PASHIELD.000 [DIRS 186103], file: *Tables for DTN Readme.doc*, Table 1.
[c] DTN: MO0701PASHIELD.000 [DIRS 186103], file: *SAPHIRE OUTPUT.zip*.
[d] DTN: MO0701PASHIELD.000 [DIRS 186103], file: *EarlyFail-WeldDefects.zip*, Section A.7.

100%, and 105% of the yield strength of Alloy 22). The intermediate value of 100% has been included because damaged areas may be a nonlinear function of RST. For convenience, these three values are referred to as the 90%, 100%, and 105% RST, respectively (SNL 2007 [DIRS 176828], Section 6.1.4). The probabilities evaluated at the 90% RST level give a conservative estimate and are used for the screening evaluations.

The estimate for the probability of damage to the OCB of a TAD canister waste package due to seismic vibratory induced ground motion is given as 0.118 (SNL 2007 [DIRS 176828], Section 6.5.1.2, DTN: MO0703PASDSTAT.001 [DIRS 183148], file: *Kinematic Damage Abstraction 23-mm Intact.xls*, spreadsheet: “Probability of Damage”) at an RST value set at 90% of the yield strength of Alloy 22 for nondegraded waste package components. The probability of damage to the OCB of a TAD canister waste package is zero at an RST value set at 100% of the Alloy 22 yield strength.

The probability of damage to the OCB of a codisposal waste package due to seismic-induced vibratory ground motion is discussed in *Seismic Consequence Abstraction* (SNL 2007 [DIRS 176828], Section 6.6.1.2). From the kinematic response of the codisposal waste packages to vibratory induced ground motions, the probability of damage to the OCB is nonzero over a range of PGV levels for the three RST levels as given in Table 4.1-6. The codisposal waste package will remain undamaged for zero probability states.

Table 4.1-6. Probability of Damage for Intact Codisposal Waste Package

PGV Level (m/s)	Residual Stress Threshold as Percentage of Yield Strength		
	90%	**100%**	**105%**
0.364	0	0	0
0.4	0.029	0	0
1.05	0.559	0	0
2.44	0.941	0.147	0
4.07	1	0.412	0

Source: DTN: MO0703PASDSTAT.001 [DIRS 183148], file: *CDSP Kinematic Damage Abstraction 23-mm Intact.xls*, spreadsheet: “Probability of Damage - New.”

This data (Table 4.1-6) is used directly in DTN: MO0708FREQCALC.000 [DIRS 183006] and MO0708CDSPSEIS.000 [DIRS 183007] for integrating over the probability density functions of seismic frequency and damage probability conditional on RST over the seismic exceedance frequency range. Integrated values of damage frequency are provided in Table 4.1-6a for the CDSP and CSNF waste packages, as well as the probabilities for the number of seismic events that cause damage to waste packages over 10,000 years (P_D), which are calculated using the Poisson distribution (See Equation 6.3-1 and 6.3-2).

$$f(x)=\frac{\mu^x}{x!}e^{-\mu} \qquad \text{(Eq. 4.1)}$$

where μ = np (n is the number of independent performances, p is the probability per trial), and x is the number of times an event occurs.

The probability of one or more damaging seismic events is the complement of f(x) (i.e., 1-f(x)).

Table 4.1-6a. Integrated Probability of Damage Due to Seismic Vibratory Ground Motion

RST (%)	CDSP		CSNF	
	Damage Frequency (yr^{-1})[a]	P_D	Damage Frequency (yr^{-1})[b]	P_D
90	2.181×10^{-5}	0.196	1.575×10^{-8}	1.57×10^{-4}
100	4.242×10^{-7}	0.004	0	0
	Expected Value of Distribution for RST			
90 to 105	7.484×10^{-6}	0.072	5.249×10^{-9}	5.25×10^{-5}

NOTES: [a] DTN: MO0708CDSPSEIS.000 [DIRS 183007], FreqDamageCDSP_v5.pdf
[b] DTN: MO0708FREQCALC.000 [DIRS 183006]. FreqDamageTAD.pdf

Significant rockfall onto and around the drip shields is likely to occur during seismic vibratory events, which have the potential of rupturing the drip shields. The likelihood of such damage in the lithophysal zones is discussed in *Seismic Consequence Abstraction* (SNL 2007 [DIRS 176828], Section 6.8.2.2). The probability of commercial SNF and codisposal waste packages breaching from the combination of drip shield rupture and localized corrosion, considering the environmental conditions for localized corrosion of the waste package OCB (see Section 4.1.14), is developed from DTN: MO0810PANLNNWP.001 [DIRS 185842], file: *CSNF_CDSP.zip*, folders: 3D and 4D. The conditional distribution of probability that waste packages will undergo localized corrosion is obtained from an intermediate product of TSPA. Specifically, these results consist of sets of simulated outcomes for 300 realizations over a set of dominant epistemic parameters, with drip shields removed, in which the responses for a group of waste packages (i.e., localized corrosion or not) are calculated for every realization. Five sets of 300 outcomes are used, corresponding to the five percolation “bins” used in TSPA to represent variability and uncertainty in percolation flux (SNL 2008 [DIRS 184433], SNF canister fail immediately, whereas a more likely scenario is that the failure would take place over many years. This would also delay the release of actinides.

Likewise, many conservative assumptions are used to simplify the critical mass calculations presented in Table 4.1-10. For the analysis of commercial SNF and low-enriched DOE fuels discussed in *Geochemistry Model Validation Report: External Accumulation Model* (SNL 2007 [DIRS 181395]), the conservatisms are appropriate, because the results show that a criticality is unlikely. However, for the higher enriched DOE fuels, a more realistic modeling of the criticality potential will most likely be required to generate conservative but realistic results. Thus, it is concluded that the likelihood of achieving a configuration in the external environment with potential for criticality very low.

Degradation analyses indicate that, due to the boron in borated stainless steel having a very low solubility within the iron matrix of the steel, the boron is present as separate chromium boride particles instead of a solid solution (SNL 2007 [DIRS 181165], Section 6.3.3). This type of material does not dissolve into the aqueous solution during degradation of the steel but is left behind as insoluble products during corrosion.

For selected DOE-owned SNF waste forms, the neutron absorber material is in a distributed form in the waste form canister as the absorber material is added in the form of shot at the time of waste form loading per Section 5.2.3 of *Criticality Potential of Intact DOE SNF Canisters in a Misloaded Dry Waste Package* cited in *Total System Performance Assessment Data Input Package for Requirements Analysis for DOE SNF/HLW and Naval SNF Waste Package Physical Attributes Basis for Performance Assessment* (SNL 2007 [DIRS 179567], Table 4-1, Item 03-02).

Representative cases for the degradation and reconfiguration of the internal structures and waste forms in a waste package have been addressed in numerous analyses for the various SNF waste forms. These results are summarized in the following documents: *CSNF Loading Curve Sensitivity Analysis* (SNL 2008 [DIRS 182788]); *DOE SNF Phase I and II Summary Report* (BSC 2004 [DIRS 165482]); *Intact and Degraded Mode Criticality Calculations for the Codisposal of TMI-2 Spent Nuclear Fuel in a Waste Package* (BSC 2004 [DIRS 168935]); *Intact and Degraded Mode Criticality Calculations for the Codisposal of ATR Spent Nuclear Fuel in a Waste Package* (BSC 2004 [DIRS 171926]); and *Packaging Strategies for Criticality Safety for "Other" DOE Fuels in a Repository* (DOE 2004 [DIRS 170071], Section 2.1.11).

The DOE-owned SNF waste forms that require plate type neutron absorber materials ((Ni-Gd), ASTM B 932-04 [DIRS 168403], pp. 1 to 2) or gadolinium integrated shot are mixed oxide (DOE1), $UZrH_x$ (DOE2), U/Th Oxide (DOE5), aluminum-based DOE-owned SNF (DOE7), and U-Zr/U-Mo (DOE 8) (DOE 2004 [DIRS 170071], Section 2.1.11). Criticality control for the DOE1 SNF waste form is realized with a combination of both plates and shot while DOE5 and DOE8 rely on gadolinium shot for criticality control (Radulescu et al. 2004 [DIRS 165482], Sections 10.1, 10.4, and 10.5). For the canisters that incorporate neutron absorber shot, in addition to the standard quality checks similarly performed for absorber plate, a number of redundant and independent processes, involving confirmation of the shot material and loading, are expected to be available, making the absorber shot misload probability insignificant (i.e., reduce human error rates). Factors that will act to reduce human error rates with regard to neutron absorber shot as compared to neutron absorber plate include single facility loading of canisters, low total number of canisters requiring shot, processes regarding hot cell operations, and a weight measurement that would readily detect errors (i.e., shot not loaded). Thus, the DOE1, DOE2, and DOE7 waste forms (i.e., waste forms using neutron absorber plate for criticality control) are the only ones resulting in configurations with criticality potential conditional upon absorber misload.

The gadolinium in the DOE-owned SNF canisters forms phosphate or carbonate corrosion products (SNL 2007 [DIRS 181165], Section 6.3.16), both of which have low solubilities. Essentially all of the absorber material is retained in the waste package for the DOE-owned SNF waste package after 10,000 years. For commercial SNF, the lowest waste package retention fraction for fission products (modeled as gadolinium) was calculated as 0.86 (SNL 2007 [DIRS 181165], Tables 8.1-1 and 8.1-2). Table 4.1-11 summarizes miscellaneous criticality input data used in this analysis.

Table 4.1-11. Miscellaneous Direct Inputs

Description	Source
Low criticality potential for DOE-owned SNF canisters fabricated per specification	BSC 2006 [DIRS 181335], Section 7.10
Minimum critical mass of ^{235}U as schoepite	SNL 2007 [DIRS 181395], Table 6.9-1[a], Section 8.1.4[a]

4.2 CRITERIA

This section addresses the criteria relevant to the FEP screening process. These criteria stem from the applicable regulations of 10 CFR Part 63 [DIRS 180319]. These criteria are expanded upon and expressed as specific NRC acceptance criteria in *Yucca Mountain Review Plan, Final Report* (NRC 2003 [DIRS 163274], Sections 2.2.1.1.3, 2.2.1.2.1.3, 2.2.1.2.2.3, 2.2.1.3.1.3, 2.2.1.3.2.3, 2.2.1.3.3.3, 2.2.1.3.4.3, 2.2.1.3.7.3, and 2.2.1.3.9.3).

4.2.1 Yucca Mountain Review Plan (YMRP)

The bases for the NRC review of the license application and its acceptance are described in *Yucca Mountain Review Plan, Final Report* (NRC 2003 [DIRS 163274]). The FEP-related acceptance criteria and how this analysis addresses these criteria are presented in Table 4.2-1. The YMRP criteria not relevant to this analysis, as stated in Section 1.1, are YMRP Sections 2.2.1.1.3, 2.2.1.3.1.3, 2.2.1.3.2.3, 2.2.1.3.3.3, 2.2.1.3.4.3, 2.2.1.3.7.3, and 2.2.1.3.9.3 and not addressed in Table 4-2.1. The acceptance criteria for FEP screening justifications rely mainly on the collective screening tests of low probability and low consequence, but also allow for exclusion of a FEP if the process is specifically excluded by the regulations (refer to Section 4.2.2). Note that the criticality FEPs screening justifications rely exclusively on low probability.

[DIRS 179394], Section 4.1.1.5). The fuel type selected for each of the nine DOE-owned SNF groups represents the characteristics of all fuel types in that group (Radulescu et al. 2004 [DIRS 165482], Executive Summary). Representative configurations for the degradation and reconfiguration of the internal structures and waste forms in a waste package have been addressed in numerous analyses for the various SNF fuel types. These results from Section 4.1.15 are summarized in *CSNF Loading Curve Sensitivity Analysis* (SNL 2008 [DIRS 182788]), *DOE SNF Phase I and II Summary Report* (BSC 2004 [DIRS 165482]), *Intact and Degraded Mode Criticality Calculations for the Codisposal of TMI-2 Spent Nuclear Fuel in a Waste Package* (BSC 2004 [DIRS 168935]), and *Intact and Degraded Mode Criticality Calculations for the Codisposal of ATR Spent Nuclear Fuel in a Waste Package* (BSC 2004 [DIRS 171926]). The results indicated that the maximum k_{eff} of the various configurations were less than the critical limit. For selected DOE-owned SNF waste forms, the neutron absorber material is an integral part of the waste form as the absorber material is integrated into the DOE standardized SNF canister in the form of shot at the time of waste form loading per Section 5.2.3 of *Criticality Potential of Intact DOE SNF Canisters in a Misloaded Dry Waste Package* cited in *Total System Performance Assessment Data Input Package for Requirements Analysis for DOE SNF/HLW and Naval SNF Waste Package Physical Attributes Basis for Performance Assessment* (SNL 2007 [DIRS 179567], Table 4-1, Item 03-02).

The process controls for loading DOE-owned SNF canisters are expected to be similar to NUREG-1536, *Standard Review Plan for Dry Cask Storage Systems* and, since DOE-owned SNF canisters must be shipped to the repository, the quality assurance requirements of 10 CFR Part 71 [DIRS 173375], Subpart H, must be met. Thus, sufficiently rigorous requirements are expected to be in place to reduce the likelihood of accepting canisters without the shot type of absorber material to insignificant values. A possible second quality check for a lack of shot type absorber in a canister is a weight measurement of the loaded canister since such errors can be readily detected. The potential for criticality in DOE-owned SNF canisters using shot as an absorber is considered insignificant as discussed in Section 4.1.15, however, because the packaging strategies for the DOE SNF waste forms have not been finalized, results are provided including neutron absorber shot loading error (analogous with neutron absorber plate loading error) as well as results crediting the neutron absorber shot resulting in an insignificant contribution to the overall probability of criticality in the repository. The DOE-owned SNF waste forms that require plate type neutron absorber materials (Ni-Gd) from Section 4.1.15 are MOX (DOE1), $UZrH_x$ (DOE2), and aluminum-based SNF (DOE7). The DOE-owned SNF waste forms that require shot type neutron absorber from Section 4.1.15 are MOX (DOE1), U/Th Oxide (DOE5), and U-Zr/U-Mo alloy (DOE8). Errors in canister fabrication that result in an improper performance of the neutron absorber material are captured in the configuration generator model report (BSC 2004 [DIRS 172494], Figure I-5) as Top Events “NA-MISLOAD” (neutron absorber-misload). Such a misload of the absorber material in a DOE-owned SNF canister is possible during canister fabrication from installation of material not meeting specifications and the probability of such an event is evaluated in a similar manner as absorber misloads for commercial SNF canisters.

Scenarios important for criticality in the 10,000-year period following repository closure primarily result from potential deviations from the design configuration in the fabrication and loading processes prior to shipment to the repository. For commercial SNF, analyses demonstrate that intact, fully flooded with water (i.e., a neutron moderator) TAD canister waste package configurations as designed will not achieve criticality (Section 4.1.5). In addition, commercial and DOE-owned SNF canisters must meet requirements for handling, transportation, and storage of fissile material as specified, for example, in ANSI/ANS-8.17-2004 [DIRS 176225] or Regulatory Guide 3.71 [DIRS 176331]. These requirements specify criteria for establishing subcritical configurations in the transportation and storage containers. Demonstration that these criteria have been met, a necessary requirement for shipment, will the gadolinium in the DOE-owned SNF canisters forms phosphate or carbonate corrosion products (SNL 2007 [DIRS 181165], Section 6.3.16), which have very low corrosion rates.

The neutron absorber material within canisters is the primary mechanism for criticality control throughout the postclosure era. This material must be able to maintain its function under long-term exposure to environments with varying levels of corrosive potential, mechanical disruption from seismic events, and immersion in high temperature magmatic environments. The very low corrosion rates of the Ni-Gd alloy absorber material (Table 4.1-8), and the insolubility of the gadolinium shot proposed for use in the DOE-owned SNF canisters effectively limit the absorber loss, given a waste package breach. Thus, the estimated probability of a criticality developing from this sequence of events is sufficiently low such that, if quantified, it would not significantly increase the overall probability of criticality in the repository (Table 4.1-10).

The absorber material designated for the TAD canisters is borated stainless steel (Table 4.1-8) 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). This material has acceptable long-term neutron control characteristics based upon the near uniform particle dispersion in the absorber material together with acceptable corrosion behavior as extrapolated from short-term exposure tests. The corrosion rates from Table 4.1-8 indicate that absorber loss from corrosion, given a waste package breach, is expected to be on the order of millimeters or less over the first 10,000 years after emplacement.

The early failure event criticality FEP scenarios are identified as FEPs 2.1.14.15.0A, 2.1.14.16.0A, 2.1.14.17.0A, and 2.2.14.09.0A (Table 1.2-1). The scenarios associated with FEPs are: (1) in-package criticality (intact configuration), (2) in-package criticality (degraded configuration), (3) near-field criticality, and (4) far-field criticality. The early failure event FEP scenarios incorporate three locations. As noted in Section 1.2, the two in-package locations (intact and degraded) are essentially the same since the degraded in-package configurations differ from the intact configurations primarily in the waste form composition, once the waste package is breached. The same initial set of events must occur in the scenarios for the in-package location prior to splitting into separate sequences that lead to configurations with potential for criticality. The sequences evaluated in this analysis have been truncated prior to their split for evaluating events peculiar to the intact and degraded locations, respectively. Therefore, only the set of events for the in-package location associated with the degraded scenarios have been selected for evaluation. This applies to all of the in-package FEPs, disruptive as well as early failure of engineered barrier events, in this analysis.

The criticality potential of the in-package intact configuration scenario is negligible since intact configurations, fabricated and loaded according to specifications, will remain subcritical given that any degradation of intact configurations is insufficient by design to compromise the functioning of criticality control structures (Section 1.2). Although configurations not conforming to design specifications are applicable to both intact and degraded scenarios, configurations with potential for criticality require sufficient water for moderation. Since the internals are degraded for configurations in the in-package degraded scenario, the cladding is considered breached within the failed waste package and the interior of the fuel rods are assumed to be exposed to the repository environment allowing the fissile material to convert to schoepite. The criticality potential of the in-package degraded configuration scenario is negligible provided mitigation processes can lead to a waste package breach from either weld flaw propagation or SCCs initiated by the residual stresses. Localized corrosion of a waste package OCB can occur if a suitable environment develops where the two primary components are elevated temperature and the presence of advective flow (Output DTN: MO0705CRITPROB.000, file: *DSLC 01–29–08.zip*). A drip shield emplacement error could result in an advective flow path to the waste package OCB creating an environment for subsequent localized corrosion processes that could breach the waste package OCB.

These events are analyzed in *Analysis of Mechanisms for Early Waste Package/Drip Shield Failure* (SNL 2007 [DIRS 178765], Section 6.3.5). If a flaw that is approximately normal to the circumferential tensile stress exists, SCC can occur since the weld flaw is an SCC initiator. The propagation rate for SCCs in Alloy 22 is given in Section 4.1.14 as 1.1×10^{-9} mm per second, which will penetrate the 25-mm-thick waste package OCB lid in < 1,000 years, causing a breach. Events requiring probability values for the screening calculation are listed as follows:

1. Probability of a failure for the low-plasticity burnishing process on the waste package OCB closure lid, or a failure of processes for stress mitigation for the waste package OCB, or a drip shield emplacement error

2. Probability of improper absorber material in a canister

3. Probability of a loading curve violation for a PWR TAD canister.

The probabilities of events in this scenario are derived from preclosure activities, making those values independent of the postclosure period. The mean value of the probability distribution for failure of the low-plasticity burnishing process is given in DTN: MO0705EARLYEND.000 [DIRS 186104], *Table 6-8 and 6-12.doc*, as 3.77×10^{-5}. The probability that a waste package OCB closure weld has a flaw that can propagate through the OCB was estimated previously as 1.25×10^{-3}per waste package. The mean probability of waste package OCB fabrication defects as 1.13×10^{-4} per waste package and the mean probability value for improper emplacement of a drip shield is given in Table 4.1-1 as 2.19×10^{-9} per drip shield. The probability of localized corrosion breaching the waste package OCB from advective seepage flow resulting from a misplaced drip shield is conservatively set to 1.0. The probability of installing improper neutron absorber material in a TAD or DOE canister is a fabrication related error. This type of error was evaluated in *Analysis of Mechanisms for Early Waste Package/Drip Shield Failure* (SNL 2007 [DIRS 178765], Section 6.3.2). The mean value of the probability distribution for a fabrication failure is given in DTN: MO0705EARLYEND.000 [DIRS 186104], *Table 6-8 and 6-12.doc*, as 1.25×10^{-7} per canister.

An analysis of commercial SNF misload probabilities was documented in *Commercial Spent Nuclear Fuels Waste Package Misload Analysis* (BSC 2003 [DIRS 166316]). Results from this analysis establish that the probability of a loading curve violation in a 21-PWR Absorber Plate Waste Package is 1.18×10^{-5} (BSC 2003 [DIRS 166316], Table 41). The TAD canister specifications require the canisters for pressurized water reactor SNF to contain 21 assemblies similar to the 21-PWR Absorber Plate Waste Package (SNL 2007 [DIRS 179394], Section 4.1.1.2). The cited analysis is used as a surrogate for misloading waste forms in a TAD canister since the misloading of an assembly into a TAD canister requires the same improper

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:

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

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 $3.77 \times 10^{-5} \times 1.25 \times 10^{-3}$, 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 $2.19 \times 10^{-9} \times 1.0$, 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:

$$(3.77 \times 10^{-5} \times 1.25 \times 10^{-3}) + (1.13 \times 10^{-4}) + (2.19 \times 10^{-9} \times 1.0) = 1.13 \times 10^{-4}$$

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 4.1-2 as 4,568, the number of 44-BWR canisters as 2,915, 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:
$\{1\text{-}P_B(0; ((3.77 \times 10^{-5} \times 1.25 \times 10^{-3} + 1.13 \times 10^{-4} + 2.19 \times 10^{-9} \times 1.0) \times 1.65 \times 10^{-7}), 4568)\} = 8.5 \times 10^{-8}$

PWR TAD canister absorber misload:
$\{1\text{-}P_B(0; ((3.77 \times 10^{-5} \times 1.25 \times 10^{-3} + 1.13 \times 10^{-4} + 2.19 \times 10^{-9} \times 1.0) \times 1.25 \times 10^{-7}), 4568)\} = 6.5 \times 10^{-8}$

44-BWR TAD canister absorber misload:
$\{1\text{-}P_B(0; ((3.77 \times 10^{-5} \times 1.25 \times 10^{-3} + 1.13 \times 10^{-4} + 2.19 \times 10^{-9} \times 1.0) \times 1.25 \times 10^{-7}), 2915)\} = 4.1 \times 10^{-8}$

DOE-owned SNF canister absorber plate misload (DOE1, DOE2, and DOE7):
$\{1\text{-}P_B(0; ((3.77 \times 10^{-5} \times 1.25 \times 10^{-3} + 1.13 \times 10^{-4} + 2.19 \times 10^{-9} \times 1.0) \times 1.25 \times 10^{-7}), 1223)\} = 1.7 \times 10^{-8}$

Evaluating the event sequences with an additional absorber loading constraint for the DOE7 waste form (aluminum-based DOE-owned SNF) to include neutron absorber shot, and under the premise that the absorber shot misload probability is insignificant as discussed in Section 4.1.15

to eliminate these waste forms (DOE1, DOE5, DOE7, and DOE8) from the set that has potential for criticality, results in an estimated DOE-owned SNF canister absorber misload probability given by:

DOE-owned SNF canister absorber plate misload (89 DOE2 canisters, Table 4.1-2):
$\{1\text{-}P_B\ (0; ((3.77 \times 10^{-5} \times 1.25 \times 10^{-3} + 1.13 \times 10^{-4} + 2.19 \times 10^{-9} \times 1.0) \times 1.25 \times 10^{-7}), 89)\} = 1.3 \times 10^{-9}$.

Evaluating the event sequences for DOE-owned SNF accounting for the probability of neutron absorber shot misload for the DOE1 (MOX), DOE5 (U/Th Oxide), and DOE8 (U-Zr/U-Mo alloy) waste forms, the estimated canister misload probability for these waste forms is given by:

DOE-owned SNF canister absorber shot misload (214 DOE1, DOE5, and DOE8 canisters, Table 4.1-2):
$\{1\text{-}P_B\ (0; ((3.77 \times 10^{-5} \times 1.25 \times 10^{-3} + 1.13 \times 10^{-4} + 2.19 \times 10^{-9} \times 1.0) \times 1.25 \times 10^{-7}), 214)\} = 3.0 \times 10^{-9}$.

Thus, a conservative estimate for the probability of achieving a configuration with criticality potential in the repository due to early failure initiating events, based on summing the results above, including the DOE1 (absorber plate error), DOE2, and DOE7 contributions is 2.1×10^{-7} for 10,000 years. The estimate, including only the DOE2 contribution, is 1.9×10^{-7} for 10,000 years, and the estimate combining the DOE1 (absorber plate and shot error), DOE2, DOE5, DOE7, and DOE8 contributions is 2.1×10^{-7} for 10,000 years. Since the events in the above evaluation are all associated with operations during the preclosure period, the probabilities are constant over the postclosure time period.

The critical configuration is potentially achievable for waste packages for which either an absorber misload or loading curve violation has occurred in combination with either: 1) a schoepite-moderated system as a result of water vapor entry through SCC or 2) a flooded configuration resulting from drip shield breach and subsequent OCB failure due to localized corrosion. These probability evaluations have been developed for the in-package degraded scenario, FEP 2.1.14.16.0A (Table 1.2-1). The events in the in-package intact configuration scenario, FEP 2.1.14.15.0A, are the same as those for the in-package degraded scenario and do not increase the probability of achieving a configuration with potential for criticality. The probability values for FEP 2.1.14.15.0A are thus insignificant.

An early failure induced breach of a waste package is not expected to increase the criticality potential for the near-field or for the far-field configurations (FEPs 2.1.14.17.0A and 2.2.14.09.0A, respectively) since the waste package breach is limited to SCCs that, with the exception of a drip shield misplacement event, do not permit sufficient accumulation for criticality in the external environment. The probability of drip shield misplacement followed by localized corrosion is sufficiently low (2.19×10^{-9} per drip shield $\times$ 10,767 $\times$ P(LC) $< 2.4 \times 10^{-5}$, where P(LC) is the probability of localized corrosion) to limit the contribution from this initiating event to an insignificant level. 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 2.1.14.17.0A and 2.2.14.09.0A from an early failure event that breaches the waste package is insignificant.

Events such as the following have probabilities less than one, some much less than one and, individually or in combination, impact the probability that the early failure event scenario can lead to configurations that have criticality potential. This list is not exhaustive nor is the supporting discussion for each complete. However, it illustrates some of the additional events in the early failure event scenario for which information is unavailable to adequately quantify the probability, but would be necessary for achieving configurations that have criticality potential.

- Accumulation or presence of a critical mass of fissionable material—Credit is not taken for the stainless steel liner or TAD canister as a barrier for commercial SNF waste packages that are breached, and loss of the barrier capability of the cladding must also be

Table 6.4-6. Probability of Seismic Vibratory Ground Motion Events with Potential to Cause Damage to Codisposal Waste Packages

PGV Value (m/s)	λ_1 (events/year)	λ_2 (events/year)	t_1 (years)	t_2 (years)	Probability
< 0.364	1.27×10^{-4}	NA	NA	NA	NA
0.364 to 0.4	9.30×10^{-5}	1.27×10^{-4}	10,000	0	2.87×10^{-1}
0.4 to 1.05	9.96×10^{-6}	9.30×10^{-5}	10,000	0	5.64×10^{-1}
1.05 to 2.44	4.52×10^{-7}	9.96×10^{-6}	10,000	0	9.07×10^{-2}
2.44 to 4.07	1.0×10^{-8}	4.52×10^{-7}	10,000	0	4.41×10^{-3}

Source: Output DTN: MO0705CRITPROB.000, file: *Fault Displacement Abstraction for Criticality Updated DTN 10-25-07.xls*, spreadsheet: "Tables by WP Type," rows 250 to 260.
NA = not available.

The probability over 10,000 years of a seismically induced vibratory ground motion event that could result in damage to the outer corrosion barrier of a codisposal waste package varies with the exceedance frequency range as listed in the last column of Table 6.4-6 (Output DTN: MO0705CRITPROB.000, file: *Fault Displacement Abstraction for Criticality Updated DTN 10-25-07.xls*, spreadsheet: "Tables by WP Type").

If a seismic vibratory ground motion event occurs, the estimated probability of damage to a TAD waste package from impacts is given as 0.118 at the 4.07 m/s PGV range (Section 4.1.13), assuming a damage threshold at the 90% RST level. Integrating over the distribution for seismic hazard (Table 6.4-6) results in a probability of damage for a TAD waste package given by Table 4.1-6a as 1.57×10^{-4} for the 90% RST level, and zero for a damage threshold at either the 100% and 105% RST levels. The probability of damage evaluations, assuming a threshold at the 90% RST level, are conservatively used in the final summary to provide additional conservatism.

Similarly, the estimated probability of damage to a codisposal waste package from impacts is given in Table 4.1-6a, assuming a damage threshold at the 90% RST level, resulting in a probability of damage to a codisposal waste package of 0.196 and 0.004 at the 90% and 100% RST levels, respectively. The estimated probability of damage from impacts for a codisposal waste package is zero, assuming a damage threshold at the 105% RST level.

From Section 6.3.2, the probability of a potentially critical configuration resulting from an assembly misload (loading curve violation) of a PWR TAD canister was evaluated as $0.014 \times 1.18 \times 10^{-5} = 1.65 \times 10^{-7}$ per canister. Likewise, the probability of absorber plate misloads was evaluated in Section 6.3.2 as 1.25×10^{-7} per canister.

The probability of the initiating event for the suite of evaluations for the vibratory impact event in the seismic scenario is given above as 1.57×10^{-4} for the commercial SNF TAD waste packages and 0.196 for the codisposal waste packages. Evaluating the event sequences for commercial SNF and DOE-owned SNF with potential for criticality using the number of waste packages given in Table 4.1-3 as 4,568 for 21-PWR TAD canisters, as 2,915 for 44-BWR TAD canisters, as 1,223 for DOE-owned SNF canisters with criticality potential (DOE1, DOE2, and DOE7 groups) for seismic vibratory induced impact damage, assuming a damage threshold at the 90% RST level, and noting that the seismic probability results from a Binominal evaluation, gives:

PWR TAD canister loading curve violation:
$1.57 \times 10^{-4} \times \{1-P_B\,(0; (1.65 \times 10^{-7}), 4568)\} = 1.2 \times 10^{-7}$

PWR TAD canister absorber misload:
$1.57 \times 10^{-4} \times \{1-P_B\,(0; (1.25 \times 10^{-7}), 4568)\} = 9.0 \times 10^{-8}$

44-BWR TAD canister absorber misload:
$1.57 \times 10^{-4} \times \{1-P_B\,(0; (1.25 \times 10^{-7}), 2915)\} = 5.7 \times 10^{-8}$

DOE-owned SNF canister absorber plate misload (DOE1, DOE2, and DOE7):
$0.196 \times \{1-P_B\,(0; (1.25 \times 10^{-7}), 1223)\} = 3.0 \times 10^{-5}$.

Evaluating the event sequences with an additional absorber loading constraint for the DOE7 waste form (aluminum-based DOE-owned SNF) to include neutron absorber shot, and under the premise that the absorber shot misload probability is insignificant as discussed in Section 4.1.15 to eliminate these waste forms (DOE1, DOE5, DOE7, and DOE8) from the set that has potential for criticality, results in an estimated DOE-owned SNF canister absorber misload probability given by:

DOE-owned SNF canister absorber plate misload (89 DOE2 canisters, Table 4.1-2):
$0.196 \times \{1-P_B\,(0; (1.25 \times 10^{-7}), 89)\} = 2.2 \times 10^{-6}$.

Evaluating the event sequences for DOE-owned SNF accounting for the probability of neutron absorber shot misload for the DOE1 (MOX), DOE5 (U/Th Oxide), and DOE8 (U-Zr/U-Mo alloy) waste forms, the estimated canister misload probability for these waste forms is given by:

DOE-owned SNF canister absorber shot misload (214 DOE1, DOE5, and DOE8 canisters, Table 4.1-2):
$0.196 \times \{1-P_B\,(0; (1.25 \times 10^{-7}), 214)\} = 5.2 \times 10^{-6}$

Thus, a conservative estimate for the probability of achieving a configuration with criticality potential in the repository resulting from seismic vibratory induced impact damage, assuming a damage threshold at the 90% RST level, with subsequent SCC breaching of the waste package OCB for commercial SNF and DOE-owned SNF, based on summing this set of events, including the DOE1 (absorber plate error), DOE2, and DOE7 contributions is 3.0×10^{-5} for 10,000 years. The estimate, including only the DOE2 contribution, is 2.4×10^{-6} for 10,000 years, and the estimate combining the DOE1 (absorber plate and shot error), DOE2, DOE5, DOE7, and DOE8 contributions is 3.5×10^{-5} for 10,000 years. These results have been developed on a very conservative basis (e.g., use of damage probabilities at the 90% RST level. As stated in Section 6.3.2, the probabilities evaluated from the complete event sequences are expected to be significantly lower than from using a truncated sequence of events to estimate the probability of achieving a configuration with potential for criticality. Evaluating the probability with Equation 6.3-1 that at least one of the seismic vibratory events occur that induce impact damage to the commercial SNF and DOE-owned SNF waste package OCB, assuming a damage threshold at the 100% RST level, gives:

PWR TAD canister loading curve violation:
0.0

PWR TAD canister absorber misload:
0.0

44-BWR TAD canister absorber misload:
0.0

DOE-owned SNF canister absorber plate misload (DOE1, DOE2, and DOE7):
$4.0 \times 10^{-3} \times \{1-P_B (0; (1.25 \times 10^{-7}), 1223)\} = 6.1 \times 10^{-7}$.

Evaluating the event sequences for DOE-owned SNF accounting for the probability of neutron absorber shot misload for the DOE1 (MOX), DOE5 (U/Th Oxide), and DOE8 (U-Zr/U-Mo alloy) waste forms, the estimated canister misload probability is given by:

DOE-owned SNF canister absorber shot misload (214 DOE1, DOE5, and DOE8 canisters, Table 4.1-2):
$4.0 \times 10^{-3} \{1-P_B (0; (1.25 \times 10^{-7}), 214)\} = 1.1 \times 10^{-7}$.

Evaluating the event sequences with an additional absorber loading constraint for the DOE7 waste form (aluminum-based DOE-owned SNF) to include neutron absorber shot, and under the premise that the absorber shot misload probability is insignificant as discussed in Section 4.1.15, to eliminate these waste forms (DOE1, DOE5, DOE7, and DOE8) from the set that has potential for criticality results in an estimated DOE-owned SNF canister absorber misload probability given by:

DOE-owned SNF canister absorber plate misload (89 DOE2 canisters, Table 4.1-2)
$4.0 \times 10^{-3} \times \{1-P_B (0; (1.25 \times 10^{-7}, 89)\} = 4.4 \times 10^{-8}$.

Thus, a conservative estimate for the probability of achieving a configuration with criticality potential in the repository resulting from impact damage, assuming a damage threshold at the 100% RST level, from a seismic vibratory event with subsequent SCC breaching of the waste package OCB for commercial SNF and DOE-owned SNF, including the DOE1 (absorber plate error), DOE2, and DOE7 contributions is 6.1×10^{-7} for 10,000 years. The estimate, including only the DOE2 contribution, is 4.4×10^{-8} for 10,000 years, and the estimate combining the DOE1 (absorber plate and shot error), DOE2, DOE5, DOE7, and DOE8 contributions is 7.2×10^{-7} for 10,000 years.

The critical configuration is potentially achievable for waste packages for which either an absorber misload or loading curve violation has occurred in combination with either: 1) a schoepite-moderated system as a result of water vapor entry through SCCs or 2) a flooded configuration resulting from drip shield breach and subsequent OCB failure due to localized corrosion. These probability evaluations have been developed for the in-package degraded scenario, FEP 2.1.14.19.0A (Table 1.2-1). The events in the in-package intact configuration scenario, FEP 2.1.14.18.0A, are the same as those for the in-package degraded scenario and do not increase the probability of achieving a configuration with potential for criticality. The probability values for FEP 2.1.14.18.0A are thus insignificant.

A seismic vibratory impact induced breach of a waste package is not expected to increase the criticality potential for the near-field or for the far-field configurations (FEPs 2.1.14.20.0A and 2.2.14.10.0A, respectively) since the waste package breach from a seismic vibratory impact is limited to SCCs that do not permit sufficient accumulation for criticality in the external environment. 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 evaluated in Output DTN: MO0705CRITPROB.000, File: *DSLC 01-29-08.zip,* Folders 3D and 4D for nonlithophysal and lithophysal units, respectively. These files, derived from DTN: MO0810PANLNNWP.001 ([DIRS 185842], file: *CSNF_CDSP.zip*, folders: 3D and 4D), were extended to include the probabilities peculiar to criticality for this analysis and shown in Output DTN: MO0705CRITPROB.000], file: *DSLC 01-29-08.zip,* folders: 3D and 4D.

From Section 6.3.2, the probability of a potentially critical configuration resulting from an assembly misload (loading curve violation) of a PWR TAD canister was evaluated as $0.014 \times 1.18 \times 10^{-5} = 1.65 \times 10^{-7}$ per canister. Likewise, the probability of absorber plate misloads was evaluated in Section 6.3.2 as 1.25×10^{-7} per canister. The probabilities of occurrence of configurations with potential for criticality due to loading curve violations or absorber misloads over the 10,000-year period are listed in Table 6.4-7.

Table 6.4-7 Probability of Criticality due to Seismic Vibratory Events Resulting in Drip Shield Rupture and Waste Package Failure from Localized Corrosion

Criticality Event Sequence	Probability of Waste Package OCB Failure – Lithophysal Zone	Probability of Waste Package OCB Failure – Nonlithophysal Zone	Total Probability
PWR TAD Loading Curve Violation	1.19×10^{-9}	6.02×10^{-9}	7.2×10^{-9}
PWR TAD Canister Absorber Misload	9.04×10^{-10}	4.56×10^{-9}	5.5×10^{-9}
BWR TAD Canister Absorber Misload	5.77×10^{-10}	2.91×10^{-9}	3.5×10^{-9}
DOE-owned SNF Canister Absorber Misload [a]	8.83×10^{-10}	1.51×10^{-9}	2.4×10^{-9}
DOE-Owned SNF Canister Absorber Misload [b]	6.36×10^{-11}	9.96×10^{-11}	1.6×10^{-10}
DOE-Owned SNF Canister Absorber Misload [c]	1.55×10^{-10}	2.59×10^{-10}	4.1×10^{-10}

Output DTN: MO0705CRITPROB.000], file: *DSLC 01-29-08.zip*, folders 3D and 4D.

[a] Includes DOE-owned SNF waste form groups DOE1, DOE2, and DOE7 for neutron absorber plate loading error.

[b] Includes only DOE-owned SNF waste form group DOE2.

[c] Includes DOE-owned SNF waste form groups DOE1, DOE5, and DOE8 for neutron absorber shot loading error.

PWR = Pressurized Water Reactor, BWR = Boiling Water Reactor, OCB = outer corrosion barrier.

Thus, a conservative estimate for the probability of achieving a configuration with criticality potential in the repository resulting from a seismic vibratory induced drip shield rupture and subsequent localized crevice corrosion breaching of the waste package OCB for commercial SNF and DOE-owned SNF, including the DOE1 (absorber plate error), DOE2, and DOE7 contributions is 1.9×10^{-8} for 10,000 years. The estimate, including only the DOE2 contribution, is 1.6×10^{-8} for 10,000 years, and the estimate combining the DOE1 (absorber plate and shot error), DOE2, DOE5, DOE7, and DOE8 contributions is 1.9×10^{-8} for 10,000 years. These probability evaluations have been developed for the in-package degraded scenario, FEP 2.1.14.19.0A (Table 1.2-1). The events in the in-package intact configuration scenario, FEP 2.1.14.18.0A, are the same as those for the in-package degraded scenario and do not increase the probability of achieving a configuration with potential for criticality. The probability values for FEP 2.1.14.18.0A are thus insignificant.

A seismic vibratory rockfall and localized corrosion induced breach of a waste package would permit degradation and transport of fissile material into the external environment. However, such an event is not expected to increase the criticality potential for either the near-field or

PWR TAD canister absorber misload
$1.2 \times 10^{-4} \times (1\text{-}P_B\ (0;\ 1.25 \times 10^{-7}, (19.4 \times 4568/7483)) + 4.3 \times 10^{-4} \times (1\text{-}P_B\ (0;\ 1.25 \times 10^{-7}, (27.6) \times 4568/7483)) + 1.7 \times 10^{-4} \times (1\text{-}P_B\ (0;\ 1.25 \times 10^{-7}, (32.1) \times 4568/7483)) = 1.4 \times 10^{-9}$

44-BWR TAD canister absorber misload
$1.2 \times 10^{-4} \times (1\text{-}P_B\ (0;\ 1.25 \times 10^{-7}, (19.4 \times 2915/7483)) + 4.3 \times 10^{-4} \times (1\text{-}P_B\ (0;\ 1.25 \times 10^{-7}, (27.6) \times 2915/7483)) + 1.7 \times 10^{-4} \times (1\text{-}P_B\ (0;\ 1.25 \times 10^{-7}, (32.1) \times 2915/7483)) = 9.0 \times 10^{-10}$

DOE-owned SNF canister absorber plate misload (DOE1, DOE2, and DOE7)
$1.0 \times 10^{-4} \times (1\text{-}P_B\ (0;\ 1.25 \times 10^{-7}, (2.6+3.5) \times 1223/3074)) + 6.9 \times 10^{-4} \times (1\text{-}P_B\ (0;\ 1.25 \times 10^{-7}, (3.7 + 4.9) \times 1223/3074)) + 2.8 \times 10^{-4} \times (1\text{-}P_B\ (0;\ 1.25 \times 10^{-7}, (4.3 + 5.7) \times 1223/3074)) + 3.0 \times 10^{-5} \times (1\text{-}P_B\ (0;\ 1.25 \times 10^{-7}, (21.6 + 28.5) \times 1223/3074)) = 5.4 \times 10^{-10}$.

Evaluating the event sequences for DOE-owned SNF with the probability of neutron absorber shot misload for the DOE1 (MOX), DOE5 (U/Th Oxide), and DOE8 (U-Zr/U-Mo alloy) waste forms is given by:

DOE-owned SNF canister absorber shot misload (214 DOE1, DOE5, and DOE8 canisters, Table 4.1-2):
$1.0 \times 10^{-4} \times (1\text{-}P_B\ (0;\ 1.25 \times 10^{-7}, (2.6+3.5) \times 214/3074)) + 6.9 \times 10^{-4} \times (1\text{-}P_B\ (0;\ 1.25 \times 10^{-7}, (3.7 + 4.9) \times 214/3074)) + 2.8 \times 10^{-4} \times (1\text{-}P_B\ (0;\ 1.25 \times 10^{-7}, (4.3 + 5.7) \times 214/3074)) + 3.0 \times 10^{-5} \times (1\text{-}P_B\ (0;\ 1.25 \times 10^{-7}, (21.6 + 28.5) \times 214/3074)) = 9.4 \times 10^{-11}$.

Evaluating the event sequences with an additional absorber loading constraint for the DOE7 waste form (aluminum-based DOE-owned SNF) to include neutron absorber shot, and under the premise that the absorber shot misload probability is insignificant as discussed in Section 4.1.15 to eliminate these waste forms (DOE1, DOE5, DOE7, and DOE8) from the set that has potential for criticality, results in an estimated DOE-owned SNF canister absorber misload probability given by:

DOE-owned SNF canister absorber plate misload (89 DOE2 canisters, Table 4.1-2)
$1.0 \times 10^{-4} \times (1\text{-}P_B\ (0;\ 1.25 \times 10^{-7}, (2.6+3.5) \times 89/3074)) + 6.9 \times 10^{-4} \times (1\text{-}P_B\ (0;\ 1.25 \times 10^{-7}, (3.7 + 4.9) \times 89/3074)) + 2.8 \times 10^{-4} \times (1\text{-}P_B\ (0;\ 1.25 \times 10^{-7}, (4.3 + 5.7) \times 89/3074)) + 3.0 \times 10^{-5} \times (1\text{-}P_B\ (0;\ 1.25 \times 10^{-7}, (21.6 + 28.5) \times 89/3074)) = 7.6 \times 10^{-12}$.

Thus, a conservative estimate for the probability of achieving a configuration with criticality potential in the repository resulting from a seismic faulting initiating event for commercial SNF and DOE-owned SNF, including the DOE1 (absorber plate error), DOE2, and DOE7 contributions is 4.8×10^{-9} for 10,000 years. The estimate, including only the DOE2 contribution, is 4.2×10^{-9} for 10,000 years, and the estimate combining the DOE1 (absorber plate and shot error), DOE2, DOE5, DOE7, and DOE8 contributions is 4.8×10^{-9} for 10,000 years.

The probability of criticality as a result of a misload in the above calculations inherently assumes that the system has adequate moderation to support criticality.

As discussed in Section 6.3.2, additional events having probabilities less than one, some much less than one, and individually or in combination likely reduce the probability that a seismic faulting event can lead to conditions needed to support criticality.

Although the waste package configuration is susceptible to waste form degradation and accumulation in the external environment, a seismic faulting event initiating a breach of a waste package is not expected to increase the criticality potential for the near-field or for the far-field configurations (FEPs 2.1.14.20.0A and 2.2.14.10.0A, respectively). The accumulation of fissile material in the external environment depends on a number of events, the first of which is the occurrence of the seismic event that has a low probability, followed by degradation, separation of fissile material from neutron absorber material, transport of the material from the waste package, The impact of an intrusive igneous event on waste packages and various SNF types has been evaluated for configurations with criticality potential (i.e., presence of fissile material, neutron moderator, lack of neutron absorbers) by considering a representative configuration in lieu of attempting to evaluate a range of specific environmental parameters and configurations, along with an estimate of their probability of occurrence, that could generate a large number of possible event sequences and outcomes. The single representative configuration is considered representative of ones having criticality potential following an initiating intrusive igneous event and provides a basis for demonstrating the additional events and processes that would be required to result in criticality following an intrusive igneous event. A detailed criticality assessment of configurations for the various DOE-owned SNF waste forms has been performed (SNL 2007 [DIRS 181373]; BSC 2006 [DIRS 181335]) with all configurations shown to be subcritical. In addition, a qualitative evaluation of the additional events and processes that would be required for criticality has been developed as discussed in Section 6.3.2.

The specific geometry and composition of the numerous intermediate configurations are dependent on the environmental conditions and cannot all be defined individually for analysis. Considering the increased variability in the potential geometric reconfigurations, effects on material performance, and neutron spectrum changes resulting in varied neutron absorber effectiveness, the numbers would be of limited value considering the high degree of uncertainty associated with any given scenario that may be evaluated. The initiating event probability for the igneous intrusive event (1.7×10^{-4}) is already a factor of 1,100 below the probability of seismic vibratory ground motion damaging the codisposal waste package (0.196) as provided in Table 4.1-6a. Therefore, considering the probability values associated with the conditions necessary for criticality discussed previously (e.g., absorber misload, assembly misload) the resultant probability of criticality resulting from this disruptive igneous 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.

7. CONCLUSIONS

7.1 SUMMARY OF PROBABILITY EVALUATIONS

Results of the event sequences evaluated for the nominal criticality FEP scenario, seismic disruptive FEP scenario, rockfall disruptive FEP scenario, and igneous disruptive FEP scenario are shown in Table 7.1-1 which summarize the values from Sections 6.3, 6.4, 6.5, and 6.6 calculated as conservative estimates for their contributions to the probability of achieving a configuration with criticality potential in the repository over the initial 10,000-year period following closure.

Table 7.1-1. Estimated Probability of Criticality Configurations in the Repository over 10,000 Years

Waste Package Variant	In-Package Intact	In-Package Degraded	Near-Field	Far-Field
	Probability Estimate for FEPs Associated with Nominal (Early Failure) Event Sequence Initiators (Section 6.3.2)			
PWR TAD canister	Insignificant	1.499×10^{-7}	Insignificant	Insignificant
44-BWR TAD canister	Insignificant	4.119×10^{-8}	Insignificant	Insignificant
DOE-owned SNF canister [a]	Insignificant	1.728×10^{-8}	Insignificant	Insignificant
DOE-owned SNF canister [b]	Insignificant	1.263×10^{-9}	Insignificant	Insignificant
DOE-owned SNF canister [c]	Insignificant	3.024×10^{-9}	Insignificant	Insignificant
SubTotal [a]	NA	2.080×10^{-7}	NA	NA
SubTotal [b]	NA	1.923×10^{-7}	NA	NA
SubTotal [d]	NA	2.114×10^{-7}	NA	NA
	Probability Estimate for FEPs Associated with Seismic Event Sequence Initiator - Vibratory Impact at 90% RST (Section 6.4.2.1)			
PWR TAD canister	Insignificant	2.081×10^{-7}	Insignificant	Insignificant
44-BWR TAD canister	Insignificant	5.720×10^{-8}	Insignificant	Insignificant
DOE-owned SNF canister [a]	Insignificant	2.996×10^{-5}	Insignificant	Insignificant
DOE-owned SNF canister [b]	Insignificant	2.181×10^{-6}	Insignificant	Insignificant
DOE-owned SNF canister [c]	Insignificant	5.243×10^{-6}	Insignificant	Insignificant
SubTotal [a]	NA	3.023×10^{-5}	NA	NA
SubTotal [b]	NA	2.446×10^{-6}	NA	NA
SubTotal [d]	NA	3.547×10^{-5}	NA	NA
	Probability Estimate for FEPs Associated with Seismic Event Sequence Initiator - Vibratory Drip Shield Rupture (Section 6.4.2.2)			
PWR TAD canister	Insignificant	1.267×10^{-8}	Insignificant	Insignificant
44-BWR TAD canister	Insignificant	3.487×10^{-9}	Insignificant	Insignificant
DOE-owned SNF canister [a]	Insignificant	2.389×10^{-9}	Insignificant	Insignificant
DOE-owned SNF canister [b]	Insignificant	1.632×10^{-10}	Insignificant	Insignificant
DOE-owned SNF canister [c]	Insignificant	4.140×10^{-10}	Insignificant	Insignificant
SubTotal [a]	NA	1.854×10^{-8}	NA	NA
SubTotal [b]	NA	1.632×10^{-8}	NA	NA
SubTotal [d]	NA	1.896×10^{-8}	NA	NA

Table 7.1-1.Estimated Probability of Criticality Configurations in the Repository over 10,000 Years (Continued)

	Probability Estimate for FEPs Associated with Seismic Event Sequence Initiator - Single Block Rockfall (Section 6.4.2.3)			
PWR TAD canister	Insignificant	Insignificant	Insignificant	Insignificant
44-BWR TAD canister	Insignificant	Insignificant	Insignificant	Insignificant
DOE-owned SNF canister [a]	Insignificant	Insignificant	Insignificant	Insignificant
DOE-owned SNF canister [b]	insignificant	Insignificant	Insignificant	Insignificant
DOE-owned SNF canister [c]	Insignificant	Insignificant	Insignificant	Insignificant
SubTotal [a]	NA	NA	NA	NA
SubTotal [b]	NA	NA	NA	NA
SubTotal [d]	NA	NA	NA	NA
Waste Package Variant	In-Package Intact	In-Package Degraded	Near-Field	Far-Field
	Probability Estimate for FEPs Associated with Seismic Event Sequence Initiator - Faulting (Section 6.4.3)			
PWR TAD canister	Insignificant	3.317×10^{-9}	Insignificant	Insignificant
44-BWR TAD canister	Insignificant	8.975×10^{-10}	Insignificant	Insignificant
DOE-owned SNF canister [a]	Insignificant	5.394×10^{-10}	Insignificant	Insignificant
DOE-owned SNF canister [b]	Insignificant	7.647×10^{-12}	Insignificant	Insignificant
DOE-owned SNF canister [c]	Insignificant	9.439×10^{-11}	Insignificant	Insignificant
SubTotal [a]	NA	4.754×10^{-9}	NA	NA
SubTotal [b]	NA	4.222×10^{-9}	NA	NA
SubTotal [d]	NA	4.848×10^{-9}	NA	NA
	Probability Estimate for FEPs Associated with Rockfall Event Sequence Initiator (Section 6.5)			
All Waste Package Variants	Insignificant	Insignificant	Insignificant	Insignificant
	Probability Estimate for FEPs Associated with Igneous Event Sequence Initiator (Section 6.6.2)			
PWR TAD canister	Insignificant	Insignificant	Insignificant	Insignificant
44-BWR TAD canister	Insignificant	Insignificant	Insignificant	Insignificant
DOE-owned SNF canister	Insignificant	insignificant	Insignificant	Insignificant
Total [a]	Insignificant	3.05×10^{-5}	Insignificant	Insignificant
Total [b]	Insignificant	2.66×10^{-6}	Insignificant	Insignificant
Total [d]	Insignificant	3.57×10^{-5}	Insignificant	Insignificant

[a] DOE-owned SNF waste forms DOE1, DOE2, and DOE7 without distributed neutron absorber in shot form.
[b] DOE-owned SNF waste form DOE2 without distributed neutron absorber in shot form.
[c] DOE-owned SNF waste forms DOE1, DOE5, and DOE8 with distributed neutron absorber in shot form.
[d] Combined DOE-owned SNF waste forms DOE1, DOE2, DOE5, DOE7, and DOE8 with neutron absorber in plate and/or shot form ([a] + [c]).

Source: Output DTN: MO0705CRITPROB.000, file: *"Prob Calc.xls"*
NA = not applicable.

Using the available geologic repository and engineered barrier systems information, and surrogate evaluations based on the best available information, a conservative value for the total probability of achieving a configuration with criticality potential was estimated as 3.0 5 $\times 10^{-5}$ over the 10,000-year period following repository closure under the premise that the probability of neutron absorber shot misload is insignificant. The total estimated probability of achieving a configuration with criticality potential becomes 2.66 $\times 10^{-6}$ over the 10,000-year period following repository closure, provided that the neutron absorber shot is used for criticality control and the misload probability is insignificant for DOE-owned SNF canisters for MOX SNF (DOE1), $UZrH_x$ (DOE2), U/Th Oxide (DOE5), aluminum-based SNF (DOE7), and U-Zr/U-Mo (DOE 8) (Section 4.1.15). The estimated total probability of achieving a configuration with criticality potential, treating both neutron absorber shot misload and neutron absorber plate misload conistently, for the DOE1, DOE2, DOE5, DOE7, and DOE8 waste forms is 3.57 $\times 10^{-5}$ over the 10,000-year period following repository closure.

The probability of achieving a configuration with criticality potential (3.57 $\times 10^{-5}$ over 10,000 years) has been developed on a very conservative basis with respect to criticality events and is below the regulatory probability criterion of 1×10^{-4} over 10,000 years. As discussed in Section 6.3.2, the probabilities evaluated from complete event sequences are expected to be significantly lower than the calculated value of 3.57 $\times 10^{-5}$ over 10,000 years. However, this estimate of the probability of criticality does not include the evaluation of naval SNF. The overall probability will remain below the regulatory criterion provided that the value for the naval SNF is less than ($1.0 \times 10^{-4} - 3.57 \times 10^{-5} =$) 6.43 $\times 10^{-5}$ for the repository over 10,000 years.

7.2 EVALUATION OF YUCCA MOUNTAIN REVIEW PLAN CRITERIA

The YMRP (NRC 2003 [DIRS 163274]) contains acceptance criteria intended to establish the basis for the review of the material contained in the license application. Because this report serves, in part, as the basis for the license application, the information contained herein conforms to applicable acceptance criteria. The acceptance criteria that are applicable to this calculation as presented in Table 4.2-1 are evaluated with respect to the method of addressing the criteria that is also listed in Table 4.2-1. The acceptance criteria for FEP screening analysis rely primarily on the collective screening tests of low probability, but regulations also allow for exclusion of a FEP on the basis of low consequence or if the process is specifically excluded by the regulations (Section 4.2.2).

7.3 CRITICALITY FEPS SCREENING JUSTIFICATION

The justification for screening postclosure criticality from further consideration in the repository is on low probability (Section 4.2.2.1) as the total probability bound for all configurations with criticality potential occurring in the repository is below the criterion from Section 4.2.2.1 (Table 7.1-1).

183006 MO0708FREQCALC.000. Seismic Frequency Calculation of Waste Package Containers. Submittal date: 08/10/2007.

183007 MO0708CDSPSEIS.000. CDSP Seismic Damage Calculation. Submittal date: 08/13/2007.

8.4 PRODUCT OUTPUT, LISTED BY DATA TRACKING NUMBER

MO0705CRITPROB.000. Probability of Criticality. Submittal date: 02/05/2008.

8.5 SOFTWARE CODES

160873 SAPHIRE V. 7.18. 2002. WINDOWS 2000/NT 4.0. STN: 10325-7.18-00.

Impacts from changes to ANL-DS0-NU-000001 REV 00

LA-SAR

Text on page 2.2-49 clarified regarding which waste forms rely on absorber shot for criticality control. Include equation for shot absorber misload on p. 2.2-52. Update the 90% RST damage probabilities reported on p. 2.2-54. Update the discussion of the dominant breach probability on p. 2.2-55 and subsequent probabilility values listed on p. 2.2-56. Add text to third bullet on p. 2.2-56 to discuss the 214 packages that use absorber shot for criticality control, or add as a separate bullet. Update "… a factor of 1,400 below…" to the new value of 1,100 on p. 2.2-58. Update values in Table 2.2-8.

ANL-WIS-MD-000027 Rev 00

Changes to add text to criticality FEPs 2.1.14.15.0A and 2.1.14.19.0A to include the discussions regarding the absorber shot misload and update quoted probability values.