DOC.20080424.0001

QA: QA

CAL-DN0-NU-000002 REV 00C

February 2008

Waste Package Flooding Probability Evaluation

THIS DOCUMENT IS IMPACTED BY THE FOLLOWING "ERROR RESOLUTION DOCUMENTS", WHICH
SHOULD BE REVIEWED PRIOR TO USING THIS DOCUMENT:

---

1) CAL-DN0-NU-000002 ERD 01 - ACCESSION NO. LLR.20080401.0269

THIS DOCUMENT CONTAINS THE FOLLOWING, LOCATED AT THE BACK OF THE DOCUMENT:
1) ADDENDUM 001, DATED 04/21/2008

Prepared for:
U.S. Department of Energy
Office of Civilian Radioactive Waste Management
Office of Repository Development
1551 Hillshire Drive
Las Vegas, Nevada 89134-6321

Prepared by:
Sandia National Laboratories
OCRWM Lead Laboratory for Repository Systems
1180 Town Center Drive
Las Vegas, Nevada 89144

Under Contract Number
DE-AC04-94AL85000

QA: QA

Waste Package Flooding Probability Evaluation

CAL-DN0-NU-000002 REV 00C

February 2008

Scientific Analysis/Calculation Signature Page/Change History

Page iii

1. Total Pages: 92

Complete only applicable items.

2. Document Title
Waste Package Flooding Probability Evaluation

3. DI (Including Revision No. and Addendum No.)
CAL-DN0-NU-000002 REV 00C

	Printed Name	Signature	Date
4. Originator	John Scaglione		2/20/08
5. Checker	Charles Henkel	Charles Henkel	20 Feb 08
6. QCS/Lead Lab QA Reviewer	Bruce Foster		2/20/2008
7. Responsible Manager/Lead	John Scaglione		2/20/08
8. Responsible Manager	Cliff Howard	Cliff Howard	2/20/08

9. Remarks

Appendix

		Total Number of Pages
A.	List of the Electronic Files in Output DTNs to this calculation	2
B.	Methodology for Calculating Joint Probability of Drip Shield And Waste Package Failure That May Allow Advective Water Ingress to Waste Package	28
C.	Qualification of Data	4

Cliff Hansen and John Case contributed to the development of the methodology presented in Appendix B and the implementation of the methodology within the Mathcad files presented in Output DTNs MO0712PANLNNWP.000 and MO0712PBANLNWP.000

Change History

10. Revision No. and Addendum No.	11. Description of Change
00A	Initial Issue
00B	Update Direct Inputs from Current Analyses, Develop Document in Accordance with SCI-PRO-005 Scientific Analyses and Calculations
00C	Revise calculations based on updated TSPA seepage rates and updated fault displacement data, Output DTN MO0802WPFLOODG.001 supersedes previous output DTN: MO0705WPFLOODG.000; Added discussions regarding hydraulic states internal to breached waste packages. New calculations added for combinatorial probability calculations related to drift collapse, drip shield collapse/rupture and localized corrosion.

INTENTIONALLY LEFT BLANK

CONTENTS

Page

ACRONYMS ix

1. PURPOSE 1

2. QUALITY ASSURANCE 1

3. USE OF SOFTWARE 2

4. INPUTS 2
   4.1 DIRECT INPUTS 2
   4.2 CRITERIA 6
   4.3 CODES, STANDARDS, AND REGULATIONS 7

5. ASSUMPTIONS 7
   5.1 BATHTUB GEOMETRY 8
   5.2 STEADY-STATE FLOW WITH CONSTANT VOLUME 8

6. SCIENTIFIC ANALYSIS DISCUSSION 8
   6.1 SEISMIC FAULT DISPLACEMENT PROBABILITY OF FILLING A WASTE PACKAGE 9
      6.1.1 Seepage Rate Distribution 12
      6.1.2 Water-Filling Probability Calculation 18
   6.2 PROBABILITY OF ADVECTIVE WATER INGRESS INTO A WASTE PACKAGE 19
      6.2.1. Unsaturated Steady-State Resulting from Stress Corrosion Cracking Damage 21
      6.2.2. Localized Corrosion/Seepage 25

7. RESULTS AND CONCLUSIONS 26
   7.1 SEEPAGE DUE TO SEISMIC FAULT DISPLACEMENT 26
   7.2 ADVECTIVE WATER INGRESS TO WASTE PACKAGES 29
   7.3 CONCLUSIONS 34
   7.4 YUCCA MOUNTAIN REVIEW PLAN 35

8. INPUTS AND REFERENCES 36
   8.1 DOCUMENTS CITED 36
   8.2 CODES, STANDARDS, REGULATIONS, AND PROCEDURES 39
   8.3 SOURCE DATA, LISTED BY DATA TRACKING NUMBER 39
   8.4 OUTPUT DATA, LISTED BY DATA TRACKING NUMBER 40
   8.5 SOFTWARE CODES 40

APPENDIX A – LIST OF THE ELECTRONIC FILES IN OUTPUT DTNS TO THIS CALCULATION A-1

CONTENTS (Continued)

Page

APPENDIX B – METHODOLOGY FOR CALCULATING JOINT PROBABILITY OF DRIP SHIELD AND WASTE PACKAGE FAILURE THAT MAY ALLOW ADVECTIVE WATER INGRESS TO WASTE PACKAGE........ B-1

APPENDIX C – QUALIFICATION OF DATA C-1

FIGURES

Page

6-1. Bin 1 Commercial SNF Seepage Rate 13
6-2. Bin 2 Commercial SNF Seepage Rate 13
6-3. Bin 3 Commercial SNF Seepage Rate 14
6-4. Bin 4 Commercial SNF Seepage Rate 14
6-5. Bin 5 Commercial SNF Seepage Rate 15
6-2. Cumulative Distribution Function of the Seepage Rates and Weibull Fit 17

7-1. Probability of Filling a Waste Package as a Function of Volume 28

TABLES

Page

4-1. Direct Inputs Used in Calculation 3

6-1. Estimated Number of Waste Packages Failed 11
6-2. Weibull Parameters and Seepage Fractions 18

7-1. Probability of Filling a Waste Package within 10,000 Years 27
7-2. Total Probability of Filling a Naval Waste Package within 10,000 Years 29
7-3. Total Probability of Filling a Commercial SNF Waste Package within 10,000 Years 29
7-4. Failure Mode Analysis for Water Ingress to Commercial SNF and Codisposal Waste Packages 31
7-5. Cumulative Probability of Seepage Exceeding the Required Value 35

B-1. Failure Mode Analysis for Water Ingress to Naval Waste Packages B-2
B-2. Expected Rockfall Volumes for Various PGV Values B-26

INTENTIONALLY LEFT BLANK

ACRONYMS

CDF	cumulative distribution function
CDSP	codisposal
DOE	U.S. Department of Energy
FEPs	features, events, and processes
HLW	high-level waste
NRC	U.S. Nuclear Regulatory Commission
OCB	outer corrosion barrier
PGV	peak ground velocity
SCC	stress corrosion cracking
SNF	spent nuclear fuel
SNL	Sandia National Laboratories
TAD	transportation, aging, and disposal (canister)
TSPA	total system performance assessment
WPOB	waste package outer barrier

INTENTIONALLY LEFT BLANK

1. PURPOSE

The objective of this calculation is to evaluate the probability of flooding a waste package with seepage water. Disruptive events can affect the Engineered Barrier System (EBS) components and have the potential to allow an advective flow of seepage water to reach the waste package. The advective and diffusive flow paths into the waste package have the potential to result in water accumulation inside the waste package, which in turn can lead to a potentially critical configuration. This calculation will evaluate the following:

1) The probability of sufficient seepage to fill a naval or commercial spent nuclear fuel (SNF) waste package which has failed from seismic fault displacement to the extent of the free volume available, which is using a range from 100 to 4,000 gallons (0.379 to 15.1 m^3) per container. Free volume is the void space which can be filled by water in the waste package. Due to the significant difference in diameter between the TAD and DOE canisters and the fact that multiple DOE SNF canisters are loaded in some codisposal waste packages, they are not considered in this evaluation.

2) The probability of advective water ingress into a waste package (not including igneous and seismic faulting events) over the 10,000 years following repository closure.

This activity supports the evaluation of features, events, and processes (FEPs) that could lead to waste package criticality. The intended use of these results will be in performing assessments of conditions necessary for criticality.

The development of this report is consistent with Work Package S31013 specified in *Technical Work Plan for: Postclosure Criticality* (SNL 2007 [DIRS 178869], Table 1). The calculation follows the approach outlined in the technical work plan (SNL 2007 [DIRS 178869], Section 2.1.4).

Any change to the direct input data sets will have a direct impact on the results of this report. Therefore, the limitations of this evaluation are as follows:

- Direct inputs listed in Section 4.1
- Assumptions listed in Section 5
- Advective flow methodology in Appendix B regarding drip shield misplacement early failure is based on the number of drip shields being equal to number of waste packages.

The results presented in Section 7.1 apply specifically to naval and commercial SNF waste packages. For other types of waste packages the direct inputs and results would be different.

2. QUALITY ASSURANCE

Development of this report has been determined to be subject to the Yucca Mountain Project quality assurance requirements as described in *Technical Work Plan for: Postclosure Criticality* (SNL 2007 [DIRS 178869], Section 8.1). Approved quality assurance procedures identified in the technical work plan (SNL 2007 [DIRS 178869], Section 4.1) have been used to conduct and document the activities described in this report. The technical work plan also identifies the methods used to control the electronic management of data (SNL 2007 [DIRS 178869], Section 8.4) during the calculation and documentation activities.

This report is prepared in accordance with SCI-PRO-004, *Managing Technical Product Inputs*, SCI-PRO-005, *Scientific Analyses and Calculations*, and TST-PRO-001, S*ubmittal and Incorporation of Data to the Technical Data Management System*.

3. USE OF SOFTWARE

Mathcad Version 14 (STN: 611161-14.0-00), which is commercially available off-the-shelf software, was installed on a DELL OptiPlex GX745 personal computer running Microsoft Windows XP Professional and used in the preparation of this report. Mathcad is a problem-solving environment used in calculations and analyses to manipulate the inputs using standard mathematical expressions and operations. It is also used to tabulate and chart results. Standard functions of Mathcad are used. The inputs and results are documented in sufficient detail to allow an independent repetition of computations. Thus, Mathcad is used only as a worksheet and not as a software routine. Mathcad V. 14 is an exempt software product in accordance with IM-PRO-003, *Software Management*, Section 2. Thus, there are no known limitations on the outputs based on the selected software.

Inputs, outputs, and formulas used for the various Mathcad calculations are documented in Sections 6, 7, and Appendix B. The electronic files for the calculations may be found in output DTN: MO0802WPFLOODG.001, MO0712PANLNNWP.000, and MO0712PBANLNWP.000. Note that if the Mathcad file is recalculated after opening, the seed may need to be set to the default value of 1 to generate identical results (i.e., *Seed(1)*).

4. INPUTS

Technical product input usage is categorized in SCI-PRO-004 as either direct input or indirect input. Direct input is used to develop the results or conclusions in a technical product, whereas indirect input provides additional information that is not used in the development of results or conclusions.

Section 4.1 identifies direct inputs used in this calculation. The direct inputs were obtained from qualified source documents and other appropriate sources in accordance with SCI-PRO-004. Section 4.2 identifies any relevant acceptance or completion criteria. Section 4.3 identifies codes and standards applicable to the evaluation of the probability of flooding the waste package.

4.1 DIRECT INPUTS

Table 4-1 presents the direct inputs used to perform the evaluations of the probability of waste package flooding. Use of these data is justified, as they are extracted from qualified project sources and their application as documented in Section 6 and Appendix B is compatible with their developed purpose and limitations as described in Section 1.

Table 4-1. Direct Inputs Used in Calculation

Input Description	Data Tracking Number/Source	Value
Intersections of known faults with emplacement drifts	DTN: MO0705FAULTABS.000 [DIRS 183150], file *Fault Displacement Abstraction for Criticality.xls,* worksheet "Tables by WP Type"	Drill Hole, Pagany Wash, and Sevier Wash = 26 West Ghost Dance = 11 Sundance = 6 Total = 43
Annual exceedance probability range for TAD canister size packages	DTN: MO0705FAULTABS.000 [DIRS 183150], file *Fault Displacement Abstraction for Criticality.xls,* worksheet "Tables by WP Type"	10^{-8}/yr to 8.2 × 10^{-8}/yr
Waste packages in the repository inventory	DTN: MO0702PASTREAM.001 [DIRS 179925], worksheet "Unit Cell" in file *DTN-Inventory-Rev00.xls,* cells B15 to L15	Navy = 400 (sum of long and short) CSNF = 7,483 (sum of 21P-TAD and 44B-TAD and 12P-Long-TAD) Total = 11,162
TSPA seepage rate, seepage fraction, for five bin locations	DTN: MO0705TSPASEEP.000 [DIRS 183008], v5.005_GS_9.60.300_Seismic-FD_1Myr.zip, folder: GoldSim_Exported_Results	Seepage rates time history are in v5.005_Seismic-FD_1Myr_*CSNF_SeepRate_Bin1.txt,* v5.005_Seismic-FD_1Myr_*CSNF_SeepRate_Bin2.txt,* v5.005_Seismic-FD_1Myr_*CSNF_SeepRate_Bin3.txt,* v5.005_Seismic-FD_1Myr_*CSNF_SeepRate_Bin4.txt,* v5.005_Seismic-FD_1Myr_*CSNF_SeepRate_Bin5.txt*. Seepage fractions at five bin locations are in *v5.005_Seismic-FD_1Myr_SeepFrac.txt*
TSPA localized corrosion results	DTN: MO0709TSPALOCO.000 [DIRS 182994], folder *Additional_Information/LC_for_ Criticality*	Lith_Fraction_CDSP_Bin1 Lith_Fraction_CDSP_Bin2 Lith_Fraction_CDSP_Bin3 Lith_Fraction_CDSP_Bin4 Lith_Fraction_CDSP_Bin5 NonLith_Fraction_CDSP_Bin1 NonLith_Fraction_CDSP_Bin2 NonLith_Fraction_CDSP_Bin3 NonLith_Fraction_CDSP_Bin4 NonLith_Fraction_CDSP_Bin5 Lith_Fraction_CSNF_Bin1 Lith_Fraction_CSNF_Bin2 Lith_Fraction_ CSNF _Bin3 Lith_Fraction_ CSNF _Bin4 Lith_Fraction_ CSNF _Bin5 NonLith_Fraction_ CSNF _Bin1 NonLith_Fraction_ CSNF _Bin2 NonLith_Fraction_ CSNF _Bin3 NonLith_Fraction_ CSNF _Bin4 NonLith_Fraction_ CSNF _Bin5

Table 4-1. Direct Inputs Used in Calculation (Continued)

Input Description	Data Tracking Number/Source	Value
Percolation bin fraction within each geologic unit	DTN: MO0709TSPALOCO.000 [DIRS 182994], folder *Additional_Information/LC_Initiation_Uncertainty_Analysis_v2_NonLith/LC_Plots_NonLith* file *NonLith_Frac_CSNF_out.xls*	**Bin Lith Fraction Nonlith Fraction** 1 0.680982 0.319018 2 0.762546 0.237454 3 0.826923 0.173077 4 0.958537 0.041463 5 0.890244 0.109756
Bin fractions of the waste package parsing of percolation flux	DTN: MO0505SPAROCKM.000 [DIRS 173893]; SNL 2008 [DIRS 184433], Appendix VIII	0.05, 0.25, 0.4, 0.25, 0.05
Waste package outer corrosion barrier length	SNL 2007 [DIRS 179394], Table 4-3	5,691.38 mm (5.6914 m)
Waste package outer corrosion barrier diameter	SNL 2007 [DIRS 179394], Table 4-3	1,881.60 mm (1.8816 m)
Drip shield emplacement error	SNL 2007 [DIRS 178765], Table 6-8	4.36×10^{-9} per drip shield
DOE waste forms using absorber plates for criticality control	DOE 2004 [DIRS 170071], Section 2.1.11	See Section 4.2
Hazard curve relationship to exceedance frequency and peak ground velocity	DTN: MO0703PASDSTAT.001 [DIRS 183148], file *Lith_Rubble_Abstraction.xls,* worksheet *Data for Bounded Hazard*	See Output DTN: MO0712PBANLNWP.000, file *Lith Probability of DS Failure.xmcd* in folder 4D
Regression constants and standard deviation relationships	SNL 2007 [DIRS 176828], Figure 6-56	μ_v (PGV m/s) $m^3/m = 20.307PGV^2 - 18.023PGV + 4.0102$ σ_v (PGV m/s) $m^3/m = -3.5613PGV^2 + 18.018PGV - 6.6202$
Probability that a seismic event causes drip shield damage in nonlithophysal unit and conditional probabilities for different drip shield damage states, and probabilities of drip shield plate failure	DTN: MO0703PASEISDA.002 [DIRS 183156], Tables 1-2, 1-10, and 1-11	See Mathcad files in Output DTN: MO0712PANLNNWP.000 folder 3D/CSNF and MO0712PBANLNWP.000 folder 3D
Repository geographic and geologic location	SNL 2007 [DIRS 179466], Table 4-1, Item 01-01 and 01-03	15% of repository is in the nonlithophysal unit and 85% is in the lithophysal unit
DOE HLW waste forms using absorber plates for criticality control	DOE 2004 DIRS 170071], Section 2.1.11	Mixed oxide (MOX) represented by Fast Flux Test Facility (FFTF) fuel, $UZrH_x$ represented by Training, Research, Isotopes, General Atomic (TRIGA) fuel, U/Th Oxide represented by Shippingport Light Water Breeder Reactor fuel, aluminum-based DOE-owned SNF represented by Advanced Test Reactor (ATR) fuel, and U-Zr/U-Mo represented by Enrico Fermi fuel
Number of codisposal waste packages	Wheatley (2007 [DIRS 181533], p. 2)	MOX canister count = 143 ATR canister count = 991 TRIGA canister count = 89

Table 4-1. Direct Inputs Used in Calculation (Continued)

Input Description	Data Tracking Number/Source	Value
PGV frequency for probability of nonzero rockfall	DTN: MO0703PASEISDA.002, [DIRS 183156], Equation 1-1,	$P_{rockfall} = MIN(1.0, MAX(0.0, (1.288)PGV - 0.353)).$
Rubble volume resulting in waste package temperature increase to 300°C	MO0709HOTWASTE.000 [DIRS 184821], Folder: *Drift Collapse*, File: *Worksheet in Seismic Consequence Analysis.xls*, Worksheet: *P10L Peak T vs Vol. LKT*	7.5 m^3/m
Heat of vaporization for water	Incropera and DeWitt 2002 [DIRS 163337], Physical Constants	2257 kJ/kg
Definition of Hazard Parameters and Drip Shield Fragility for the Seismic Damage Abstractions	DTN: MO0703PASEISDA.002 [DIRS 183156], Table 1-15	Function of the value of LAMBDA for each seismic event. Use a power law (log) interpolation between points in the table. **λ (1/yr)** **PGV (m/s)** 4.287 × 10^{-4} 0.219 1.000 × 10^{-4} 0.4019 3.826 × 10^{-5} 0.6 1.919 × 10^{-5} 0.8 9.955 × 10^{-6} 1.05 6.682 × 10^{-6} 1.2 3.812 × 10^{-6} 1.4 2.136 × 10^{-6} 1.6 1.288 × 10^{-6} 1.8 8.755 × 10^{-7} 2.0 6.399 × 10^{-7} 2.2 4.518 × 10^{-7} 2.44 3.504 × 10^{-7} 2.6 2.507 × 10^{-7} 2.8 1.731 × 10^{-7} 3.0 1.137 × 10^{-7} 3.2 7.168 × 10^{-8} 3.4 4.362 × 10^{-8} 3.6 2.508 × 10^{-8} 3.8 1.319 × 10^{-8} 4.0 5.967 × 10^{-9} 4.2
Probability of non-zero damage to a TAD waste package with intact internals for different residual stress thresholds	DTN: MO0703PASEISDA.002 [DIRS 183156], Table 1-6	See Output DTN: MO0712PBANLNWP.000, folder C
Frequency from bounded hazard curve corresponding to a PGV of 1.05 m/s	DTN: MO0703PASEISDA.002 [DIRS 183156], Table 1-1	9.96 × 10^{-6} /yr
Maximum flow rate through a crack or cracks into a given waste package	DTN: SN0705WFLOWSCC.001 [DIRS 184848], Excel file: *Bounding calc for water flow through SCC cracks.xls*, Spreadsheet "Impinging drip flow rate", cell H29)	223 g
Source for indicating localized corrosion from dust deliquescence is insignificant	SNL 2007 [DIRS 181267], Section 7[a]	0

Table 4-1. Direct Inputs Used in Calculation (Continued)

Input Description	Data Tracking Number/Source	Value
Horizontal peak ground velocity (PGV) associated with a seismic event. Obtained as a function of recurrence frequency, and called the "bounded hazard curve"	DTN: MO0501BPVELEMP.001 [DIRS 172682]	See Mathcad file in Output DTN: MO0712PBANLNWP.000, folder C
Maximum static load on drip shield range	SNL 2007 [DIRS 176828], Section 6.7.1.5	30 to 120 m^3/m

CSNF = commercial SNF.

4.2 CRITERIA

There are no specific design criteria for postclosure criticality control in 10 CFR Part 63 [DIRS 180319] but requirements are consistent with a risk-informed, performance-based regulation, which treats criticality in 10 CFR Part 63 as one of the features, events, and processes (FEPs) that must be considered for the overall system performance assessment, i.e.:

> …The features, events, and processes considered in the performance assessment should represent a wide range of beneficial and potentially adverse effects on performance (e.g., beneficial effects of radionuclide sorption; potentially adverse effects of fracture flow or a criticality event)…. [§ 102(j)]

Disposal Criticality Analysis Methodology Topical Report (YMP 2003 [DIRS 165505]) presents a risk-informed, performance-based approach for evaluating potential postclosure criticality situations in the monitored geologic repository. The use of risk-informed, performance-based analyses in regulatory matters is consistent with the U.S. Nuclear Regulatory Commission (NRC) policy statement 60 FR 42622 [DIRS 103662]. It is likewise consistent with correspondence among the NRC commissioners on risk-informed, performance-based regulation (Jackson 1998 [DIRS 150737]). Requirements for the overall postclosure performance of the repository in 10 CFR Part 63, Section 113 include the use of multiple barriers, limits on the expected annual dose to the reasonably maximally exposed individual, limits on the release of radionuclides to the accessible environment, and a limit on individual radiological exposures in the event of human intrusion.

Various measures are implemented to satisfy the 10 CFR Part 63 acceptance criteria applicable to the postclosure performance assessment for the Yucca Mountain site that include examining the significant factors contributing to the probability of criticality in the repository and possibly implementing additional analyses or design enhancements to reduce the overall probability of criticality if the respective criteria are exceeded. Such measures are addressed in 10 CFR Part 63 which, in discussing "concepts" of the performance assessment regulations, states in part:

> …Those features, events, and processes expected to materially affect compliance with § 63.113(b) or be potentially adverse to performance are included, while events (event classes or scenario classes) that are very unlikely (less than one chance in 10,000 over 10,000 years) can be excluded from the analysis… [§ 102(j)]

10 CFR 63.114(a)(4) (proposed) requires any performance assessment used to demonstrate compliance with 63.113 for 10,000 years after disposal to "Consider only features, events, and processes consistent with the limits on performance assessment specified at 63.342." 10 CFR 63.342(a) (proposed rule) requires "DOE's performance assessments conducted to show compliance with 63.311(a)(1), 63.321(b)(1), and 63.331 shall not include consideration of very unlikely features, events, and processes, i.e., those that are estimated to have less than one chance in 10,000 of occurring within 10,000 years of disposal (less than one chance in 100,000,000 per year)" (70 FR 53313 [DIRS 178394], pp. 53319 to 53320). In other words, very unlikely events have a probability of occurring of less than 10^{-8} per year. Thus, very unlikely FEPs can be excluded (screened out) from the performance assessment to show compliance with the individual protection standards for the 10,000 years following disposal on the basis of low probability.

4.3 CODES, STANDARDS, AND REGULATIONS

This report is prepared to comply with the NRC acceptance criteria as discussed in the technical work plan (SNL 2007 [DIRS 178869], Section 3.2), as well as the NRC regulations governing high-level waste, 10 CFR Part 63 [DIRS 180319].

Specific criteria applicable to this calculation are listed as follows:

Yucca Mountain Review Plan, Final Report (NRC 2003 [DIRS 163274]).

- Section 2.2.1.2.2.3, Scenario Analysis and Event Probability – Identification of Events with Probabilities Greater than 10^{-8} Per Year – Acceptance Criterion (AC 1)
- Section 2.2.1.3.3.3, Model Abstraction – Quantity and Chemistry of Water Contacting Waste Packages and Waste Forms – Acceptance Criterion (AC 1).

The following is a list of industry and technical standards that are applicable to this calculation:

- ANSI/ANS-8.1-1998. *Nuclear Criticality Safety in Operations with Fissionable Material Outside Reactors* [DIRS 123801]
- ANSI/ANS-8.10-1983 (Reaffirmed 2005). *American National Standard Criteria for Nuclear Criticality Safety Controls in Operations with Shielding and Confinement* [DIRS 176885]
- ANSI/ANS-8.17-2004. 2004. *American National Standard, Criticality Safety Criteria for the Handling, Storage and Transportation of LWR Fuel Outside Reactors* [DIRS 176225].

5. ASSUMPTIONS

Assumptions used in the absence of direct confirming data or evidence are provided in this section.

5.1 BATHTUB GEOMETRY

Assumption: For the fault displacement event, it is assumed that the breach of the waste package and its inner canister forms a bathtub-type geometry (aqueous solution filling all voids within the waste package) for the current calculation with the breach near the top of the waste package.

Rationale: Bathtub is a conservative geometry to use in assessing the amount of water collected by a waste package. It maximizes the amount of moderator (e.g., water) inside the waste package for criticality concern. The use of a bathtub geometry assumes the waste package is more likely to be filled by seepage than flow-through for the same influx. For maximum water accumulation, the waste package and its inner canister are assumed to fail simultaneously.

Confirmation Status: This assumption requires no further confirmation.

Use in the Calculation: This assumption is used in output DTN: MO0802WPFLOODG.001, *Mathcad files*.

5.2 STEADY-STATE FLOW WITH CONSTANT VOLUME

Assumption: For the fault displacement event, a steady-state filling process is assumed, such that during the filling stage the waste package volume and seepage flow rate are constant.

Rationale: Steady-state flow is a simplifying assumption when modeling water flux into the waste package. It excludes transient flow, evaporation, and condensation. Transient analysis requires integration of the flow and volume along with time. The volume change in the waste package due to degradation and seismic event may not be available during the regulatory period. Nevertheless the results in Section 7.1 provide filling probabilities for a range of free volumes.

Confirmation Status: This assumption requires no further confirmation.

Use in the Calculation: This assumption is used in output DTN: MO0802WPFLOODG.001, *Mathcad files*.

6. SCIENTIFIC ANALYSIS DISCUSSION

To estimate the quantity of water that could potentially enter a waste package by advection, a representative set of conditions and parameters must be selected. First the drip shield needs to be damaged as a barrier to flow, and at the same location, the outer corrosion barrier, inner vessel, and fuel canister (TAD, naval, or DOE) of waste inside the package must be breached, and finally this combination must be colocated under a seep. Mechanisms for drip shield failure and waste package failure have been identified and are provided in Sections 6.1 and 6.2 along with an assessment of the waste package hydrologic conditions.

Throughout the remainder of this report, the terms “damage” and “failure” are often used. The following are definitions:

- “Damage” refers to regions of plastic deformation wherein the residual tensile stress is high enough to initiate stress corrosion crack development in the drip shield plates or the waste package outer corrosion barrier. The plastic deformation of EBS components may be induced by impact denting (e.g., from rock block impact or from impact of EBS components during seismic shaking) or by quasi-static forces from rock rubble loading (which may be amplified by ground acceleration during seismic shaking).

- "Failure" refers to an immediate loss of function of an EBS component, including a tensile rupture, tearing or puncture of the drip shield plates or waste package outer corrosion barrier, or the collapse of the drip shield framework.

6.1 SEISMIC FAULT DISPLACEMENT PROBABILITY OF FILLING A WASTE PACKAGE

Multiple seismic faults can be found in the vicinity of the Yucca Mountain repository. Displacement resulting from a seismic event is considered to have the potential to fail drip shields and waste packages placed on the fault line that could result in filling a waste package. Forty-three fault intersections with emplacement drifts have been identified as having a possibility to result in such failures (DTN: MO0705FAULTABS.000 [DIRS 183150]). There is a specific criterion for naval waste packages that requires an 8.2-ft (2.5-m) minimum emplacement standoff distance from mapped faults with vertical displacements greater than 6.5 ft (2 m) (BSC 2007 [DIRS 182131], Section 8.2.3.1.1). Note that the subsurface repository layout includes a certain amount of additional drift length for use as a contingency region in the event that geologic anomalies such as faults or fault splay zones, zones of unusually large lithophysae, or changes in rock types are encountered that preclude emplacement of waste packages in some sections of drifts. Although general requirements or criteria for avoiding or selecting a standoff distance from these anomalies has not been established with the exception of naval waste packages, it is expected that as these anomalies are encountered, appropriate waste package standoffs will be determined on a case-by-case basis. Fault identification and avoidance in affected drifts during waste emplacement are preventive measures that would significantly decrease the probability of waste package failure due to seismic faulting events. Naval waste packages are not expected to be placed on existing/visible faults, however, they are still evaluated in this analysis.

Potential waste package failure from seismic faulting is dependent upon: (1) the amount of clearance between the top of a waste package and the bottom of the drip shield, and (2) the amount of fault displacement. The clearance between the top of a waste package and the bottom of the drip shield is a function of the waste package diameter. The amount of fault displacement is a function of the severity of the seismic event causing the fault displacement. Failure to a waste package is considered possible when the fault displacement exceeds the clearance between a waste package located on the fault and the drip shield surrounding it. A waste package and its inner canister are considered to fail if the mean annual seismic exceedance frequency is within the range of 10^{-8} to 8.2×10^{-8} (Table 4-1).

The primary function of the drip shield is to keep seepage water from reaching the waste package. Once this function has failed and the waste package is breached, the internal cavity region may be exposed to seepage water. The calculation for waste package filling is based directly on a seismically induced fault displacement damaging the drip shield and waste package, which can allow advective or diffusive flow into the waste package.

The process developed to calculate fault displacement-induced failure uses Latin Hypercube sampling in order to quantify the uncertainty in the seismic disruptive events. Time and exceedance frequency are sampled in the scheme. The principle of Latin Hypercube sampling is provided by Modarres (1993 [DIRS 104667], p. 244). Results from "Assessment of Waste Package Failure Due to Fault Displacement for Criticality" (DTN: MO0705FAULTABS.000 [DIRS 183150], *Fault Displacement Abstraction for Criticality.xls*), based on hazard curves, identify what seismic event exceedance frequency is required to potentially fail the waste package.

To determine the mean number of waste packages impacted by fault intersections a hypergeometric distribution can be used. The definition of hypergeometric distribution is as follows: Suppose that, from a population of N elements of which M are successes (i.e., possess a certain attribute) a sample of *n* items is drawn without replacement. The number of successes in such a sample is a hypergeometric distribution. The probability function (probability of exactly *x* successes) (Evans et al. 1993 [DIRS 112115], p. 85) is given in Equation 1:

$$P(x;N,M,n)=\frac{\binom{M}{x}\binom{N-M}{n-x}}{\binom{N}{n}} \qquad \text{(Eq. 1)}$$

where

P = probability of success
x = number of successes
n = sample size
M = population of certain attribute
N = total population.

The numerator and denominator in Equation 1 indicate the number of combinations.

The same probability applies to having *x* out of M waste packages of a certain type from a total of N waste packages impacted by *n* number of fault intersections, if and only if one waste package is impacted by one fault intersection.

The mean number of waste packages of any given type impacted by fault intersections can be calculated using the hypergeometric distribution as shown in Equation 2 (Evans et al. 1993 [DIRS 112115], p. 85):

$$\text{Mean} = nM/N \qquad \text{(Eq. 2)}$$

where

n = number of faults
M = number of waste packages of a given type
N = total number of waste packages in the repository inventory.

From "Assessment of Waste Package Failure Due to Fault Displacement for Criticality" (DTN: MO0705FAULTABS.000 [DIRS 183150], file: *Fault Displacement Abstraction for Criticality.xls*), the number of known faults (n) that could impact the waste package is 43. The number of waste packages of a given type (M) and the total number of waste packages in the repository inventory (N) are 400 (for the naval waste package configuration) and 11,162, respectively (DTN: MO0702PASTREAM.001 [DIRS 179925], worksheet "Unit Cell" in file *DTN-Inventory-Rev00.xls*). The number of commercial SNF waste packages is 7,483 (Table 4-1). By applying Equation 2, the estimated number of waste packages failed is shown in Table 6-1.

Table 6-1. Estimated Number of Waste Packages Failed

Waste Package Type	**Hypergeometric Distribution**	**DTN: MO0705FAULTABS.000 [DIRS 183150], *Fault Displacement Abstraction for Criticality.xls,* worksheet "Tables by WP Type"**[a]
Navy	1.54	0[b]
CSNF	28.83	31.8

[a] For comparison, different waste package lengths are factored in the estimate.

[b] Naval waste packages will not be placed on faults, in this case total probability of filling a naval waste package in Table 7-2 will be 0.

CSNF = commercial SNF.

The Weibull distribution is widely used to represent the time to failure or life length of the components in a system, measured from a start time to the time that a component fails. The probability density function is shown in Equation 3 (Modarres 1993 [DIRS 104667], p. 36):

$$f(t) = \frac{\beta t^{\beta - 1}}{\alpha^{\beta}} \exp\left[-(t/\alpha)^{\beta} \right] \qquad \text{(Eq. 3)}$$

where

t = time
α = scale parameter
β = shape parameter.

In the original Weibull distribution, t is defined as time, but t will be used as the seepage rate in order to obtain its cumulative distribution function (CDF) in this calculation. The plot of the CDF versus the seepage rate is shown in Figure 6-2. The parameter α is related to the scale of the seepage rate, and parameter β is related to the shape of the plot. The CDF for Weibull distribution is shown in Equation 4 (Modarres 1993 [DIRS 104667], p. 43):

$$F(t) = 1 - \exp\left[-(t/\alpha)^{\beta} \right] \qquad \text{(Eq. 4)}$$

A Weibull distribution can be used for data believed to have an increasing, decreasing, or constant rate of failure. Estimates of α and β parameters of the Weibull distribution can be obtained from Equations 5 and 6 (Modarres 1993 [DIRS 104667], p. 109):

$$\frac{\sum_{i=1}^{n}(t_i)^{\beta}\ln(t_i)}{\sum_{i=1}^{n}(t_i)^{\beta}}-\frac{1}{\beta}=\frac{1}{n}\sum_{i=1}^{n}\ln(t_i) \qquad \text{(Eq. 5)}$$

$$\alpha=\left(\frac{\sum_{i=1}^{n}(t_i)^{\beta}}{n}\right)^{\frac{1}{\beta}} \qquad \text{(Eq. 6)}$$

The seepage rate required to fill a waste package is described in Section 6.2. The probability of seepage exceeding the required value is calculated by utilizing the Weibull CDF (Equation 4) as shown in Equation 7.

$$R(t)=1-F(t)=\exp\left[-(t/\alpha)^{\beta}\right] \qquad \text{(Eq. 7)}$$

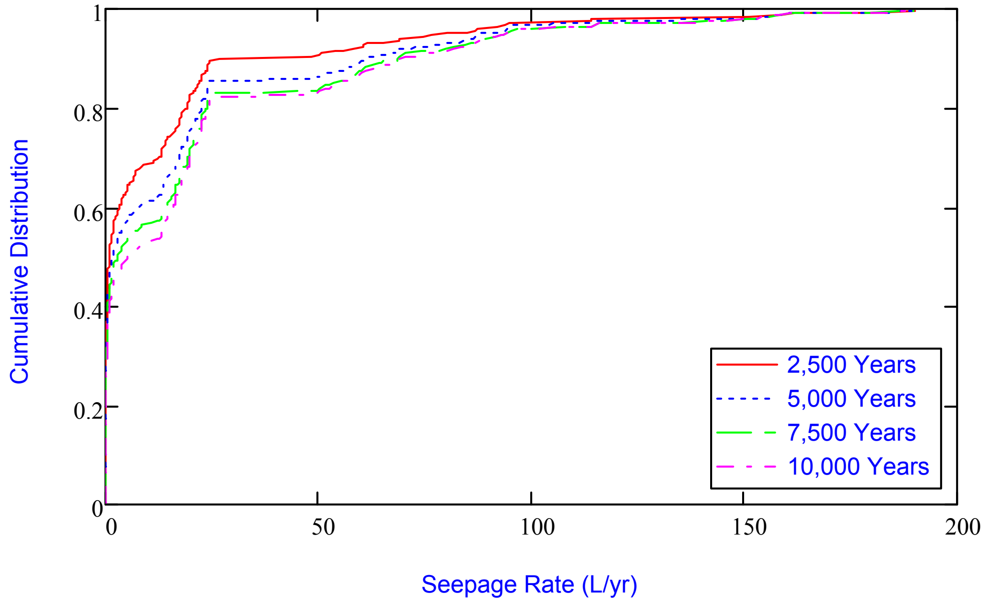
where

R = probability of seepage exceeding the required value
t = seepage rate.

6.1.1 Seepage Rate Distribution

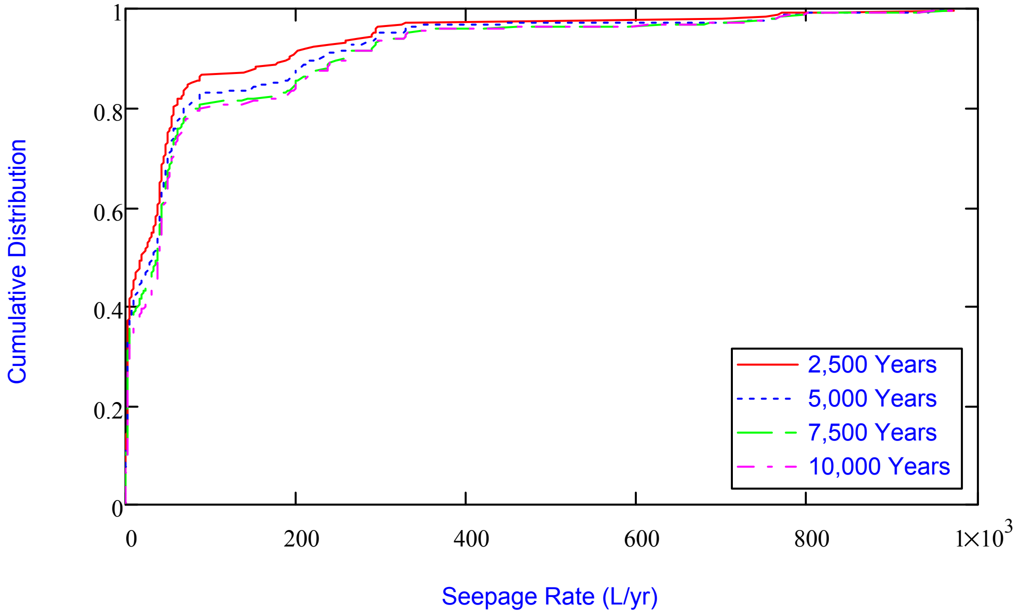
The relevant parameters for seepage rate calculations are capillary strength, permeability, and adjusted percolation flux. Capillary strength is one of the key parameters affecting the capillary barrier behavior at the drift crown. The larger this parameter, the stronger the capillary force, which holds water in the fractures and prevents it from seeping into the drift. The second key parameter affecting the diversion of water around drifts is the tangential fracture permeability in the boundary layer near the drift wall. The larger this parameter, the more likely that water will flow around the drift and the less likely that seepage will occur. The magnitude (and spatial distribution) of local percolation fluxes at the repository horizon is the third key parameter affecting seepage into drifts. The larger the local percolation flux, the higher the potential for seepage to occur and the larger the amount of water that can seep into drifts. All of these parameters are described in *Abstraction of Drift Seepage* (SNL 2007 [DIRS 181244], Section 6.6).

Figures 6-1 through 6-5 illustrate the predicted seepage rates per commercial SNF package for five individual percolation bins. There are 300 samples in each of the five bins. The climate scenario change leads to a jump in mean seepage rates around 2000 years. The mean seepage rates gradually increase after 2,000 years except for the first bin. Figures 6-1 through 6-5 show seepage rates at different time periods are relatively similar with the maximum seepage rates within the first 10,000 years occurring at 10,000 years. Therefore, the 10,000-year seepage values are used for the probability calculations.



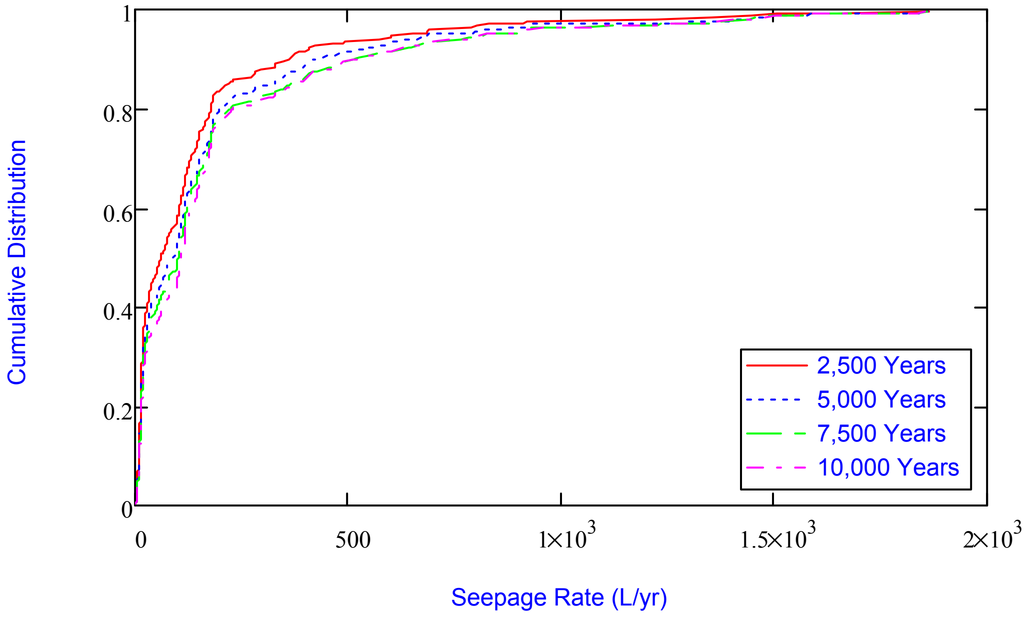
Source: Output DTN: MO0802WPFLOODG.001, *seep_plot.xmcd*.

Figure 6-1. Bin 1 Commercial SNF Seepage Rate



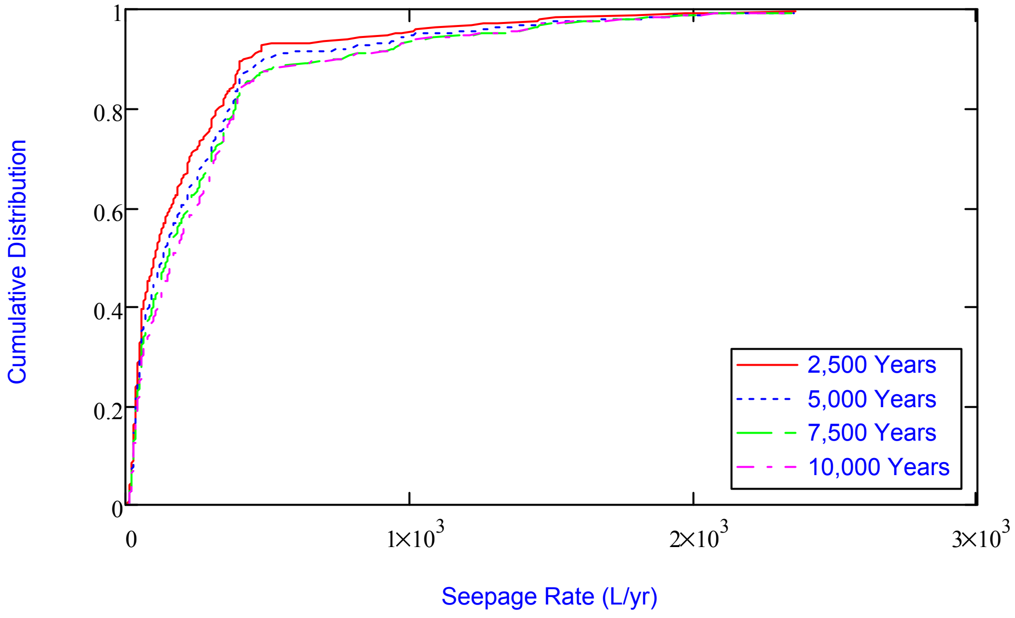
Source: Output DTN: MO0802WPFLOODG.001, *seep_plot.xmcd*.

Figure 6-2. Bin 2 Commercial SNF Seepage Rate



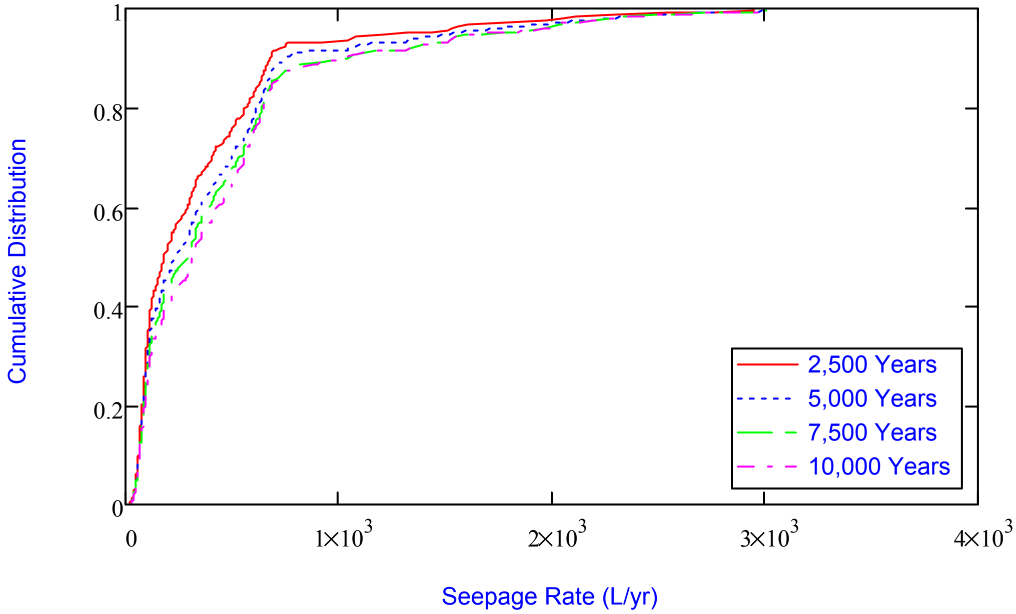
Source: Output DTN: MO0802WPFLOODG.001, *seep_plot.xmcd*.

Figure 6-3. Bin 3 Commercial SNF Seepage Rate



Source: Output DTN: MO0802WPFLOODG.001, *seep_plot.xmcd*.

Figure 6-4. Bin 4 Commercial SNF Seepage Rate



Source: Output DTN: MO0802WPFLOODG.001, *seep_plot.xmcd*.

Figure 6-5. Bin 5 Commercial SNF Seepage Rate

Since these seepage rates are considered what would enter the full footprint area of the waste package, they overestimate the seepage collection area for a waste package that has failed from a fault displacement event. Therefore, a scaling factor is necessary in order to adjust the TSPA seepage values to a value that is more representative for the current evaluation. Considering a waste package failure from a fault displacement event, the failed area is conceptualized to be a shear that lies in a plane normal to the central axis of the waste package. This results in a maximum failure area equal to the area of the waste package lid. Since the package would still be in a relatively horizontal orientation, the area for seepage water collection would vary depending on the azimuth of the opening. Therefore, in order to maximize the collection area, the maximum package failure area will be used for the scaling factor. The area of the lid for the TAD-bearing waste package (which is the same size for the naval canister waste package) (SNL 2007 [DIRS 179394], Section 4.1.2.1) is 2.78 m^2. This area is divided by the waste package footprint area to provide the seepage rate scaling factor.

$Failure\,area = \frac{\pi d^2}{4}$ where d = waste package outer corrosion barrier diameter (1.8816 m (SNL 2007 [DIRS 179394], Table 4-3))

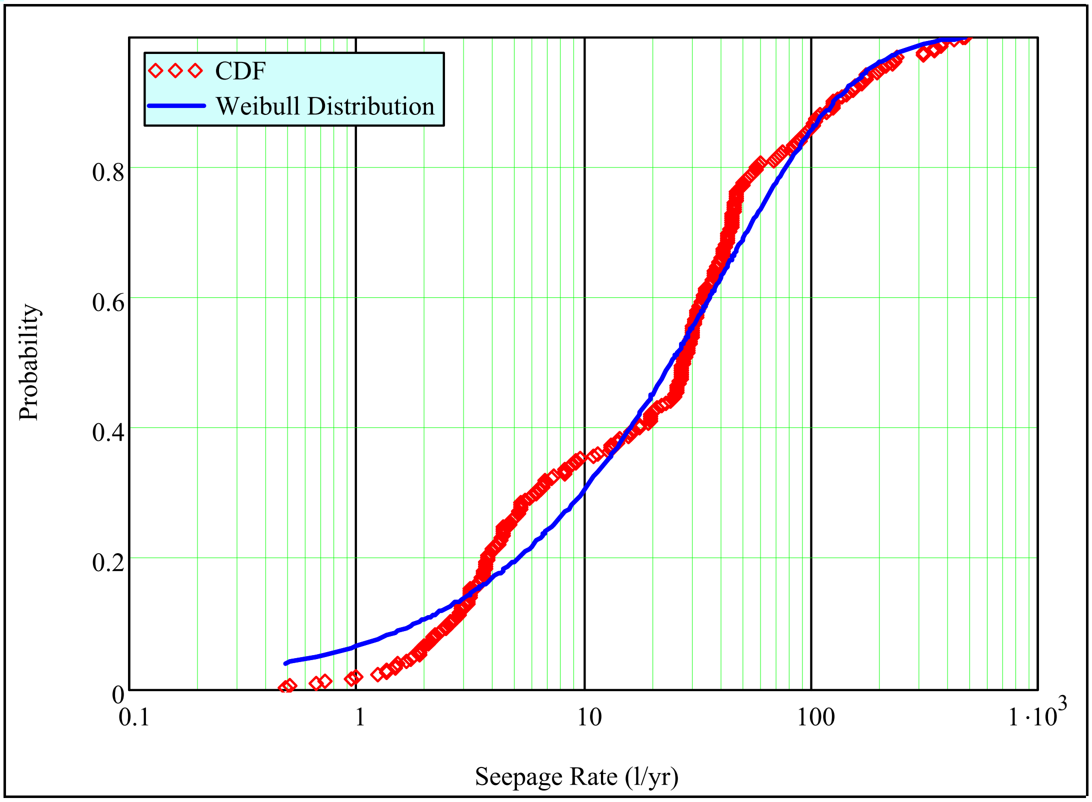
Waste package footprint area = ld where l = the waste package outer corrosion barrier length (5.6914 m (SNL 2007 [DIRS 179394], Table 4-3))

Failure area = 2.78 m^2

Waste package footprint area = 10.71 m^2

Scaling factor = $\frac{2.78\,m^2}{10.71\,m^2} = 0.26$

The predicted seepage values are substituted into t of Weibull distribution Equations 5 and 6 to obtain the shape (β) and scale (α) parameters, respectively. Figure 6-2 provides a representative plot of the CDF of the seepage rates (CSNF_PS_3 at 10,000 years) and Weibull fit. It is an indication of how good the seepage rates are represented by the Weibull distribution. Plots for all five bins are present in output DTN: MO0802WPFLOODG.001, *WPfillprob_faultdisplacement-R1_JMS.xmcd*.



Source: Output DTN: MO0802WPFLOODG.001, *WPfillprob_faultdisplacement-R1_JMS.xmcd*.

NOTE: Plot of CSNF_PS_3 at 10,000 years, weibull distribution fit to cumulative distribution function.

Figure 6-2. Cumulative Distribution Function of the Seepage Rates and Weibull Fit

The seepage fraction is the fraction of waste package locations that can expect seepage. The mean seepage fractions are shown in the worksheet "Seepage Fraction" of *v5.0_Seismic-FD_Seepage_Results.xls* (output DTN: MO0802WPFLOODG.001). The weighting factors are from the bin fractions of the waste package parsing (DTN: MO0505SPAROCKM.000 [DIRS 173893]). Table 6-2 lists the output parameters for a Weibull distribution fit to the seepage rates along with the mean seepage fractions for each of the five bins.

Table 6-2. Weibull Parameters and Seepage Fractions

Weibull Parameters	**Without Seepage Collection Scaling Factor**	**With Seepage Collection Scaling Factor**	**Mean Seepage Fraction**
CSNF_PS_1			
α (scale)	9.79	2.55	0.467
β (shape)	0.436	0.436	
CSNF_PS_2			
α (scale)	52.2	13.6	0.649
β (shape)	0.562	0.562	
CSNF_PS_3			
α (scale)	157	40.9	0.719
β (shape)	0.726	0.726	
CSNF_PS_4			
α (scale)	270	70.2	0.704
β (shape)	0.86	0.86	
CSNF_PS_5			
α (scale)	461	120	0.752
β (shape)	0.987	0.987	

Source: Values derived from output DTN: MO0802WPFLOODG.001, *WPfillprob_faultdisplacement-R1_JMS.xmcd, WPfillprob_faultdisplacement-R2_JMS.xmcd* and v5.0_Seismic-FD_*Seepage_Results.xls*.

6.1.2 Water-Filling Probability Calculation

The water-filling probability uses all of the parameters shown in Table 6-2. The process calculates 50,000 different probabilities, one for each seismic sample (output DTN: MO0802WPFLOODG.001, *Mathcad files*), which provides a mechanism to calculate the mean probability and other parameters (i.e., 5th percentile, 95th percentile). However for this calculation, only the mean probability is calculated. The steps used in this calculation to calculate the water-filling probability are discussed below.

The first step is to sample the time when a seismic disruptive event has occurred. The time range used in this calculation is from one year after repository closure to 10,000 years. The time is sampled once for each of the 50,000 samples. The next step is to sample the seismic exceedance frequency. The seismic exceedance frequency is used to determine the probability of waste package failure caused by fault displacement. A waste package is considered failed if the mean annual seismic exceedance frequency is within the range of 10^{-8} to 8.2×10^{-8}. This annual seismic exceedance frequency is applicable to naval SNF and commercial SNF packages (DTN: MO0705FAULTABS.000 [DIRS 183150], *Fault Displacement Abstraction for Criticality.xls*).

Next, the required seepage rate at the drift needs to be determined in order for the exceedance probability to be calculated. The required seepage rate is calculated based on the free volume of the waste package being analyzed along with the time when the seismic event occurs. The free volume (in liters) is divided by 10,000 years minus the time the seismic event occurs. This seepage rate (in liters/year) is the seepage rate at the waste package failure path required to fill the waste package.

The calculated required seepage rate at the drift is then substituted into *t* of the Weibull CDF (Equation 4) to obtain the cumulative probability of seepage from 0 to the required rate. This cumulative probability is again subtracted from 1 to obtain the probability of seepage exceeding the required value to fill the waste package. This probability is then multiplied by the seepage fraction to consider the fact that only a fraction of locations can expect seepage. The probabilities from five bins are summed together using the bin fractions of the waste package parsing.

The final step in the probability calculation is to factor in the probability of having a seismic event. This probability is calculated by taking 8.2×10^{-8}/yr minus 10^{-8}/yr (DTN: MO0705FAULTABS.000 [DIRS 183150], *Fault Displacement Abstraction for Criticality.xls*) and multiplying it by 10,000 years. This seismic probability is then multiplied by each sampled probability. This provides 50,000 probabilities, one for each sample. Using the 50,000 probabilities, the overall mean probability is calculated for each of the ten specified free volumes. These are then multiplied by the mean number of waste packages of any given type residing on faults to obtain the total probability.

6.2 PROBABILITY OF ADVECTIVE WATER INGRESS INTO A WASTE PACKAGE

This section considers hydrologic conditions within commercial SNF and naval SNF packages, and DOE SNF/high-level waste (HLW) codisposal waste packages subject to damage by seismic ground motion or localized corrosion. The initiating events and possible modes of damage or failure to drip shields and waste packages that may allow liquid water inflow are listed below. Damage is defined as any breach that can allow water flow through by diffusion and/or advection. Damage states are divided into two types – those that involve an area of stress corrosion cracking that is capable of diverting a substantial fraction of any liquid water present on the surface, and those where the waste package or drip shield has failed so that liquid flow is not diverted.

Drip Shield

- Early failure from fabrication (behaves like stress corrosion cracking (SCC)
- Early failure from misplacement (provides no seepage diversion)
- Rockfall (large rock block) in nonlithophysal zone (provides no seepage diversion)
- Drift collapse and rupture in the lithophysal zone (provides no seepage diversion).

Waste Package

- Early failure from fabrication (behaves like SCC)
- Damage induced by seismic ground motion (behaves like SCC)

- Puncture/rupture induced by seismic ground motion (provides no seepage diversion)
- Localized corrosion (provides no seepage diversion).

An early failure is defined as the through-wall penetration of a waste package or drip shield due to manufacturing or handling-induced defects, at a time earlier than would be predicted by mechanistic degradation models for a defect-free waste package or drip shield. Failure mechanisms associated with waste package early failure include: 1) failure of the low-plasticity burnishing process such that the compressive stress layer in the waste package outer corrosion barrier (OCB) closure lid is not produced, 2) failure of the waste package OCB stress mitigation processes to function properly, and 3) weld flaws in the waste package OCB lid. Early failures associated with drip shields include fabrication process deficiencies such as those originating with material selection, weld quality, stress mitigation by heat treatment, and failure to properly emplace drip shields. Weld flaws in the waste package OCB lid or a failure of the stress mitigation processes can lead to a waste package breach from either weld flaw propagation or SCC initiated by the residual stresses. Drip shield fabrication flaws could take the form of SCC or physically similar defects. A drip shield emplacement error could create an advective flow path to the waste package OCB creating an environment for localized corrosion processes that could breach the waste package. These events are analyzed in detail in *Analysis of Mechanisms for Early Waste Package/Drip Shield Failure* (SNL 2007 [DIRS 178765], Section 6.5).

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. The nonlithophysal host-rock comprises approximately 15% of the emplacement area, and the lithophysal rock constitutes the balance (Table 1 of the reference cited in SNL 2007 [DIRS 179466], Table 4-1, Item 01-01 and 01-03). The lithophysal rock is more deformable and has less compressive strength (BSC 2004 [DIRS 166107], p. vii). The presence of lithophysal cavities and more prevalent fracturing will produce more rubble, with smaller particles, in response to seismic loading. It is expected that the accumulation of rubble from a single seismic event or multiple events and the dynamic motion once the drip shield is loaded with rubble, may generate damaged and failed areas on the drip shield. The accumulation of rubble can also produce a thermal blanketing effect with higher waste package temperature during the first few hundred years after repository closure (SNL 2008 [DIRS 179962], Section 6.5.1). The drip shields may accumulate damage from rockfall induced by vibratory ground motion after repository closure until the drip shield plates eventually rupture (SNL 2007 [DIRS 176828], Section 6.8). In the nonlithophysal host rock, blocks released by seismic motion can impact the drip shield, and partial drift collapse may occur, but complete collapse is very unlikely. Rock block impacts may result in damaged areas on the drip shield plates and, in more extreme cases, may cause tearing or rupture of the plates (SNL 2007 [DIRS 176828], Section 6.10).

Waste packages may be contacted by limited amounts of water from condensation or slow leakage through damaged drip shields. However, flow of such condensation or leakage through stress corrosion cracks in the WPOB (e.g., seismically induced) will be insignificant (SNL 2007 [DIRS 181648], Section 6.1.2[a]). For certain conditions waste packages may be contacted directly by seepage from the host rock. If seepage contact causes localized corrosion of the WPOB, then waste package flooding may occur. If WPOB damage is limited to SCC, then the in-package hydrologic condition is limited to an unsaturated steady-state. The term flooding as used here represents the accumulation of liquid water in all or part of a waste package where drainage is precluded. The unsaturated steady-state is defined as a system in which the potential energy of water throughout the waste package is less than (more negative) than that associated with free water, and the liquid saturation in the macroscopic voids of the waste package is very small (essentially zero). In the unsaturated steady state water can be adsorbed on the internal surfaces of the waste package, and held by capillary forces in small pores or cracks. Note that general corrosion of the drip shields and waste packages is sufficiently slow (SNL 2007 [DIRS 180778], Section 8.3; SNL 2007 [DIRS 178519], Section 6.4.3) that breach from this corrosion mode need not be considered.

In this analysis of hydrologic conditions the commercial and naval waste packages are treated the same, since the waste package and canister configurations used for performance assessment are the same (SNL 2007 [DIRS 179394], Section 4.1.2.1). The DOE codisposal package does not have the equivalent of a TAD canister inside the inner vessel and is thus less rigid and more susceptible to mechanical damage from seismic vibration.

6.2.1. Unsaturated Steady-State Resulting from Stress Corrosion Cracking Damage

6.2.1.1 Description of Cracking Damage

The following discussion of damage is based on structural response calculations for peak ground velocity (PGV) levels of 1.05 m/s, 2.44 m/s, and 4.07 m/s (corresponding approximately to recurrence probabilities of 10^{-5}/yr, 5×10^{-7}/yr, and 10^{-8}/yr; SNL 2007 [DIRS 176828], Table 6-3). Damage to the commercial SNF and naval SNF waste packages occurs for single-event recurrence probabilities of 5×10^{-7}/yr or less (greater than 2.44 m/s PGV), for intact internals. Damage to HLW codisposal waste packages occurs at lower PGV levels, corresponding to a single event recurrence probability of approximately 4×10^{-4}/yr or less (greater than 0.364 m/s PGV). Taking into account the slow degradation of waste package internals after initial breach, for a 10,000-year assessment the internals are considered to retain their intact strength properties (SNL 2007 [DIRS 176828], Section 6.1.3.2). The probability values listed here may be too large, considering the uncertainty as to whether residual stress damage equal to 100% or more of the yield strength is required for SCC to initiate (SNL 2007 [DIRS 176828], Section 6.1.4). In summary, for discussion of hydrologic conditions, and taking into account uncertainties in the seismic consequence analyses, SCC damage has a mean probability on the order of 10^{-7}/yr for commercial SNF and naval SNF waste packages, and 10^{-5}/yr for HLW codisposal waste packages.

Seismic ground motion causes impacts between the waste package and pallet, end-to-end collisions between adjacent waste packages, and collisions between waste packages and drip shields (SNL 2007 [DIRS 176828], Section 6.5). Kinematic simulations show that damage to waste packages is “almost exclusively” due to impacts with the pallet, with only a few instances of damage from end-to-end collisions between adjacent waste packages (SNL 2007 [DIRS 176828], Sections 6.5.4 and 6.6.4). Accordingly, waste package-pallet impacts are by far the most significant seismic consequences for consideration of hydrologic conditions. These impacts produce residual stress conditions in the Alloy 22 that are modeled to cause propagation of SCC.

The location of damage resulting from waste package-pallet impacts is initially on the lower surface of the waste package, but continued ground motion and multiple events may rotate and translate the packages, producing a more uniform distribution of cracking damage (SNL 2007 [DIRS 176828], Sections 6.5.4 and 6.6.4). This result holds for both spent-fuel and HLW packages.

For criticality analysis the full 25.4-mm thickness of the Alloy 22 waste package outer barrier (WPOB) (represented by 23-mm calculations, SNL 2007 [DIRS 176828], Section 6.5) may be used because general corrosion reduces this thickness by only a fraction of a millimeter in 10,000 years. Propagation of SCC damage through the WPOB after seismic damage will take on the order of 1,000 years (SNL 2007 [DIRS 181953], Table 7-4), affording the opportunity for plugging of cracks coincident with crack propagation as discussed below.

Damage to the Stainless Steel Type 316 inner vessel occurs with high probability for events that damage the WPOB, as discussed for evaluation of oxide wedging processes associated with general corrosion (SNL 2008 [DIRS 183041], FEP 2.1.09.03.0B). Moreover, as discussed for FEP 2.1.09.03.0B the inner vessel (and the naval SNF or commercial SNF canister) is not stress-relief annealed, so significant residual stresses are likely to be present at emplacement. Development of SCC can initiate when moisture enters the gap between the WPOB and the inner vessel, after the WPOB is breached. Hence cracks in the inner vessel wall (and the naval SNF or commercial SNF canister) are likely to coexist with cracks in the WPOB.

6.2.1.2 Crack Flow Processes

Stress corrosion cracking is well-known in industrial practice as a failure mode for pressure piping, including for aqueous conditions at elevated temperatures (SNL 2007 [DIRS 181953], Section 6.1). By contrast, while SCC may damage the WPOB or waste package inner vessel, the flow potential is limited by the low pressure head available and the unsaturated hydrologic setting.

Laboratory testing of crack flow was undertaken to evaluate the frequency and rate of water flow, for conditions relevant to repository performance (Walton 2005 [DIRS 175401 and 175407]). The results from bench-scale tests on parallel-plate simulated fractures, and SCC damaged SS316 plates, showed that liquid can flow through stress corrosion cracks for sheet flow (i.e., zero head) and falling-drop conditions. For the more realistic SCC damaged plates, most of the through-going cracks did not flow at experimental conditions. A single crack was flow tested, with observed flow rates less than for parallel-plate openings with similar nominal aperture. This occurred because stress corrosion cracks are tortuous, with limited connectivity, compared to idealized openings. Such tortuous cracks are susceptible to plugging by particulate matter and precipitation. Flow through cracks in the WPOB will be impeded by accumulation of particles, clogging by corrosion products from the crack walls, and precipitation of minerals (SNL 2008 [DIRS 183041], FEPs 2.1.03.10.0A and 2.1.03.10.0B).

A cracked drip shield or WPOB contributes a substantial fractional reduction of flow, of at least several orders of magnitude (SNL 2008 [DIRS 183041], FEPs 2.1.03.10.0A and 2.1.03.10.0B). This is attributed to tortuosity and limited permeability of the cracks, and the likelihood that drips or rivulets will exist at crack locations. Leakage through a crack-damaged drip shield is an insignificant source for liquid water penetration through cracks in the underlying waste package, especially when compared to the threshold flow rate (0.1 kg/yr) used in TSPA to define whether seepage occurs (SNL 2007 [DIRS 181244], Section 6.7.1.1). Accordingly, the analysis below considers in-package hydrologic conditions for the case of drift seepage impinging directly on the crack-damaged waste package surface (with sheet or rivulet flow). Note that water accumulation in waste packages is excluded from TSPA on low consequence (SNL 2007 [DIRS 177407], Section 6.6.1), but the justification is not directly applicable to criticality analysis.

6.2.1.3 Moisture-Induced Corrosion Damage within the Waste Package

Any inflow through cracks in the WPOB that occurs immediately after crack penetration of the WPOB cannot access the internal volume of the package because it is limited to the gap between the WPOB and the inner vessel (1 to 5 mm on the radius; SNL 2007 [DIRS 179394], Table 4-1, Parameter 03-04). Stress corrosion cracks are expected to be distributed on the surface of a damaged waste package, so drainage would occur.

Corrosion of the SS316 inner vessel (and the WPOB inner surface) begins immediately upon damage to the WPOB. With Stainless Steel Type 316 freshwater general corrosion rates on the order of 0.0007 to 0.51 μm/yr (BSC 2004 [DIRS 169982], Table 6-5), corrosion products accumulate on the inner vessel at up to approximately 1 mm per 1,000 years. Film flow processes, and capillary flow in the gradually accumulating corrosion products, will distribute moisture throughout the gap. Corrosion penetration of the inner vessel in 10,000 years may occur by SCC or localized corrosion of Stainless Steel Type 316. If localized corrosion of Stainless Steel Type 316 occurs, it is likely to initiate in the contact crevice at the bottom of the gap where the WPOB and the inner vessel are in closest contact. Penetration of the inner vessel opens up the inner gap in commercial SNF and naval SNF waste packages, tripling the surface area of corroding Stainless Steel Type 316. Corrosion reactions (over a surface area approaching 100 m^2, but accessible by vapor through cracks) have the potential for significant reduction in humidity and oxygen fugacity, slowing down degradation processes. Corrosion penetration of the inner canister wall in 10,000 years is also limited to SCC or localized corrosion of Stainless Steel Type 316. Eventually the WPOB, inner vessel, and inner canister of the commercial SNF and naval SNF package can be breached by SCC and/or localized corrosion, producing a heterogeneous hydrologic system with high-conductivity drainage and bypass flow paths, and limited connectivity through the nested vessels to the spent fuel waste forms within.

6.2.1.4 Waste Package Internal Thermal Hydraulics

The average waste package internal heat generation is 67.7 W/m at 1,000 years; and 17.1 W/m at 10,000 years (SNL 2007 [DIRS 179354], Table 4-4, Parameter 05-03). These reference-case values may be considered typical for spent fuel packages (some hotter, some cooler) because the commercial SNF and HLW packages are averaged in the “unit cell” for postclosure analysis. A separate analysis for a waste stream that is likely to be received at the repository (SNL 2007 [DIRS 179962], Section 6.1) shows that the global average line load is similar.

An average thermal line load of 10 W/m (such as will be the output of a cooler commercial SNF package at 10,000 years), has the capability to evaporate approximately 140 kg/yr-m of liquid water (convert to Joules/yr/m and divide by 2257 kJ/kg, the heat of vaporization for water) (Incropera and DeWitt 2002 [DIRS 163337], Physical Constants). A more complex calculation that accounts for diffusion limited vapor transfer is developed in *Water Pooling-Evaporation in a Waste Package* (CRWMS 2000 [DIRS 149626]) and demonstrates that the rate of evaporative potential decreases with time and repository temperature. According to this calculation, for nominal to low thermal loads and a waste package inflow rate of 10 kg/yr, the waste package environment will not allow the presence of liquid (free) water until between 7,700 and 11,300 years (CRWMS 2000 [DIRS 149626], Table 10). This inflow rate is far greater than the estimated flow through stress corrosion cracks (SNL 2008 [DIRS 183041], FEP 2.1.03.10.0A). Thus even though heat will be transported primarily by thermal conduction, convection, and radiation inside the package, there is ample heat flux to support evaporation, vapor transport, and condensation as a competing mechanism. Accordingly, thermal-hydrologic processes will maintain an unsaturated hydrologic environment inside waste packages breached by SCC.

Sheet flow of water on the WPOB surface, from leakage through or condensation under the drip shield, produces a saturated (or very nearly so) boundary condition at the openings of cracks. Internal temperatures are warmer, so this boundary condition corresponds to an unsaturated condition (relative humidity less than unity) anywhere inside the package. Thermal-hydrologic processes (i.e., moisture movement in both the gas and liquid phases) will disperse the water, so that the waste package inner vessel and the inner canister will be progressively drier.

The slow rate of liquid inflow through cracks, combined with the heat output of the packages, will allow evaporation, vapor flow, and capillary or adsorptive condensation to be important moisture distribution processes within gaps between the outer barrier and inner vessel, and between the inner vessel and the spent fuel canister. Within the inner canister moisture can exist as vapor, adsorbed water films, or capillary water. Whereas quenching of such a system by high inflow is possible, flooding of the waste packages will not occur because of the slow rate of liquid inflow through cracks in the WPOB.

Film flow and capillary flow processes will readily transport liquid water within the waste package, under the impetus of gravity or gradients in water potential. Gravity driven flow will help to maintain drainage pathways through the gaps, and out through cracks in the lower part of the WPOB. Accumulation of liquid water is possible under such conditions, but the amount will be limited by outward flow through cracks, and by evaporation.

In summary, moisture leakage through cracks in the WPOB will initially affect only the gap at the inner vessel. Cracks on the lower part of the WPOB, where seismic damage occurs first and with the greatest intensity, will drain this gap. During crack propagation, debris and precipitates will begin to clog the WPOB cracks. The process will be repeated for the gap at the inner spent fuel canister, allowing additional time for clogging. Once the inner canister wall is breached by SCC or localized corrosion, thermal-hydrologic processes will distribute the available moisture throughout the package internals, where it will be adsorbed to surfaces or exist as capillary condensation in cracks and pores. Vapor will be transported by gaseous convection or diffusion down the thermal gradient. Because of vapor transport and drainage out of the waste package, the limited rate of liquid flow through cracks in the successive layers of the package will not be sufficient to cause significant ponding in the inner spent fuel canister in 10,000 years.

Flooding of the inner spent fuel canister could occur when paths for inflow (e.g., localized corrosion on top of the waste package) have greater transmissivity than paths for drainage (e.g., SCC on the bottom). This condition is discussed in Section 6.2.2.

6.2.2. Localized Corrosion/Seepage

Localized corrosion of the WPOB (Alloy 22; SNL 2007 [DIRS 179394], Table 4-1, Parameter 03-03) requires contact with seepage water and does not initiate as a result of condensation (SNL 2008 [DIRS 183041], FEP 2.1.08.14.0A). Seepage contact with the WPOB occurs in the event of seismically induced SCC damage to the drip shield, seismically induced rockfall rupture of the drip shield, or drip shield early failure as misplacement or cracking.

Seepage flow through rockfall ruptures in the drip shield, or through gaps caused by misplacement, occurs with sufficient flow rate that localized corrosion can result. Seepage flow through cracks caused by seismic ground motion or other potential causes of drip shield early failure (SNL 2007 [DIRS 178765], Table 6-8) allows only a small flow of water to contact the waste package (SNL 2008 [DIRS 183041], FEP 2.1.03.10.0B). As noted above, the amount of seepage that flows through drip shield cracks will be much less than the seepage threshold (0.1 kg/yr) used to define seepage in TSPA. By analogy to the effect of dust deliquescence, the amount of solute carried by that leakage will not be sufficient to cause significant localized corrosion to the WPOB (SNL 2008 [DIRS 183041], FEP 2.1.09.28.0A).

Localized (crevice) corrosion depends strongly on temperature as well as composition of contacting waters (SNL 2007 [DIRS 178519], Section 6.4.4.3) so the WPOB becomes much less sensitive to initialization after the thermal period (e.g., when waste package temperature cools below 90°C after approximately 2,000 years; SNL 2007 [DIRS 179962], Figure 6.4.2-4b). The cumulative amount of seepage that could flow through cracks in the drip shield and contact the waste package during the period starting after cool-down of the drift wall to 100°C when seepage is possible (SNL 2007 [DIRS 181244], Section 6.5.2), and ending at 2,000 years is on the order of a kilogram or less (multiplying the range of rates developed for FEP 2.1.03.10.0B (SNL 2008 [DIRS 183041]), by 1,000 years (it takes ~1,000 years for temperatures to lower enough for water to enter the drift)). Much of this leakage will run down the underside of the drip shield, or flow off the waste package, so that only a fraction will effectively interact with the WPOB. As shown for localized corrosion from dust deliquescence (SNL 2007 [DIRS 181267], Section 7[a]) the amount of potential corrosion from small quantities of salts contacting the WPOB is insignificant. Finally, if localized corrosion were to occur on the WPOB, a likely site for initiation is the contact crevice between the package and pallet, which is on the lower side and cannot result in the WP filling with water. In addition, if leakage through drip shield cracks did cause penetration of the WPOB by localized corrosion, the amount of water available to enter the package is still limited by the drip shield. In summary, this discussion shows that the potential for localized corrosion to produce significant breach of the WPOB, resulting from drip shield cracking damage to the drip shield is insignificant.

Localized corrosion breach of the WPOB can occur when sufficient seepage flow contacts the waste package directly, during the thermal transitional period when seepage is possible and waste package temperatures are sufficiently high that Alloy 22 is vulnerable to localized corrosion. Seepage is likely to continue after the breach occurs, and because of proximity, some or all of that seepage will enter the waste package. Thermal and chemical conditions are such that the inner vessel and inner spent fuel canister may also be penetrated by localized corrosion, so that the inner contents of the package are exposed. Given the strength of seeps expected to occur (SNL 2007 [DIRS 181244], Table 6-10[a] to 6-12[a]) the seepage flow into the waste package could fill the internal void volume of a waste package in a few thousand years, if the inflow rate exceeds the rate that moisture is rejected by thermal-hydrologic processes (quenching the thermal-hydrologic environment inside the waste package). Note that for much water to accumulate, breaches must occur on the upper surface without breaches in the lower part that could function as drains. Because breach due to localized corrosion is most likely on the lower part (at the pallet contact crevice) the assumption that localized corrosion breach leads to water accumulation in the waste package is conservative.

For HLW codisposal packages the probability of seismically induced SCC damage is approximately 100 times greater than damage to naval or commercial packages, as discussed above. Thus it is much more likely that there will be cracking damage that permits drainage, even in the event of inflow through breaches caused by localized corrosion. For example, if seismic cracking damage occurs with events that have frequency of 10^{-5}/yr, there is approximately a 0.01 probability that cracking damage will occur in 1,000 years, while the probability that any waste package is filled with water due to drip shield misplacement or rupture, followed by seepage and localized corrosion of the WPOB, is less than approximately 10^{-4} (summing the total probabilities associated with cases 2D, 3D, and 4D from Table 7-4). Hence cracking damage to the codisposal WPOB is more likely than water accumulation, and drainage conditions are therefore likely for codisposal packages.

7. RESULTS AND CONCLUSIONS

7.1 SEEPAGE DUE TO SEISMIC FAULT DISPLACEMENT

The probability of water filling a naval waste package failed by a seismic fault displacement was calculated using a Latin Hypercube sampling process. Calculations were performed using various waste package free volumes. Ten free volumes were specified between 100 and 4,000 gallons (0.379 and 15.1 m^3) to account for the range of possible free volumes in these packages. These are the boundary conditions of this analysis and are expected to encompass the naval canister internal void volume. Since the interior configuration of the canisters is uncertain, this range is also considered representative of the free volume in the waste packages. This calculation considers that drip shields that shelter the waste packages are failed by seismic fault displacement in such a way that they offer no restriction of seepage into the breached waste package. These values were calculated using output DTN: MO0802WPFLOODG.001, *Mathcad files.*

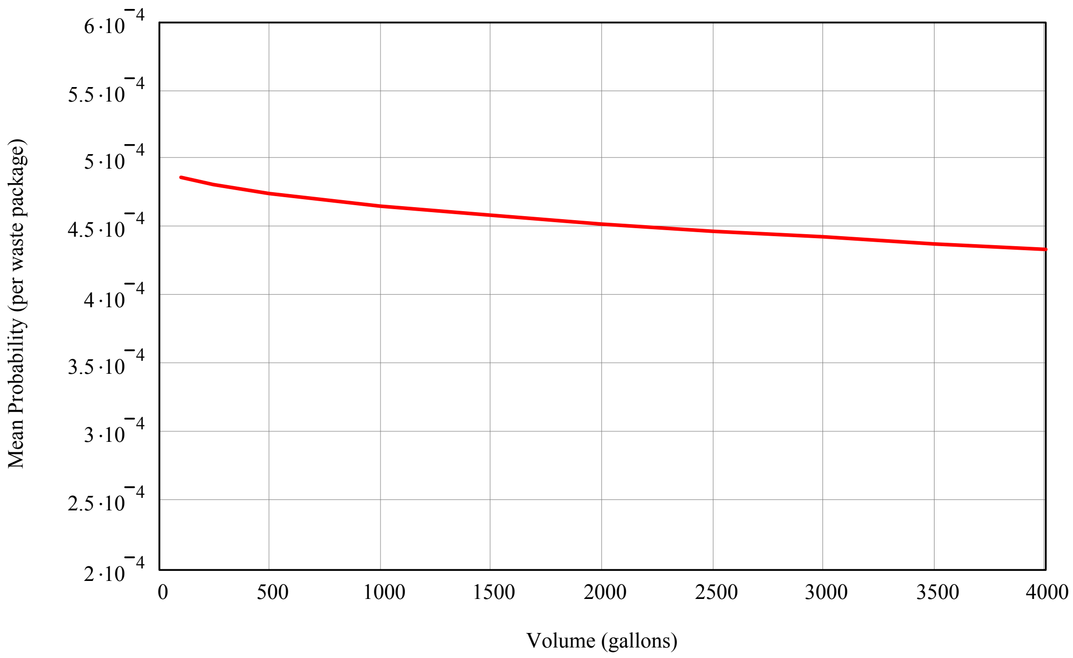
The probability of filling a waste package within the 10,000-year period as a result of a seismic fault displacement is presented in Table 7-1 and illustrated in Figure 7-1. The sample variance which is the square of the sample standard deviation is also presented in Table 7-1. The sample standard deviation is, in fact, a measure of variability.

Table 7-1. Probability of Filling a Waste Package within 10,000 Years

Volume, gallons (m^3)	**Probability Based on No Seepage Collection Scaling Factor**		**Probability Based on Seepage Collection Scaling Factor**	
	Probability	**Variance**	**Probability**	**Variance**
100 (0.379)	4.86×10^{-4}	1.52×10^{-10}	4.77×10^{-4}	4.72×10^{-10}
250 (0.946)	4.81×10^{-4}	3.31×10^{-10}	4.66×10^{-4}	9.72×10^{-10}
500 (1.89)	4.74×10^{-4}	5.83×10^{-10}	4.53×10^{-4}	1.62×10^{-10}
1,000 (3.79)	4.65×10^{-4}	1.00×10^{-9}	4.35×10^{-4}	2.60×10^{-9}
1,500 (5.68)	4.58×10^{-4}	1.36×10^{-9}	4.22×10^{-4}	3.35×10^{-9}
2,000 (7.57)	4.52×10^{-4}	1.67×10^{-9}	4.11×10^{-4}	3.95×10^{-9}
2,500 (9.46)	4.47×10^{-4}	1.95×10^{-9}	4.01×10^{-4}	4.47×10^{-9}
3,000 (11.4)	4.42×10^{-4}	2.21×10^{-9}	3.92×10^{-4}	4.90×10^{-9}
3,500 (13.2)	4.38×10^{-4}	2.44×10^{-9}	3.84×10^{-4}	5.28×10^{-9}
4,000 (15.1)	4.34×10^{-4}	2.67×10^{-9}	3.77×10^{-4}	5.62×10^{-9}

Source: Output DTN: MO0802WPFLOODG.001, *WPfillprob_faultdisplacement-R1_JMS.xmcd, WPfillprob_faultdisplacement-R2_JMS.xmcd*.

As can be seen from the results in Table 7-1, the seepage collection factor results in a minor difference in the probability of fill. This is because the seepage rates are high enough to fill a waste package in a relatively short time period. Therefore, the results presented for the rest of this report will be based on the unscaled seepage data, which is conservative with respect to calculating fill probabilities.



Source: Based on 10,000-year seepage rate, and no seepage collection scaling factor, output DTN: MO0802WPFLOODG.001, *WPfillprob_faultdisplacement-R1_JMS.xmcd*.

Figure 7-1. Probability of Filling a Waste Package as a Function of Volume

Multiplying the probability of filling a waste package by the mean number of naval waste packages impacted by fault intersections, the total probability of filling a naval waste package in the emplacement drifts as a result of a seismic fault displacement is presented in Table 7-2 (if naval packages are secluded so that they will not be emplaced on faults, then this table is not applicable). For commercial SNF waste packages, the mean number of waste packages impacted by fault intersections is much higher and the total probability is therefore higher, as shown in Table 7-3. The total probability is calculated from multiplying the probability of filling a waste package by the mean number of commercial SNF waste packages impacted by fault intersections. Note that the annual seismic exceedance frequencies which cause the waste package failures are different between commercial SNF (and naval packages, which are similar) and codisposal waste packages (DTN: MO0705FAULTABS.000 [DIRS 183150], *Fault Displacement Abstraction for Criticality.xls*) due the size difference between packages and SNF canisters. Therefore, these results are not applicable to the codisposal waste package.

Table 7-2. Total Probability of Filling a Naval Waste Package within 10,000 Years

Volume, gallons (m^3)	Probability without Seepage Collection Scaling Factor
100 (0.379)	7.49×10^{-4}
250 (0.946)	7.40×10^{-4}
500 (1.89)	7.31×10^{-4}
1,000 (3.79)	7.17×10^{-4}
1,500 (5.68)	7.06×10^{-4}
2,000 (7.57)	6.97×10^{-4}
2,500 (9.46)	6.89×10^{-4}
3,000 (11.4)	6.82×10^{-4}
3,500 (13.2)	6.75×10^{-4}
4,000 (15.1)	6.69×10^{-4}

Source: Output DTN: MO0802WPFLOODG.001, *WPfillprob_faultdisplacement-R1_JMS.xmcd*

Table 7-3. Total Probability of Filling a Commercial SNF Waste Package within 10,000 Years

Volume, gallons (m^3)	Probability without Seepage Collection Scaling Factor
100 (0.379)	1.40×10^{-2}
250 (0.946)	1.39×10^{-2}
500 (1.89)	1.37×10^{-2}
1,000 (3.79)	1.34×10^{-2}
1,500 (5.68)	1.32×10^{-2}
2,000 (7.57)	1.30×10^{-2}
2,500 (9.46)	1.29×10^{-2}
3,000 (11.4)	1.28×10^{-2}
3,500 (13.2)	1.26×10^{-2}
4,000 (15.1)	1.25×10^{-2}

Source: Output DTN: MO0802WPFLOODG.001, *WPfillprob_faultdisplacement-R1_JMS.xmcd*.

7.2 ADVECTIVE WATER INGRESS TO WASTE PACKAGES

The probability evaluations for the failure modes that could allow water accumulation in the waste package are presented in Table 7-4 for CSNF and CDSP waste packages. An example application based on the number of naval waste packages is provided in Appendix B. These are joint modes of drip shield and waste package failure, so the table is arranged as a 4 × 4 matrix with drip shield failure modes across the top and waste package failure modes along the side. Cumulative distribution functions for the three combined modes (2D, 3D, and 4D) that could result in accumulation of water in a waste package are provided in Output DTNs: MO0712PBANLNWP.000 and MO0712PANLNNWP.000. The methods of analysis are described in Appendix B.

During design, criticality analyses are performed to demonstrate that the initial emplaced configuration of the waste form remains subcritical, even under flooded conditions. 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. Several DOE SNF waste forms do not pose a criticality concern even if flooded with water. Therefore, the probability values calculated for 2D, 3D, and 4D for the DOE SNF codisposal waste packages are based on a number of codisposal waste packages in which the DOE SNF canister criticality control relies on design features (i.e., neutron absorber plates) which equals 1223 (See Section 4.1 and Appendix C).

Table 7-4. Failure Mode Analysis for Water Ingress to Commercial SNF and Codisposal Waste Packages

	Drip Shield Failure Mode ►			
▼Waste Package Failure Mode	**1. Early Failure (cracking)**	**2. Early Failure (misplacement)**	**3. Nonlithophysal Big Rock Rupture**	**4. Lithophysal Rubble Rupture**
A. Early Failure (cracking) All of the scenarios in this row result in an unsaturated hydrologic state inside the waste package.	Joint probability of independent early failures (combinatorial analysis). Water ingress is represented by unsaturated steady state. Analysis Result: Water entering in the vapor phase could lead to a schoepite moderated system. Ponded water is not predicted.	Joint probability of independent early failures (combinatorial analysis). Water ingress is represented by unsaturated steady state. Analysis Result: Water entering in the vapor phase could lead to a schoepite moderated system. Ponded water is not predicted.	Drip shield failure is independent of waste package early failure. Water ingress is represented by unsaturated steady state. Analysis Result: Water entering in the vapor phase could lead to a schoepite moderated system. Ponded water is not predicted.	Drip shield failure is independent of waste package early failure. Water ingress is represented by unsaturated steady state. Analysis Result: Water entering in the vapor phase could lead to a schoepite moderated system. Ponded water is not predicted.
B. SCC by Seismic Motion Impact All of the scenarios in this row result in an unsaturated hydrologic state inside the waste package.	Drip shield early failure is independent of seismic damage to waste packages. Qualitative Statement: Water entering in the vapor phase could lead to a schoepite moderated system. Ponded water is not predicted.	Drip shield early failure is independent of seismic damage to waste packages. Qualitative Statement: Water entering in the vapor phase could lead to a schoepite moderated system. Ponded water is not predicted.	Drip shield failure is independent of seismic damage to waste packages. Qualitative Statement: Water entering in the vapor phase could lead to a schoepite moderated system. Ponded water is not predicted.	Drip shield failure is independent of seismic damage to waste packages. Qualitative Statement: Water entering in the vapor phase could lead to a schoepite moderated system. Ponded water is not predicted.
C. Rupture by Seismic Ground Motion	Waste package seismic rupture requires a multi-event sequence starting with seismic motion sufficient to produce stress corrosion cracking damage to the WPOB. Waste package rupture is considered independent of drip shield early failure. Analysis Result: This failure mode requires that the waste package be damaged by SCC prior to rupture, thus the contribution to the potential for criticality is accounted for by Row B.	Waste package seismic rupture requires a multi-event sequence starting with seismic motion sufficient to produce stress corrosion cracking damage to the WPOB. Waste package rupture is considered independent of drip shield early failure. Analysis Result: This failure mode requires that the waste package be damaged by SCC prior to rupture, thus the contribution to the potential for criticality is accounted for by Row B.	Waste package seismic rupture requires a multi-event sequence starting with seismic motion sufficient to produce stress corrosion cracking damage to the WPOB. Waste package rupture is considered independent of drip shield failure. Analysis Result: This failure mode requires that the waste package be damaged by SCC prior to rupture, thus the contribution to the potential for criticality is accounted for by Row B.	Waste package seismic rupture requires a multi-event sequence starting with seismic motion sufficient to produce stress corrosion cracking damage to the WPOB. Waste package rupture is considered independent of drip shield failure. Analysis Result: This failure mode requires that the waste package be damaged by SCC prior to rupture, thus the contribution to the potential for criticality is accounted for by Row B.

Table 7-4. Failure Mode Analysis for Water Ingress to Commercial SNF and Codisposal Waste Package (Continued)

	DS Failure Mode ►			
▼Waste Package Failure Mode	**1. Early Failure (cracking)**	**2. Early Failure (misplacement)**	**3. Nonlithophysal Big Rock Rupture**	**4. Lithophysal Rubble Rupture**
D. Localized Corrosion	Leakage through cracks in the drip shield is insufficient to cause localized corrosion. Package is not predicted to breach. Analysis Result: Probability assigned a value of zero.	Drip shield early failure is independent of seepage and waste package localized corrosion (combinatorial analysis). See notes 2 and 4. **Conditions support localized corrosion. If localized corrosion penetrates WPOB, waste package could pond or fill with water.** Result: Commercial SNF Mean probability – 2.8 × 10^{-6}; Codisposal Mean probability – 1.1 × 10^{-6}	Drip shield damage is independent of seepage and waste package localized corrosion (combinatorial analysis). See notes 3 and 4. **Conditions support localized corrosion. If localized corrosion penetrates WPOB, waste package could pond or fill with water.** Result: Commercial SNF Mean probability – 2.17 × 10^{-5} Codisposal Mean probability – 9.6 × 10^{-6} for 1,223 codisposal packages	Drip shield damage is independent of seepage and waste package localized corrosion (combinatorial analysis). See notes 3 and 4. **Conditions support localized corrosion. If localized corrosion penetrates WPOB, waste package could pond or fill with water.** Result: Commercial SNF Mean probability – 4.2 × 10^{-5} Codisposal Mean probability – 2.8 × 10^{-5} for 1,223 codisposal packages

Source: Output DTN: MO0712PANLNNWP.000.

NOTES:

1. All probabilities are "per repository" that one or more waste packages will be breached as described in calculation methods discussed in Appendix B and with packages distributed uniformly in the lithophysal and nonlithophysal tuff, for the entire 10,000 year criticality screening analysis period unless otherwise noted.
2. Discrete distribution provided, based on a fixed (median) probability for DS misplacement, from ANL-EBS-MD-000076 Rev. 00, Section 6.5. Includes uncertainty associated with seepage and localized corrosion.
3. Discrete distributions provided for these cases, using a full description of uncertainties associated with the respective DS failure mode and WP localized corrosion.
4. Cumulative distribution functions for cases 2D, 3D, and 4D are contained in Output DTN MO0712PANLNNWP.000.

Overall probabilities (i.e., for a particular rock type, a particular waste package type, and over 10,000 years) for each failure mode shown in row D of Table 7-4 that are developed in this report are provided in output DTN: MO0712PANLNNWP.000. The methodology for the development of the probabilities are provided in Appendix B. The probabilities provided in Table 7-4 are used to illustrate, and in some cases quantify, for CSNF and DOE SNF, scenarios that contribute to the total probability of vapor or advective water ingress into a waste package occurring during the 10,000-year period following closure of the repository. Comparable calculations for naval fuel packages are developed in Appendix B with results summarized in Table B.1.

Scenario Evaluation

1A and 1B - A crack-damaged drip shield or WPOB still causes substantial fractional reduction of seepage flow, at least several orders of magnitude (SNL 2008 [DIRS 183041], FEPs 2.1.03.10.0A and 2.1.03.10.0B). A bounding analysis demonstrates leakage through a crack-damaged drip shield is an insignificant source for liquid water penetration through cracks in the underlying waste packages. Failure modes 1A and 1B (Table 7-4) result in an insignificant amount of water (less than 1 kg per waste package, for 10,000 years) entering a package. More water is likely to enter by other means, such as vapor diffusion, producing an unsaturated, slowly changing hydrologic state inside the package. Therefore, these failure modes are insignificant contributors to the probability of having ponded water inside the waste package.

1C, 2C, 3C, and 4C - Waste package rupture by seismic ground motion, is sufficiently unlikely (probability $\ll 10^{-4}$ over 10,000 years) that when combined with rupture probability of the drip shield, further consideration of in-package hydrologic consequences is not needed for criticality analysis. Therefore, 1C, 2C, 3C, and 4C result in insignificant probabilities of having ponded water inside the waste package.

2A, 2B, 3A, 3B, 4A, and 4B – These failure modes probabilities indicate that the probability of advective water ingress must be considered. However, these failure modes for the waste package are all SCC damage as the damage mode for the waste package. A bounding analysis of the amount of water that may enter a waste package damaged from waste package cracking with the drip shield having a complete loss of function, indicates that the maximum flow rate through a crack or cracks into a given waste package is approximately 223 mL/year (DTN: SN0705WFLOWSCC.001 [DIRS 184848], Excel file: *Bounding calc for water flow through SCC cracks.xls*, Spreadsheet “Impinging drip flow rate”, cell H29). This value equates to a mass of 223 g of water. Based on the discussion provided in Section 6.2.1.4, the average thermal output of the waste package is capable of evaporating several orders of magnitude (10 to 130 kg/yr-m) more water than would be present. Therefore, these systems would result in an unsaturated hydrologic state inside the package and can be considered to be insignificant contributors to the probability of creating ponded water inside the waste package.

1D – This failure mechanism is considered improbable because the amount of leakage through cracks in the drip shield is insufficient to result in a through-wall penetration of the WPOB by localized corrosion.

2D, 3D, 4D – These failure modes have been identified as contributors to the probability of water ingress which may result in a saturated system containing ponded water inside a package. Having a saturated system does not mean that a configuration is, or even can be critical, but that the configuration must be further analyzed for criticality possibilities. The probabilities for these failure modes are calculated in Output DTN: MO0712PANLNNWP.000 following the methodology discussed in Appendix B.

7.3 CONCLUSIONS

Waste Package Flooding Resulting from Fault Displacement

The results indicate that fill probabilities resulting from fault displacement are nearly independent of the free volume of the waste package. The probability of filling each volume is the mean of 50,000 sample points. The probability is dominated by the seismic exceedance frequency. The average probability is controlled by those lower seepage flow rates that still meet the minimum required to fill a waste package. The volume of the waste package, therefore, becomes a minor factor in determining the final probability outcome in a Latin Hypercube sampling scheme.

The total probability of filling a certain type of waste package given the entire inventory (Tables 7-2 and 7-3) is much higher than that of an individual waste package (Table 7-1) because 43 known faults are all considered capable of causing the waste package failures in this analysis. The total probability of filling a CSNF waste package is relatively high because the majority of waste packages are this type (7,483 out of 11,162).

The differences in probability results between using the seepage rates scaled by the seepage collection area or unscaled are very minor, as shown in Table 7-1. Since the average probability is controlled by the lower seepage flow rates, six different seepage rates below the bin 5 median value (314 L/yr) are chosen to calculate the cumulative probability of seepage exceeding the required value to fill the waste package using Equation 7. The Weibull parameters (α and β) in bin CSNF_PS_5 are from Table 6-2. The probability results are shown in Table 7-5. The cumulative probability decreases only in a small fraction while the seepage rate increases in several folds. This explains why the volume is a minor factor and the differences from the seepage collection scaling factor in the probabilities are so small in Table 7-1. This confirms that the seepage rates are high enough to fill the waste package in a relatively short time period.

Table 7-5. Cumulative Probability of Seepage Exceeding the Required Value

Seepage Rate (L/yr)	Without Seepage Collection Scaling Factor	With Seepage Collection Scaling Factor
0.1	1	0.999
1	0.998	0.991
10	0.977	0.917
100	0.801	0.433
200	0.645	0.19
300	0.52	0.084

Source: Output DTN: MO0802WPFLOODG.001, *WPfillprob_faultdisplacement-R1_JMS.xmcd, WPfillprob_faultdisplacement-R2_JMS.xmcd*.

Advective Water Ingress Resulting from Drip Shield Failure

The results from the advective water ingress to a waste package evaluation have identified three potential failure mechanisms that may lead to filling the void volume of the waste package. Given the strength of seeps expected to occur (SNL 2007 [DIRS 181244], Table 6-10[a] to 6-12[a]) the leakage flow into the WP could readily fill the internal void volume in a few thousand years or sooner. Note that for the WP to fill with water, breaches must occur on the upper surface without breaches in the lower part which could function as drains. Whereas breach due to localized corrosion may be more likely on the lower part (at the pallet contact crevice) the assumption that localized corrosion breach leads to flooding of the WP is conservative.

All outputs are reasonable compared to the inputs. Information is applicable, technically adequate and complete in the context of the intended purpose. The results of this calculation are sufficiently accurate and suitable for their intended purpose and use. There are no restrictions on the results.

7.4 YUCCA MOUNTAIN REVIEW PLAN

The acceptance criteria in *Yucca Mountain Review Plan, Final Report* (NRC 2003 [DIRS 163274]) are intended for use by the NRC staff when reviewing the License Application submittal. Some of the acceptance criteria listed in the technical work plan (SNL 2007 [DIRS 178869], Section 3.2) contain sub-criteria that are not applicable to this document, and therefore are not addressed. The following criteria are applicable to the current report and are considered project requirements.

Section 2.2.1.2.2.3, Scenario Analysis and Event Probability – Identification of Events with Probabilities Greater than 10^{-8} Per Year

- Acceptance Criterion 1 – Events Are Adequately Defined

Response: The seismic fault event, its annual exceedance probability range and intersections of known faults with emplacement drifts are clearly defined in Table 4-1. Definitions of faults are derived from the historical record.

Section 2.2.1.3.3.3, Quantity and Chemistry of Water Contacting Waste Packages and Waste Forms

- Acceptance Criterion 1 – System Description and Model Integration Are Adequate

  (2) The abstraction of the quantity and chemistry of water contacting waste packages and waste forms uses assumptions, technical bases, data, and models that are appropriate and consistent with other related U.S. Department of Energy abstractions.

Response: The seepage rate is the same value used by TSPA.

8. INPUTS AND REFERENCES

8.1 DOCUMENTS CITED

169982 BSC (Bechtel SAIC Company) 2004. *Aqueous Corrosion Rates for Waste Package Materials.* ANL-DSD-MD-000001 REV 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20041012.0003; DOC.20060403.0001.

166107 BSC 2004. *Drift Degradation Analysis.* ANL-EBS-MD-000027 REV 03. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20040915.0010; DOC.20050419.0001; DOC.20051130.0002; DOC.20060731.0005.

182131 BSC 2007. *Basis of Design for the TAD Canister-Based Repository Design Concept.* 000-3DR-MGR0-00300-000-001. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20071002.0042; ENG.20071026.0033; ENG.20071108.0002; ENG.20071109.0001; ENG.20071120.0023; ENG.20071126.0049; ENG.20071214.0009; ENG.20071213.0005; ENG.20071227.0018; ENG.20080207.0004; ENG.20080212.0003.

149626 CRWMS M&O 2000. *Water Pooling-Evaporation in a Waste Package.* CAL-EBS-NU-000009 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000424.0698.

170071 DOE (U.S. Department of Energy) 2004. *Packaging Strategies for Criticality Safety for "Other" DOE Fuels in a Repository.* DOE/SNF/REP-090, Rev. 0. Idaho Falls, Idaho: U.S. Department of Energy, Idaho Operations Office. ACC: MOL.20040708.0386.

112115 Evans, M.; Hastings, N.; and Peacock, B. 1993. *Statistical Distributions.* 2nd Edition. New York, New York: John Wiley & Sons. TIC: 246114.

182752 Golan, P.M. 2004. “Issuance of Audit Report No. 04-DOE-AU-004 for the Department of Energy Idaho Operations Office Spent Nuclear Fuel Program.” Memorandum from P.M. Golan (DOE) to E.D. Sellers (DOE/ID), September 23, 2004, with attachment. ACC: MOL.20041214.0129; MOL.20041214.0130.

146529 Hahn, G.J. and Shapiro, S.S. 1967. *Statistical Models in Engineering.* New York, New York: John Wiley & Sons. TIC: 247729.

163337 Incropera, F.P. and DeWitt, D.P. 2002. *Fundamentals of Heat and Mass Transfer.* 5th Edition. New York, New York: John Wiley & Sons. TIC: 254280.

150737 Jackson, S.A. 1998. "Discussion on Risk-Informed, Performance-Based Regulation." Memorandum from S.A. Jackson (NRC) to Commissioner Dicus, Commissioner Diaz, Commissioner McGaffigan, February 20, 1998, COMSAT-9B-003, with attachment. ACC: MOL.19980626.0154.

104667 Modarres, M. 1993. *What Every Engineer Should Know About Reliability and Risk Analysis.* New York, New York: Marcel Dekker. TIC: 238168.

163274 NRC (U.S. Nuclear Regulatory Commission) 2003. *Yucca Mountain Review Plan, Final Report.* NUREG-1804, Rev. 2. Washington, D.C.: U.S. Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguards. TIC: 254568.

178869 SNL (Sandia National Laboratories) 2007. *Technical Work Plan for: Postclosure Criticality.* TWP-EBS-MD-000018. REV 01. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20070206.0003.

181244 SNL 2007. *Abstraction of Drift Seepage.* MDL-NBS-HS-000019 REV 01 AD 01. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20041103.0003.

181267 SNL 2007. *Analysis of Dust Deliquescence for FEP Screening.* ANL-EBS-MD-000074 REV 01 AD 01. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20070911.0004; DOC.20070824.0001; DOC.20080109.0005.

178765 SNL 2007. *Analysis of Mechanisms for Early Waste Package/Drip Shield Failure.* ANL-EBS-MD-000076 REV 00. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20070629.0002.

177407 SNL 2007. *EBS Radionuclide Transport Abstraction.* ANL-WIS-PA-000001 REV 03. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20071004.0001.

180778 SNL 2007. *General Corrosion and Localized Corrosion of the Drip Shield.* ANL-EBS-MD-000004 REV 02 ADD 01. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20060427.0002; DOC.20070807.0004; DOC.20071003.0019.

178519 SNL 2007. *General Corrosion and Localized Corrosion of Waste Package Outer Barrier.* ANL-EBS-MD-000003 REV 03. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20070730.0003; DOC.20070807.0007.

176828 SNL 2007. *Seismic Consequence Abstraction.* MDL-WIS-PA-000003 REV 03. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20070928.0011.

181953 SNL 2007. *Stress Corrosion Cracking of Waste Package Outer Barrier and Drip Shield Materials.* ANL-EBS-MD-000005 REV 04. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20070913.0001.

179354 SNL 2007. *Total System Performance Assessment Data Input Package for Requirements Analysis for Engineered Barrier System In-Drift Configuration.* TDR-TDIP-ES-000010 REV 00. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20070921.0008.

181648 SNL 2007. *In-Drift Natural Convection and Condensation.* MDL-EBS-MD-000001 REV 00, AD 01. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20041025.0006; DOC.20050330.0001; DOC.20051122.0005.

184433 SNL 2008. *Multiscale Thermohydrologic Model.* ANL-EBS-MD-000049 REV 03 AD 02. Las Vegas, Nevada: Sandia National Laboratories.

179962 SNL 2007. *Postclosure Analysis of the Range of Design Thermal Loadings.* ANL-NBS-HS-000057 REV 00. Las Vegas, Nevada: Sandia National Laboratories.

179466 SNL 2007. *Total System Performance Assessment Data Input Package for Requirements Analysis for Subsurface Facilities.* TDR-TDIP-PA-000001 REV 00. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20070921.0007.

179394 SNL 2007. *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.* TDR-TDIP-ES-000006 REV 00. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20070918.0005.

183041 SNL 2008. *Features, Events, and Processes for the Total System Performance Assessment: Analyses for the License Application.* ANL-WIS-MD-000027 REV 00. Las Vegas, Nevada: Sandia National Laboratories.

184719 Triay, I.R. 2007. Issuance of Audit Report No. 07-DOE-AU-002 for the Department of Energy Idaho Operations Office, National Spent Nuclear Fuel Program Memorandum from I.R. Triay (DOE) to E.D. Sellers (DOE/ID), May 07, 2007, with attachment ACC: MOL.20070702.0077, MOL.20070702.0078.

175407 Walton, Z.P. 2005. Testing of Stress Crack Flow [final closure]. Scientific Notebook SN-SNL-SCI-032-V2. Cover-150. ACC: MOL.20060724.0109.

175401 Walton, Z.P. and Ho, C. 2005. Testing of Stress Crack Flow [final submittal]. Scientific Notebook SN-SNL-SCI-032-V1. Cover - 296. ACC: MOL.20050908.0167.

181533 Wheatley, P.D. 2007. "Canister Counts for Criticality Analyses for DOE SNF in the License Application." Letter from P.D. Wheatley (INL) to R.M. Kacich (BSC) and M.K. Knowles (SNL), CCN 210126, June 20, 2007. ACC: LLR.20070627.0004.

165505 YMP (Yucca Mountain Site Characterization Project) 2003. *Disposal Criticality Analysis Methodology Topical Report.* YMP/TR-004Q, Rev. 02. Las Vegas, Nevada: Yucca Mountain Site Characterization Office. ACC: DOC.20031110.0005.

8.2 CODES, STANDARDS, REGULATIONS, AND PROCEDURES

180319 10 CFR 63. Energy: Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada. Internet Accessible.

103662 60 FR 42622. Use of Probabilistic Risk Assessment Methods in Nuclear Regulatory Activities; Final Policy Statement. TIC: 238369.

178394 70 FR 53313. Implementation of a Dose Standard After 10,000 Years. Internet Accessible.

123801 ANSI/ANS-8.1-1998. *Nuclear Criticality Safety in Operations with Fissionable Material Outside Reactors*. La Grange Park, Illinois: American Nuclear Society. TIC: 242363.

176885 ANSI/ANS-8.10-1983 (Reaffirmed 2005). *American National Standard Criteria for Nuclear Criticality Safety Controls in Operations with Shielding and Confinement*. La Grange Park, Illinois: American Nuclear Society. TIC: 258158.

176225 ANSI/ANS-8.17-2004. 2004. *American National Standard, Criticality Safety Criteria for the Handling, Storage and Transportation of LWR Fuel Outside Reactors*. La Grange Park, Illinois: American Nuclear Society. TIC: 257593.

IM-PRO-003, *Software Management*.

SCI-PRO-004, *Managing Technical Product Inputs*.

SCI-PRO-005, *Scientific Analyses and Calculations*.

TST-PRO-001, S*ubmittal and Incorporation of Data to the Technical Data Management System*.

8.3 SOURCE DATA, LISTED BY DATA TRACKING NUMBER

172682 MO0501BPVELEMP.001. Bounded Horizontal Peak Ground Velocity Hazard at the Repository Waste Emplacement Level. Submittal date: 01/11/2005.

173893 MO0505SPAROCKM.000. Rock Mass and Invert Properties for TSPA-LA. Submittal date: 05/23/2005.

179925 MO0702PASTREAM.001. Waste Stream Composition and Thermal Decay Histories for LA. Submittal date: 02/15/2007.

183148 MO0703PASDSTAT.001. Statistical Analyses for Seismic Damage Abstractions. Submittal date: 09/21/2007.

183156 MO0703PASEISDA.002. Seismic Damage Abstractions for TSPA Compliance Case. Submittal date: 09/21/2007.

183150 MO0705FAULTABS.000. Assessment of Waste Package Failure Due to Fault Displacement for Criticality. Submittal date: 09/21/2007.

183008 MO0705TSPASEEP.000. Seepage Results From the TSPA-LA Model. Submittal date: 01/15/2008.

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

184821 MO0709HOTWASTE.000. Probabilistic Analysis of Hottest Waste Package Temperature for Drift Collapse Immediately After Repository Closure. Submittal date: 09/17/2007.

182994 MO0709TSPALOCO.000. TSPA Localized Corrosion Analysis. Submittal date: 09/13/2007.

184848 SN0705WFLOWSCC.001. Analysis for Water Flow through Stress Corrosion Cracking (SCC) Cracks in Waste Package and Drip Shield. Submittal date: 01/25/2008.

8.4 OUTPUT DATA, LISTED BY DATA TRACKING NUMBER

MO0802WPFLOODG.001. Waste Package Flooding Probability Due to Seismic Fault Displacement. Submittal date: 02/11/2008.

MO0712PANLNNWP.000. Probabilistic Analyses of Drip Shield Failure and CSNF and CDSP Package OCB Localized Corrosion. Submittal date: 12/17/2007.

MO0712PBANLNWP.000. Probabilistic Analyses of Navy Waste Packages. Submittal date: 12/13/2007.

8.5 SOFTWARE CODES

None.

APPENDIX A
LIST OF THE ELECTRONIC FILES IN OUTPUT DTNS TO THIS CALCULATION

APPENDIX A

LIST OF THE ELECTRONIC FILES IN OUTPUT DTNs: MO0802WPFLOODG.001, MO0712PANLNNWP.000, AND MO0712PBANLNWP.000

This appendix contains a listing and description of the files contained in the output DTNs of this report (DTNs: MO0802WPFLOODG.001, MO0712PANLNNWP.000, and MO0712PBANLNWP.000). A brief description, file names, their size in bytes, and the date and time of last update are also shown.

OUTPUT DTN: MO0802WPFLOODG.001

Filename	File Size (bytes)	File Date	File Time		Description
Seismic-FD.zip	1,987,526	2/11/2008	4:46	PM	Archive containing Mathcad, Excel, and data files for CSNF and Navy waste packages for calculating probability of filling with water presented in Section 7

OUTPUT DTN: MO0712PANLNNWP.000

Filename	File Size (bytes)	File Date	File Time		Description
CSNF_CDSP.zip	15,128,178	2/12/2008	9:22	AM	Archive containing Mathcad and data files for CSNF and CDSP waste package calculations presented in Table 7-4

OUTPUT DTN: MO0712PBANLNWP.000

Filename	File Size (bytes)	File Date	File Time		Description
Navy.zip	7,831,099	2/16/2008	1:13	PM	Archive containing Mathcad and data files for Navy waste package calculations presented in Table B-1 and Section B2.4.2

INTENTIONALLY LEFT BLANK

APPENDIX B

METHODOLOGY FOR CALCULATING JOINT PROBABILITY OF DRIP SHIELD AND WASTE PACKAGE FAILURE THAT MAY ALLOW ADVECTIVE WATER INGRESS TO WASTE PACKAGE

APPENDIX B
METHODOLOGY FOR CALCULATING JOINT PROBABILITY OF DRIP SHIELD AND WASTE PACKAGE FAILURE THAT MAY ALLOW ADVECTIVE WATER INGRESS TO WASTE PACKAGE

B.1 INTRODUCTION

This appendix provides the methodology for the probabilistic evaluations of the combined modes for drip shield and waste package failure that are identified in Section 6.2. For these cases two hydrologic conditions are considered for breached waste packages: an unsaturated steady state (Section 6.2), and the condition in which ponding or flooding of the waste package internal volume can occur. These cases are shown in Tables 7-4 and B-1 for different target waste package variants.

For the cases that involve waste package rupture due to successive seismic events (row C in Table B-1) an analysis is provided in Section B.2.1 that shows these cases (specifically 2C, 3C, and 4C) are very unlikely to occur in 10,000 years. For those cases in which ponding or flooding has greater probability (2D, 3D, and 4D in Table B-1) probabilistic analyses are provided in Sections B.2.2 through B.2.4. Section B.2.4.2 evaluates a variation on case 4D in which seismic events occurring during the first few hundred years cause significant rockfall, which may lead to alteration of the waste by elevated temperatures and thus is of interest. Each probabilistic analysis is accompanied by a summary of the conservative assumptions used in the development of the analysis and the uncertainties in the results.

Importantly, the analyses in this appendix and Output DTN: MO0712PBANLNWP.000 are illustrative and do not include any additional probabilistic processes (e.g., thermal damage/failure to waste forms). Derivations that include such a process were developed for application to non-naval (e.g., commercial SNF and codisposal) waste packages, as discussed in Section 6.2 and Output DTN: MO0712PANLNNWP.000.

Note that a number of Mathcad files implementing the methodology described throughout this Appendix are provided in Output DTNs: MO0712PBANLNWP.000 and MO0712PANLNNWP.000. In the Mathcad files, an introductory section is provided that summarizes the methodology used, but may not be verbatim consistent with what is presented in this Appendix. Therefore, this Appendix should be referred to for the actual methodology that has been implemented in the Output DTNs.

Table B-1. Failure Mode Analysis for Water Ingress to Naval Waste Packages

	Drip Shield Failure Mode ►			
▼Waste Package Failure Mode	**1. Early Failure (cracking)**	**2. Early Failure (misplacement)**	**3. Nonlithophysal Big Rock Rupture**	**4. Lithophysal Rubble Rupture**
A. Early Failure (cracking)	The consequence of this case is limited to an unsaturated steady state.	The consequence of this case is limited to an unsaturated steady state.	The consequence of this case is limited to an unsaturated steady state.	The consequence of this case is limited to an unsaturated steady state.
B. SCC by Seismic Motion Impact	The consequence of this case is limited to an unsaturated steady state.	The consequence of this case is limited to an unsaturated steady state.	The consequence of this case is limited to an unsaturated steady state.	The consequence of this case is limited to an unsaturated steady state.
C. Rupture by Seismic Ground Motion The cases in this row (except for 1C) may result in waste package ponding or flooding conditions.	WP seismic rupture requires a multi-event sequence starting with seismic motion sufficient to produce stress corrosion cracking damage to the WPOB. WP rupture is considered independent of DS EF. Result: The mean probability for WP rupture alone is 2.2×10^{-8}. The mean of the joint probability is $<<10^{-8}$.	WP seismic rupture requires a multi-event sequence starting with seismic motion sufficient to produce stress corrosion cracking damage to the WPOB. WP rupture is considered independent of DS EF. Result: The mean probability for WP rupture alone is 2.2×10^{-8}. The mean of the joint probability is $<<10^{-8}$.	WP seismic rupture requires a multi-event sequence starting with seismic motion sufficient to produce stress corrosion cracking damage to the WPOB. WP rupture is considered quasi-independent of DS EF. Result: The mean probability for WP rupture alone is 2.2×10^{-8}. The mean of the joint probability is $<<10^{-8}$.	WP seismic rupture requires a multi-event sequence starting with seismic motion sufficient to produce stress corrosion cracking damage to the WPOB. WP rupture is considered quasi-independent of DS rupture. Result: The mean probability for WP rupture alone is 2.2×10^{-8}. The mean of the joint probability is $<<10^{-8}$.
D. Localized Corrosion The cases in this row (except for 1D) may result in waste package ponding or flooding conditions.	Leakage through cracks in the DS is insufficient to cause localized corrosion. The consequence of this case is therefore limited to unsaturated steady state.	DS EF is independent of seepage and WP localized corrosion. **Conditions support LC. If LC penetrates WPOB, WP could pond or fill with water.** Result: Mean probability 1.5×10^{-7} (see text of Appendix B, and Note 2).	DS rupture is independent of seepage and WP localized corrosion. **Conditions support LC. If LC penetrates WPOB, WP could pond or fill with water.** Result: Mean probability 7.75×10^{-6} (see text of Appendix B, and Note 2).	DS rupture is independent of seepage and WP localized corrosion. **Conditions support LC. If LC penetrates WPOB, WP could pond or fill with water.** Result: mean probability 3.0×10^{-5} (see text of Appendix B, and Note 2).

NOTES: 1. All probabilities given are "per repository" that one or more naval waste packages will be breached as described, over 10,000 years, with 400 naval SNF packages distributed randomly throughout the repository in the lithophysal and nonlithophysal tuff. 2. Probabilities for 2D, 3D, and 4D are given for illustrative purposes only, and do not reflect the full detail of the screening justifications for criticality processes for naval SNF. 3. Evaluation for cases 2C, 3C, and 4C and probability distributions for cases 2D, 3D, and 4D are discussed in Appendix B.

WP = waste package, DS = drip shield, LC = localized corrosion, WPOB = waste package outer barrier, EF = early failure, SCC = stress corrosion cracking.

B.2.1 Probabilistic Analysis for Bounding Failure Cases 1C, 2C, 3C, and 4C

Cases 1C, 2C, 3C, and 4C combine: 1) waste package rupture due to seismic ground motion (a breach of substantial size, greater than damage from stress corrosion cracking alone), with 2) various modes for breach of the drip shield (Section B.1). A complete solution would evaluate the common-mode seismically induced behaviors affecting both the waste package and drip shield. However, a useful upper bound on the joint probabilities for cases 1C, 2C, 3C, and 4C is obtained by considering only the probability that one or more waste packages is ruptured due to seismic ground motion. This analysis is implemented in Mathcad (Output DTN: MO0712PBANLNWP.000, file: *Rupture of TAD WP.xmcd*; this file calls other Mathcad files as indicated in its internal annotations). The result is applicable to all TAD-bearing waste packages, although it may not be used in analyses for CSNF waste packages.

Rupture is conceptualized to occur when extreme deformation of the waste package outer barrier (WPOB) accumulates, from successive package-to-pallet impacts as discussed in *Seismic Consequence Abstraction* (SNL 2007 [DIRS 176828], Sections 6.5.2.1). Rupture first requires initial breach of the WPOB from stress corrosion cracking due to seismic damage that allows ingress of moisture and oxygen, which then degrade the waste package internal structure. This must be followed by one or more additional events with sufficient intensity to cause major failure of the structurally degraded package, when waste packages can move freely beneath their drip shields (SNL 2007 [DIRS 176828], Section 6.6.2). Hence, rupture requires that a damaging seismic event has already occurred, and that the drip shield plates are still intact.

This analysis is restricted to 10,000 years during which the drip shield does not weaken significantly from general corrosion, and the likelihood of drip shield collapse or plate failure by seismic loading under collapse rubble is small. Therefore, this analysis considers only the kinematic loading case (SNL 2007 [DIRS 176828], Section 6.1.2). After the drip shield plates have failed because of rockfall or rubble loading, the waste packages are surrounded by rubble so that rupture of this type from further seismic events is not possible. The potential for general corrosion of the waste package outer barrier to increase the failure rate from seismic events is neglected for this analysis because the extent of general corrosion in 10,000 years is negligible.

Notation

v	Horizontal peak ground velocity (PGV) associated with a seismic event. Obtained as a function of recurrence frequency, and called the "bounded hazard curve" (from DTN: MO0501BPVELEMP.001 [DIRS 172682]).
λ	Recurrence frequency variable for seismic events; used with subscripts to represent different categories of events.
$p_{imm.}(v)$	Probability of immediate rupture from a seismic event, conditional on occurrence of the event after the package internals have degraded.
$p_{inc.}(v)$	Probability of incipient rupture, meaning that the event causes damage that increases the probability of rupture from a subsequent event, conditional on the occurrence of a seismic event after the package internals have degraded.

r	Index of waste package type, signifying a TAD canister-bearing SNF package (including naval SNF) or a codisposal package.
T	Performance period ($T = 10{,}000$ years).

Development

A seismic event may result in immediate rupture of a waste package with degraded internals, or it may cause damage that increases the chance that a subsequent event would cause rupture. Such damage is termed an incipient rupture. After an incipient rupture occurs, any subsequent event that would cause either incipient rupture or immediate rupture causes a rupture as discussed in *Seismic Consequence Abstraction* (SNL 2007 [DIRS 176828], Sections 6.5.2.1). The probabilities of immediate rupture, $p_{imm.}(v)$, and of incipient rupture, $p_{inc.}(v)$, are developed in DTN: MO0703PASEISDA.002 [DIRS 183156], Eq. 1-12, Eq. 1-13, Eq. 1-17, Eq. 1-18, and Table 1-17).

To estimate the frequency of events that cause rupture, divide the time interval $[0,\tau]$ into n intervals of width Δt. The probability that the first damaging event (that degrades the internals) occurs within an interval $[t_i, t_i + \Delta t]$ is $e^{-\lambda_D t_i}\lambda_D \Delta t$, where $\lambda_D = \lambda_D(r \mid RST)$ is the frequency of events that cause damage to a waste package with intact internals, calculated as

$$\lambda_D(r|RST) = \int_{\lambda_{\min}}^{\lambda_{\max}} p_D(r,\nu(\lambda)|RST)\, d\lambda \qquad \text{(Eq. B.2.1-1)}$$

where

$\lambda_{\min}$, $\lambda_{\max}$	Minimum and maximum frequencies of seismic events, bracketing the frequencies of events with potential to damage waste packages with intact internals; DTN: MO0703PASEISDA.002 [DIRS 183156], Table 1-15).
$p_D(r,\nu(\lambda)\|RST)$	Probability of damage occurring to a waste package of type r with intact internals and residual stress threshold *RST*, given that a seismic event with PGV v occurs (DTN: MO0703PASEISDA.002 [DIRS 183156], Table 1-4 and Table 1-6).

Note that *RST* is uncertain and is assigned a uniform distribution from 90% to 105% of yield strength for the WPOB (SNL 2007 [DIRS 176828], Section 6.1.4).

The probability that one or more additional seismic events cause rupture during the interval $[t_i + \Delta t, T]$ is $1 - e^{-\lambda_R(T - t_i - \Delta t)}$, where λ_R is the frequency of events that cause rupture to packages with degraded internals, calculated as

$$\lambda_R(r) = \int_{\lambda_{\min}}^{\lambda_{\max}} p_R(r,\nu(\lambda))\, d\lambda \qquad \text{(Eq. B.2.1-2)}$$

where

$p_R(r,\nu(\lambda))$ Probability of immediate rupture for a waste package of type r with degraded internals given that a seismic event with PGV v occurs (DTN: MO0703PASEISDA.002_R3 [DIRS 183156], Equations 1-12, 1-13, 1-17, 1-18, and Table 1-17).

Evaluation of Equation B.2.1-2 yields frequencies of events that cause rupture of 8.327×10^{-9} yr^{-1}, for CDSP (co-disposal) waste packages, and 1.378×10^{-8} yr^{-1} for TAD-bearing SNF packages (DTN: MO0708FREQCALC.000 [DIRS 183006], folder *Frequency of rupture*, file: *FreqRupture.pdf*).

Equation B.2.1-2 is simplified by neglecting events that cause incipient rupture. The frequency of events that cause immediate rupture can be expressed as

$$\lambda_{imm.} = P(imm.|\, event)\times\lambda_S \tag{Eq. B.2.1-3}$$

where

$P(imm.|\, event)$ Probability of immediate rupture conditional on a seismic event occurring, and

λ_S Frequency (yr^{-1}) of seismic events (10^{-4} yr^{-1}).

In contrast, the frequency of rupture occurring from the sequence of an incipient rupture followed by an immediate or another incipient rupture event can be expressed as

$$\begin{aligned}&[P(imm.|\, event)\times\lambda_S]\times[(P(imm.|\, event)+P(inc.|\, event))\times\lambda_S]\\&=(P^2(inc.|\, event)+P(inc.|\, event)P(imm.|\, event))\times\lambda_S^2\end{aligned} \tag{Eq. B.2.1-4}$$

where

$P(inc.|\, event)$ Probability of an incipient rupture conditional on a seismic event occurring.

Since $P(inc.|\, event)$ is of the same order of magnitude as $P(imm.|\, event)$, the frequency of rupture from the sequence of an incipient rupture followed by a second event is several orders of magnitude less than the frequency of immediate rupture, so the frequency of immediate rupture ($\lambda_{imm.}$) can be used as the frequency of rupture.

In summary, the probability that no waste packages are ruptured by seismic events within $T = 10,000$ yr can be estimated by

$$\begin{aligned}P(\text{No rupture}) &= P(\text{No damage}) + P(\text{Damage but no rupture})\\&\geq \mathrm{e}^{-\lambda_{\mathrm{D}}(RST)T} + \left(1-\mathrm{e}^{-\lambda_{\mathrm{D}}(RST)T}\right)\mathrm{e}^{-\lambda_{\mathrm{R}}T}\end{aligned} \tag{Eq. B.2.1-5}$$

where, if *RST* is chosen as *90%* then the estimate for *P*(No rupture) is a lower bound because:

- The order of events (damage followed by rupture) is not accounted for, and
- The frequency of damage $\lambda_D(RST = 90\%)$ is based on the lowest value for the residual stress threshold (*RST = 90%*) which maximizes the frequency of events that cause damage, and in turn minimizes the probability of no damage occurring.

An upper bound for the probability that one or more waste packages are ruptured by seismic events within $T = 10{,}000$ years is the complement:

$$P(\text{Rupture}) = 1 - P(\text{No rupture}) \le 1 - \left(e^{-\lambda_D(RST)T} + \left(1 - e^{-\lambda_D(RST)T}\right)e^{-\lambda_R T}\right) \quad \text{(Eq. B.2.1-6)}$$

Based on this analysis, implemented in file: *Rupture of TAD WP.xmcd* (Output DTN: MO0712PBANLNWP.000) the probability for any TAD-bearing waste package to rupture by Mode 1C, 2C, 3C, or 4C in 10,000 years after repository closure is less than 2.2×10^{-8}. This result applies to both CSNF and naval SNF waste packages, but not to co-disposal packages which exhibit different seismic fragility characteristics.

Inherent Conservatisms

The estimate of 2.2×10^{-8} provided by Equation B.2.1-6 for the probability of rupture of CSNF or naval SNF waste packages in 10,000 years after repository closure is a conservative upper bound because *RST* is fixed at its minimum value of *90%*. This choice maximizes the resulting probability of rupture. This minimum value for *RST* is also conservative as discussed in *Stress Corrosion Cracking of Waste Package Outer Barrier and Drip Shield Materials* (SNL 2007 [DIRS 181953] Section 6.2.2). In addition, the probability resulting from Equation B.2.1-6 is also a conservative estimate of the probability of advective water ingress following rupture, because the calculation essentially assumes that advective flow contacts any ruptured waste package. The uncertainties in the state of the drip shield and the occurrence of seepage are not accounted for in this calculation.

Uncertainty in Results

The results computed from Equation B.2.1-6 reflect aleatory uncertainty in the number and nature of seismic events that can occur in 10,000 years after repository closure. These aleatory uncertainties are addressed by the expected values computed in Equation B.2.1-1 and Equation B.2.1-2, which yield the mean frequencies of events that cause damage and rupture, respectively. Epistemic uncertainty in the material properties of the waste package outer barrier is represented by the parameter *RST*, and is addressed by assuming a fixed value that results in a bounding value from Equation B.2.1-6. Because this calculation produces a bounding value, no estimate of the uncertainty is provided.

B.2.2 Probabilistic Analysis of Failure Mode 2D

Mode 2D (from Table 7-4) represents the combination of: 1) early failure of the drip shield by misplacement, leaving an estimated 15-cm gap between drip shields, and 2) resulting breach of the waste package by seepage flow through the gap, and localized corrosion of the outer barrier. This analysis develops a distribution of probability that this mode will occur for at least one waste package among those of a certain type (target group, e.g., naval SNF packages) for 10,000 years after repository closure. This analysis is implemented in Mathcad (Output DTN: MO0712PBANLNWP.000 and MO0712PANLNNWP.000, file: *Misplaced DS LC Calculation.xmcd* for each target waste package group; this file calls other Mathcad files as indicated in its internal annotations). This analysis is applicable to all waste package types, by changing the number of waste packages in the target group.

The misplacement mode for early failure is assumed to occur when the drip shields are installed just prior to repository closure, so there is no uncertainty as to the sequence of early failure and seepage/corrosion processes leading to waste package breach. The analysis requires that the number of packages in the target group be specified (e.g., 400 naval SNF packages) out of a total of 11,162 waste packages (DTN: MO0702PASTREAM.001 [DIRS 179925], file: *DTN-Inventory-Rev00.xls,* worksheet: UNIT CELL, Row 14).

The analysis is based on packages in the target group being emplaced randomly throughout the repository, but not on faults with greater than 2 m of cumulative offset which are capable of rupturing waste packages under certain conditions (SNL 2007 [DIRS 176828], Section 6.11.2.2). (If fault displacement rupture is included in analysis of waste package failure modes for the target group, then those packages would be “double counted”.) In addition, the analysis is based on drip shield misplacement failures being distributed independently throughout the repository, and that there is a one-to-one correspondence between each drip shield and the underlying waste package.

The approach combines the mean probability of drip shield misplacement, expressed per drip shield (SNL 2007 [DIRS 178765], Section 6.5), with the conditional distribution of probability that waste packages will undergo seepage and localized corrosion without drip shield protection. Note that seepage is required for localized corrosion to cause penetration of the waste package outer barrier (SNL 2008 [DIRS 183041], FEP 2.1.03.03.0A), and once penetration occurs, that seepage is then very likely to flow into the package.

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 2007 [DIRS 184433], Section 6.2.12.1[a]). The results are given for CSNF and CDSP (co-disposal) packages by files from DTN: MO0709TSPALOCO.000 [DIRS 182994]). These intermediate results also represent the uncertainties associated with host-rock lithology, localized corrosion initiation, 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 lithologies, so to obtain the total probability distribution across the entire repository the analysis must be done for each set, and the results summed as discussed below.

Notation

p_{EF}	Probability that a randomly chosen drip shield fails due to misplacement, such that advective flow can contact the underlying waste package.
nWP	The total number of waste packages in the lithophysal or nonlithophysal tuff (depending on which set of epistemic realizations are being used in the analysis implementation).
$nNWP$	The number of waste packages in the target group, that are in the lithophysal or nonlithophysal tuff (depending on which set of epistemic realizations are being used in the analysis implementation). For example, of 400 naval SNF packages, 64 would be distributed in the nonlithophysal tuff, and the remainder in the lithophysal.
b	Percolation bin number (integers 1 through 5).
$f(b)$	Fraction of all waste packages in percolation bin b (equal to 0.05, 0.25, 0.4, 0.25, 0.05 for the five respective bins; SNL 2007 [DIRS 184433], Appendix VIII).
$\mathbf{r}$	Realization of epistemic uncertainty (index for the 300 realizations used to represent outcomes that include localized corrosion). For implementation, $\mathbf{r}$ can represent the files for emplacement in the lithophysal or nonlithophysal lithologies, or both.
$f_{LC}(t,b\|\mathbf{r})$	Fraction of locations in percolation bin b for which localized corrosion conditions occur at or after time t in epistemic realization $\mathbf{r}$ of the localized corrosion part of the analysis. These results are given for CSNF and CDSP (co-disposal) packages by files from DTN: MO0709TSPALOCO.000 [DIRS 182994]. Separate sets of files are used for the lithophysal and nonlithophysal host rock, for each waste package type.
p_{ACC}	Probability that a randomly selected waste package exhibits a particular state corresponding to an accessory process such as thermal damage/failure, that is independent of drip shield early failure, seepage, or localized corrosion, and for which the probability of a joint outcome is to be calculated. Set p_{ACC} = 1 to ignore such a process.

Development

The expected number of waste packages in the target group, in percolation bin b is

$$nNWP(b) = f(b) \times nWP \tag{Eq. B.2.2-1}$$

For convenience, assume $nNWP(b)$ is an integer by use of a numerical ceiling function on $nNWP(b)$, implemented in the Mathcad file (Output DTN: MO0712PBANLNWP.000, file: *Misplaced DS LC Calculation.xmcd*). For calculation of the probability that localized corrosion occurs to one or more packages in the target group, resulting from drip shield misplacement in some fraction of the repository, such as that fraction in the nonlithophysal tuff, the number of target-group packages in that fraction (e.g., 64 naval SNF packages in the nonlithophysal tuff) should be substituted for nWP in Equation B.2.1-1.

For each waste package in the target group there is a probability p_{EF} that the corresponding drip shield has an early failure due to misplacement. The mean probability for emplacement error is 4.36×10^{-9} per drip shield (SNL (2007 [DIRS 178765]; Table 6-8).

Denote $NEFLC(b|\mathbf{r})$ as the random variable counting the number of target-group packages that are under misplaced (early failed) drip shields that also will experience localized corrosion, causing breach. The variable $NEFLC(b|\mathbf{r})$ is developed from the binomial probability density, based on the following as described by Hahn and Shapiro (1967, [DIRS 146529] p. 139):

$$p(x; p, n) = \binom{n}{x} \cdot p^x \cdot (1-p)^{n-x} \tag{Eq. B.2.2-2}$$

where

n Total number of trials.

x Number of trials subject to failure.

p Probability of failure.

The distribution function for the cumulative probability is given by:

$$p(x \le s) = \sum_{x=0}^{s} \binom{n}{x} \cdot p^x \cdot (1-p)^{n-x} \tag{Eq. B.2.2-3}$$

Considering the case that no trials are subject to failure:

$$p(x \le 0) = \sum_{x=0}^{0} \binom{n}{x} \cdot p^x \cdot (1-p)^{n-x} = (1-p)^n \tag{Eq. B.2.2-4}$$

The probability of one or more items subject to failure equals the complementary probability:

$$1-(1-p)^n \tag{Eq. B.2.2-5}$$

Applying this relationship for the several probabilities yields:

$$\begin{aligned} P\left(NEFLC\left(b\middle|\mathbf{r}\right)\geq 1\right) &= 1-P\left(NEFLC\left(b\middle|\mathbf{r}\right)=0\right) \\ &\approx 1-\binom{nNWP(b)}{0}\left(1-p_{ACC}\,p_{EF}\,F_{LC}\left(b\middle|\mathbf{r}\right)\right)^{nNWP(b)} \\ &= 1-\left(1-p_{ACC}\,p_{EF}\,F_{LC}\left(b\middle|\mathbf{r}\right)\right)^{nNWP(b)} \end{aligned} \tag{Eq. B.2.2-6}$$

where

$$\begin{aligned} F_{LC}\left(b\middle|\mathbf{r}\right) &\equiv \max_{t\geq 0}\left\{f_{LC}\left(t,b\middle|\mathbf{r}\right)\right\} \\ &= f_{LC}\left(0,b\middle|\mathbf{r}\right) \end{aligned} \tag{Eq. B.2.2-7}$$

The probability that no target-group waste package is affected by the combination of drip shield early failure by misplacement, and localized corrosion in 10,000 years, is given by

$$P\left(NEFLC=0\middle|\mathbf{r}\right)=\prod_{b=1}^{5}\left(1-P\left(NEFLC\left(b\middle|\mathbf{r}\right)\geq 1\right)\right) \tag{Eq. B.2.2-8}$$

The mean of this distribution is obtained by averaging over all epistemic uncertainties, the epistemic uncertainty in the probability of drip shield early failure and in localized corrosion, represented by **r**, results in a distribution of values for $P(NEFLC\geq 1)$.

$$P(NEFLC\geq 1)=\frac{1}{N_r}\sum_{\mathbf{r}}\left(1-\prod_{b=1}^{5}\left(1-P\left(NEFLC\left(b\middle|\mathbf{r}\right)\geq 1\right)\right)\right) \tag{Eq. B.2.2-9}$$

To obtain the total probability $P(NEFLC \geq 1)$ for both lithophysal and nonlithophysal lithologies, the foregoing analysis must be repeated with separate sets of TSPA realizations **r**, and appropriate numbers of total waste packages (in each lithology) and waste packages in the target group (in each lithology). The resulting probabilities are summed to give the total probability that one or more waste packages in the target group experience water ingress due to failure mode 2D.

Based on this analysis implemented in file: *Misplaced DS LC Calculation.xmcd* (Output DTN: MO0712PBANLNWP.000), and setting $p_{ACC} = 1$, gives a mean probability of 1.5×10^{-7} that any waste package in the target group will fail by Mode 2D in 10,000 years after repository closure. This is an illustrative calculation that does not reflect the full detail of the screening justifications for criticality processes for naval SNF.

Inherent Conservatisms

The estimate of 1.5×10^{-7} provided by Equation B.2.2-9 for the probability that one or more of the target waste packages fails by mode 2D in 10,000 years after repository closure is a reasonable estimate of this value. The calculation relies on the conservative assumptions made in developing the probabilities for early failure of drip shields (SNL 2007 [DIRS 178765]) and the model for initiation of localized corrosion (SNL 2007 [DIRS 178519]). No additional conservative assumptions are made in this analysis.

Uncertainty in Results

The results computed from Equation B.2.2-9 reflect aleatory uncertainty in the number and location of drip shields with early failure. These aleatory uncertainties are averaged in the development of the result calculated by Equation B.2.2-9. The principal epistemic uncertainties that affect this calculation are the occurrence and composition of seepage waters and the processes that lead to initiation of localized corrosion on Alloy 22. These uncertainties are represented by the use of sample elements (realizations) $\mathbf{r}$, which result in a distribution of results from Equation B.2.2-9. Because the probability of localized corrosion initiation is uncertain and is highly variable between sample elements (see analysis results in *Misplaced DS LC Calculation.xmcd* (Output DTN: MO0712PBANLNWP.000), the distribution of results from Equation B.2.2-9 is significantly influenced by a few sample elements in which localized corrosion is highly probable. Thus, the distribution of results from Equation B.2.2-9 is highly skewed, causing the mean of this distribution to be much larger than its median value.

B.2.3 Probabilistic Analysis of Failure Mode 3D

Mode 3D combines: 1) rupture of the drip shield from impact by a large rock block dislodged by seismic activity; and 2) resulting breach of the waste package by seepage flow through the drip shield, and localized corrosion of the waste package outer barrier (WPOB). This case is specific to the nonlithophysal tuff, because rock blocks of sufficient size to rupture the drip shield can only occur there.

This analysis develops a distribution of probability that this mode will occur for at least one waste package among those of a certain type (target group, e.g., naval SNF packages) for 10,000 years after repository closure. This analysis is implemented for the target group of waste packages in Mathcad (Output DTN: MO0712PBANLNWP.000 and MO0712PANLNNWP.000, file: *Nonlith LC Calculation Rev03.xmcd*) for each target waste package group.

This analysis develops an estimate of the mean probability that at least one waste package in the target group (e.g., naval SNF packages) is emplaced in the nonlithophysal tuff at a location where the drip shield is ruptured by a seismically induced impact from a large rock block, and where there is seepage, and that seepage initiates localized corrosion of the WPOB, during the first 10,000 years after closure.

Description of the analysis below is written generically, such that it can be applied to calculating probabilities that one or more naval SNF waste packages, commercial SNF packages, or DOE co-disposal packages sustains localized corrosion failure from Mode 3D.

The analysis requires that the number of packages in the target group be specified (e.g., 400 naval SNF packages) out of a total of 11,162 waste packages (DTN: MO0702PASTREAM.001 [DIRS 179925], file: *DTN-Inventory-Rev00.xls*, worksheet: UNIT CELL, Row 14). If the target group contains a significant number of waste packages that are placed randomly in the repository, and the nonlithophysal fraction is nominally 0.15 (Table 4-1) then the probability that at least one target-group waste package is in the nonlithophysal tuff is essentially 1. This analysis is based on waste packages in the target group being emplaced randomly throughout the repository, and that there is a one-to-one correspondence between each drip shield and the underlying waste package. The effect from drip shield general corrosion on its resistance to rupture is neglected, because the extent of such corrosion in 10,000 years is negligible for mechanical strength properties.

The conditional distribution of probability that waste packages will undergo seepage and localized corrosion without drip shield protection, is obtained from an intermediate product of TSPA, specifically the discrete set of simulated outcomes for 300 realizations obtained by exercising the relevant parameters and their epistemic uncertainties. These results are given for CSNF and CDSP (co-disposal) packages by files from DTN: MO0709TSPALOCO.000 [DIRS 182994]). Five such sets of 300 outcomes are used, corresponding to the five percolation "bins" used in TSPA to represent variability and uncertainty in percolation flux (SNL 2007 [DIRS 184433], Section 6.2.12.1[a]). These intermediate results also represent the uncertainties associated with localized corrosion initiation, waste package temperature and relative humidity, and uncertainty in the parameters that describe seepage chemistry. The results from TSPA, which combine representative locations in the lithophysal and nonlithophysal tuff, are sorted for this analysis to include only the nonlithophysal locations.

The number of waste packages in the target group which are emplaced in the nonlithophysal tuff, is represented using the five percolation "bins" used in TSPA (SNL 2007 [DIRS 184433], Section 6.2.12.1[a]), and the fraction of each bin that lies within the nonlithophysal tuff (see below).

Notation

nWP	The total number of waste packages in the repository ($nWP = 11162$).
$nNWPT$	The number of waste packages in the target group (e.g., for naval SNF packages, $nNWPT = 400$).
b	Percolation bin number (integers 1 through 5).
$nNWP(b)$	Number of waste packages in the target group, in the nonlithophysal tuff.
$f(b)$	Fraction of all waste packages in percolation bin b (equal to 0.05, 0.25, 0.4, 0.25, 0.05 for the five respective bins; SNL 2007 [DIRS 184433], Appendix VIII).

$f_{NL}(b)$	Fraction of percolation bin b that is in nonlithophysal tuff (equal to 0.319, 0.237, 0.173, 0.041, 0.110 for the five respective bins; from DTN: MO0709TSPALOCO.000, file: *NonLith_Frac_CSNF_out.xls*)
f_{DS}	Random variable denoting the fraction of drip shields in the nonlithophysal tuff that are ruptured given that one seismic event occurs
v	Horizontal peak ground velocity (PGV) associated with a seismic event.
$\lambda(v)$	Frequency of seismic events (yr^{-1}) as a function of PGV, described by the seismic hazard curve DTN: MO0703PASDSTAT.001 [DIRS 183148], file: *Lith_Rubble_Abstraction.xls,* worksheet *Data for Bounded Hazard*.
λ_{NL}	Frequency of seismic events (yr^{-1}) that cause rupture of one or more drip shields in the nonlithophysal tuff.
$\mathbf{r}$	Realization of epistemic uncertainty (index for the 300 realizations used to represent outcomes that include localized corrosion).
$f_{LC}(t,b\,\vert\,\mathbf{r})$	Fraction of locations in percolation bin b for which localized corrosion conditions occur at or after time t in epistemic realization $\mathbf{r}$ of the localized corrosion part of the analysis. These results are given for CSNF and CDSP (co-disposal) packages by files from DTN: MO0709TSPALOCO.000 [DIRS 182994]). Separate sets of files are used for the lithophysal and nonlithophysal host rock, for each waste package type.
p_{ACC}	Probability that a randomly selected waste package exhibits a particular state corresponding to an accessory process such as thermal damage/failure, that is independent of drip shield early failure, seepage, or localized corrosion, and for which the probability of a joint outcome is to be calculated. Set $p_{ACC} = 1$ to ignore such a process.

Development

The effect from drip shield general corrosion on its resistance to rupture from falling rock blocks is neglected, because the extent of such corrosion in 10,000 years is negligible for mechanical strength properties. In addition the probability of drip shield rupture from seismically induced rockfall is considered to be independent of its location anywhere within the nonlithophysal tuff.

For this analysis the maximum frequency is $\lambda(v_{\min}) = 1\times10^{-4}\ \text{yr}^{-1}$, because drip shield rupture is possible at PGV values exceeding 0.4 m/s (DTN: MO0703PASEISDA.002 [DIRS 183156], Table 1-11).

Given that an event occurs at time t that ruptures a fraction f_{DS} drip shields, the probability that a ruptured drip shield coincides with a location in percolation bin b with localized corrosion conditions is estimated by the fraction of drip shields in the nonlithophysal portion of percolation bin *b* that are ruptured, multiplied by the fraction of locations in the nonlithophysal tuff in percolation bin *b* that have localized corrosion conditions at or after time *t*:

$$p_{LC}\left(f_{DS},t,b\middle|\mathbf{r}\right)=f_{DS}\times f_{LC}\left(t,b\middle|\mathbf{r}\right) \qquad \text{(Eq. B.2.3-1)}$$

The expected number of waste packages in the target group, located within the nonlithophysal tuff, in percolation bin *b*, is

$$nNWP(b)=f(b)\times f_{NL}(b)\times nNWPT \qquad \text{(Eq. B.2.3-2)}$$

For convenience, assume $nNWP(b)$ is an integer by use of a ceiling function on *nNWP*(*b*), implemented in Mathcad.

Denote by $NLC\left(f_{DS},t,b\middle|\mathbf{r}\right)$ the random variable that counts the number of waste packages in the target group, in percolation bin *b*, in locations that lie under ruptured drip shields resulting from a seismic event at time *t* that ruptures f_{DS} of the drip shield in the nonlithophysal tuff, and that have localized corrosion conditions at or after time *t*, in epistemic realization **r**. The random variable $NLC\left(f_{DS},t,b\middle|\mathbf{r}\right)$ can be modeled with a binomial distribution with probability $p_{LC}\left(f_{DS},t,b\middle|\mathbf{r}\right)$:

$$\begin{aligned}P\left(NLC\left(f_{DS},t,b\middle|\mathbf{r}\right)\geq 1\right)&=1-\binom{nNWP(b)}{0}\left(1-p_{LC}\left(f_{DS},t,b\middle|\mathbf{r}\right)p_{ACC}\right)^{nNWP(b)}\\&=1-\left(1-p_{LC}\left(f_{DS},t,b\middle|\mathbf{r}\right)p_{ACC}\right)^{nNWP(b)}\\&=1-\left(1-f_{DS}\times f_{LC}\left(t,b\middle|\mathbf{r}\right)p_{ACC}\right)^{nNWP(b)}\end{aligned} \qquad \text{(Eq. B.2.3-3)}$$

The probability that one or more waste packages in the target group, in bin *b* are affected by localized corrosion, given a seismic event at time *t* is then given by:

$$\begin{aligned}P\left(NLC\left(t,b\middle|\mathbf{r}\right)\geq 1\right)&=\int_0^1 P\left(NLC\left(f_{DS},t,b\middle|\mathbf{r}\right)\geq 1\right)d_{f_{DS}}\left(f_{DS}\right)df_{DS}\\&=\int_0^1\left(1-\left(1-p_{LC}\left(f_{DS},t,b\middle|\mathbf{r}\right)p_{ACC}\right)^{nNWP(b)}\right)d_{f_{DS}}\left(f_{DS}\right)df_{DS}\\&=\int_0^1\left(1-\left(1-f_{DS}\times f_{LC}\left(t,b\middle|\mathbf{r}\right)p_{ACC}\right)^{nNWP(b)}\right)d_{f_{DS}}\left(f_{DS}\right)df_{DS}\end{aligned} \qquad \text{(Eq. B.2.3-4)}$$

where $d_{f_{DS}}\left(f_{DS}\right)$ is the density function for f_{DS}. The density function $d_{f_{DS}}\left(f_{DS}\right)$ is computed by

$$\begin{aligned}d_{f_{DS}}(K)&=P\left(f_{DS}=K\right)\\&=\int_{\nu_{\min}}^{\nu_{\max}}\left(pD_{DS}(\nu)\times pF_K(\nu)\right)d_\nu(\nu)\,d\nu\end{aligned} \qquad \text{(Eq. B.2.3-5)}$$

where

$pD_{DS}(\nu)$	Probability that a seismic event with PGV v causes failure to one or more drip shields in the nonlithophysal tuff (DTN: MO0703PASEISDA.002 [DIRS 183156], Table 1-10)
$pF_K(\nu)$	Probability that a fraction K of drip shields in the nonlithophysal tuff are ruptured given a seismic event with PGV v that causes failure to drip shields in the nonlithophysal tuff (DTN: MO0703PASEISDA.002 [DIRS 183156], Table 1-11, for values K = 0, 0.25, 0.5, 0.75, 1.0 corresponding to States 1, 2, 3, 4, 5, respectively).

Recalling that $\lambda(\nu)$ is the mean seismic hazard curve, then $\nu_{\min}$ = 0.4019 m/s and $\nu_{\max}$ = 4.07 m/s representing the range of potentially damaging seismic motion. These PGV limits correspond to $\lambda_{\max} = 10^{-4}$ yr^{-1} and $\lambda_{\min} = 10^{-8}$ yr^{-1}, respectively, and are equivalent for this analysis to the values used in Section B.2.3.

If K = 0 then the event caused no drip shields to rupture. Because K assumes only the discrete values 0, 0.25, 0.5, 0.75, 1.0, and K = 0 corresponds to no ruptured drip shields, the nonzero values of f_{DS} are $\frac{k}{4}$ for k = 1, 2, 3, and 4. Then

$$\begin{aligned} P\left(NLC(t,b|\mathbf{r})\geq 1\right) &= \int_0^1 \left(1-\left(1-f_{DS}\times f_{LC}(t,b|\mathbf{r})p_{ACC}\right)^{nNWP(b)} d_{f_{DS}}(f_{DS})df_{DS}\right) \\ &= \sum_{k=0}^{4}\left(1-\left(1-\left(\frac{k}{4}\right)\times f_{LC}(t,b|\mathbf{r})p_{ACC}\right)^{nNWP(b)}\right)d_{f_{DS}}\left(\frac{k}{4}\right) \end{aligned} \tag{Eq. B.2.3-6}$$

The density function for PGV v conditional on the occurrence of a seismic event, $d_v(v)$, is computed as

$$\begin{aligned} d_\nu(\nu) &= -\left[\frac{d\lambda(\nu)}{d\nu}\right]\frac{1}{\left(\lambda(\nu_{\min})-\lambda(\nu_{\max})\right)} \\ &= -\left[\frac{d\lambda(\nu)}{d\nu}\right]\frac{1}{\left(10^{-4}-10^{-8}\right)} \end{aligned} \tag{Eq. B.2.3-7}$$

where $\lambda(v)$ is the mean seismic hazard curve defined above. The frequency λ_{NL} of events that cause rupture to one or more drip shields in the nonlithophysal tuff is given by

$$\begin{aligned}\lambda_{NL} &= \lambda(\nu_{\min})\times(1-P(f_{DS}=0))\\ &= \lambda(\nu_{\min})\times\left(\sum_{1}^{4} P\left(f_{DS}=\frac{k}{4}\right)\right)\\ &= \lambda(\nu_{\min})\times\left(\sum_{1}^{4} d_{f_{DS}}\left(\frac{k}{4}\right)\right)\end{aligned} \quad \text{(Eq. B.2.3-8)}$$

λ_{NL} is small enough (~10^{-6} yr^{-1}) that only one event that causes rupture of drip shields within 10,000 years needs to be considered. Divide the interval [0, 10000 years] into intervals of length Δt with endpoints $t_0 = 0, t_1, \ldots, t_M, \ldots, 10{,}000$. The probability that the event occurs in one interval $[t_k, t_{k+1}]$ is

$$e^{-\lambda_{NL} t_k} \times \lambda_{NL} \Delta t \quad \text{(Eq. B.2.3-9)}$$

So the probability that the event occurs in the interval $[t_k, t_{k+1}]$ which results in one or more waste packages in the target group affected by localized corrosion is

$$e^{-\lambda_{NL} t_k} \times \lambda_{NL} \Delta t \times P(NLC(t, b|\mathbf{r}) \geq 1) \quad \text{(Eq. B.2.3-10)}$$

The probability that seismic events in 10,000 years cause one or more waste packages in the target group, in the nonlithophysal tuff, in percolation bin b to be affected by localized corrosion is given by

$$P(NLC(b|\mathbf{r}) \geq 1) = \int_{0}^{10{,}000} \lambda_{NL} e^{-\lambda_{NL} s} \times P(NLC(s, b|\mathbf{r}) \geq 1)\, ds \quad \text{(Eq. B.2.3-11)}$$

and the probability that no waste package in the target group, in the nonlithophysal tuff, is affected by the combination of drip shield rupture by seismically induced rockfall, followed by localized corrosion of the WPOB, in 10,000 years is given by

$$P(NLC = 0|\mathbf{r}) = \prod_{b=1}^{5} (1 - P(NLC(b|\mathbf{r}))) \quad \text{(Eq. B.2.3-12)}$$

Finally, the mean probability over all epistemic realizations, the probability that one or more waste packages in the target group is impacted by Mode 3D is the complement, or averaging the epistemic uncertainty in the probability of drip shield early failure and in localized corrosion, represented by **r**, results in a distribution of values for $P(NLC \geq 1)$.

$$P(NLC \geq 1) = \frac{1}{N_r} \sum_{\mathbf{r}} \left(1 - \prod_{b=1}^{5} (1 - P(NLC(b|\mathbf{r})))\right) \quad \text{(Eq. B.2.3-13)}$$

This analysis was implemented for a target number of 400 naval SNF waste packages (64 in the nonlithophysal tuff), resulting in a mean probability of 7.75×10^{-6} that one or more naval packages will be impacted by Mode 3D in 10,000 years. This is an illustrative calculation that does not reflect the full detail of the screening justifications for criticality processes for naval SNF.

Inherent Conservatisms

The estimate of 7.75×10^{-6} provided by Equation B.2.3-13 for the probability that one or more naval SNF waste packages experiences water ingress by Mode 3D in 10,000 years after repository closure is a reasonable estimate of this value. The calculation relies on the conservative assumptions made in describing the effects of seismic ground motion on drip shields (SNL 2007 [DIRS 176828]) and the model for initiation of localized corrosion (SNL 2007 [DIRS 178519]). No additional conservative assumptions are made in this analysis.

Uncertainty in Results

The results computed from Equation B.2.3-13 reflect aleatory uncertainty in the number and nature of seismic events that can occur in 10,000 years after repository closure as well as the spatial location of navy SNF waste packages within the repository. These aleatory uncertainties are addressed by the expected values computed in Equation B.2.3-5 and Equation B.2.3-8, which yield the expected number of drip shields ruptured by rockfall and the mean frequency of events that cause rockfall in the nonlithophysal tuff, respectively, and in Equation B.2.3-2, which yields the mean number of navy SNF waste packages in the nonlithophysal tuff. The principal epistemic uncertainties that affect this calculation are the occurrence and composition of seepage waters and the processes that lead to initiation of localized corrosion on Alloy 22. These uncertainties are represented by the use of sample elements (realizations) $\mathbf{r}$, which result in a distribution of results from Equation B.2.3-13. Because the probability of localized corrosion initiation is uncertain and is highly variable between sample elements (see analysis results in Ouput DTN: MO0712PANLNNWP.000, file: *Nonlith LC Calculation Rev03.xmcd*), the distribution of results from Equation B.2.3-12 is significantly influenced by a few sample elements in which localized corrosion is highly probable. Thus, the distribution of results from Equation B.2.3-12 is highly skewed, causing the mean of this distribution (Equation B.2.3-13) to be much larger than its median value.

B.2.4 Probabilistic Analysis of Failure Mode 4D

Mode 4D combines: 1) rupture of the drip shield from seismic loading after drift collapse; and 2) resulting breach of the waste package by seepage flow through the drip shield, and localized corrosion of the waste package outer barrier (WPOB). This case is specific to the lithophysal tuff, because drift collapse of sufficient extent to cause rupture of the drip shield during a seismic event, can only occur there.

This analysis develops a distribution of probability that Mode 4D will occur for at least one waste package among those of a certain type (target group, e.g., naval SNF packages) for 10,000 years after repository closure. This analysis is implemented in Mathcad (Output DTN: MO0712PBANLNWP.000 and MO0712PANLNNWP.000, file: *Lith LC Calculation*

Rev05.xmcd; for each target waste package group; this file calls other Mathcad files as indicated in its internal annotations).

Description of the analysis below is written generically, such that it can be applied to calculating probabilities that one or more naval SNF waste packages, CSNF packages, or HLW packages sustains failure from Mode 4D.

The analysis requires that the number of packages in the target group be specified (e.g., 400 naval SNF packages) out of a total of 11,162 waste packages (DTN: MO0702PASTREAM.001 [DIRS 179925], file: *DTN-Inventory-Rev00.xls*, worksheet: UNIT CELL, Row 14). If the target group contains a significant number of waste packages that are placed randomly in the repository, and the lithophysal fraction is nominally 0.85 (Table 4-1) then the probability that at least one target-group waste package is in the lithophysal tuff is essentially 1. This analysis is based on the waste packages in the target group being emplaced randomly throughout the repository, and that there is a one-to-one correspondence between each drip shield and the underlying waste package. The effect from drip shield general corrosion on its resistance to rupture is neglected, because the extent of such corrosion in 10,000 years is negligible for mechanical strength properties.

The conditional distribution of probability that waste packages will undergo seepage and localized corrosion without drip shield protection 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 (e.g., 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 2007 [DIRS 184433], Section 6.2.12.1[a]). The results are given for commercial SNF and codisposal packages by files from DTN: MO0709TSPALOCO.000 [DIRS 182994]). These intermediate results also represent the uncertainties associated with localized corrosion initiation, waste package temperature and relative humidity, temperature effect from drift collapse, and uncertainty in the parameters that describe seepage chemistry. The results from TSPA, which combine representative locations in the lithophysal and nonlithophysal tuff, are sorted for this analysis to include only the lithophysal locations.

The number of waste packages in the target group which are emplaced in the lithophysal tuff, is represented using the five percolation “bins” used in TSPA (SNL 2007 [DIRS 184433], Section 6.2.12.1[a]), and the fraction of each bin that lies within the lithophysal tuff (see below).

Notation

nWP = The total number of waste packages in the repository ($nWP = 11162$).

$nNWPT$ = The number of waste packages in the target group (e.g., for naval SNF packages, $nNWPT = 400$)

b = Percolation bin number (integers 1 through 5).

$nNWP(b)$ = Number of waste packages in the target group, in the lithophysal tuff in percolation bin b.

$f(b)$ = Fraction of all waste packages in percolation bin *b* (equal to 0.05, 0.25, 0.4, 0.25, 0.05 for the five respective bins; SNL 2007 [DIRS 184433], Appendix VIII)

$f_L(b)$ = Fraction of percolation bin *b* that is in lithophysal tuff (equal to 0.681, 0.763, 0.827, 0.959, 0.890 for the five respective bins; from DTN: MO0709TSPALOCO.000, file: *NonLith_Frac_CSNF_out.xls*)

v = Horizontal peak ground velocity (PGV) associated with a seismic event.

$\lambda(v)$ = Frequency of seismic events (yr^{-1}) as a function of PGV, described by the seismic hazard curve DTN: MO0703PASDSTAT.001 [DIRS 183148], file *Lith_Rubble_Abstraction.xls,* worksheet *Data for Bounded Hazard*

$\mathbf{r}$ = Realization of epistemic uncertainty (index for the 300 epistemic realizations for each percolation bin, used to represent outcomes that include localized corrosion)

$f_{LC}(t,b|\mathbf{r})$ = Fraction of locations in percolation bin *b* for which localized corrosion conditions occur at or after time *t* in epistemic realization $\mathbf{r}$ of the localized corrosion part of the analysis. These results are given for commercial SNF and codisposal packages by files from DTN: MO0709TSPALOCO.000 [DIRS 182994]). Separate sets of files are used for the lithophysal and nonlithophysal host rock, for each waste package type.

p_{ACC} Probability that a randomly selected waste package exhibits a particular state corresponding to an accessory process such as thermal damage/failure, that is independent of drip shield early failure, seepage, or localized corrosion, and for which the probability of a joint outcome is to be calculated. Set $p_{ACC} = 1$ to ignore such a process.

Development

In addition the probability of drip shield rupture from seismic loading with drift collapse is assumed to be independent of its location anywhere within the lithophysal tuff.

The expected number of waste packages in the target group, in the lithophysal part of percolation bin *b* is:

$$nNWP(b) = f(b) \times f_L(b) \times nNWPT \qquad \text{(Eq. B.2.4-1)}$$

For convenience, assume *nNWP*(*b*) is an integer by use of a ceiling function on *nNWP*(*b*), implemented in Mathcad. The probability that no waste package in the target group is placed in the lithophysal region of percolation bin *b* is essentially 0 for all percolation bins, therefore this analysis assumes that at least one waste package from the target group is placed in the lithophysal region of each percolation bin.

Given that an event occurs at time *t* that fails the drip shield plates, the probability that localized corrosion will occur at or after time *t* at a random location in percolation bin *b* is estimated by the fraction of locations in percolation bin *b* that have localized corrosion conditions at or after time *t*, $f_{LC}(t,b|\mathbf{r})$.

Denote by $nLC(t,b|\mathbf{r})$ the random variable that counts the number of waste packages in the target group that: 1) are in percolation bin *b*, 2) are in locations that lie under ruptured drip shields that fail at time *t* due to a seismic event that ruptures the drip shields in the lithophysal tuff, and 3) have localized corrosion conditions at or after time *t*, in epistemic realization **r**. Using the binomial probability density as described by Hahn and Shapiro (1967 [DIRS 146529], p. 139):

$$p(x;p,n)=\binom{n}{x}\cdot p^{x}\cdot(1-p)^{n-x} \qquad \text{(Eq. B.2.4-2)}$$

the random variable $nLC(t,b|\mathbf{r})$ can be modeled with a binomial distribution with probability $p_{LC}(t,b|\mathbf{r})$:

$$\begin{aligned}P(nLC(t,b|\mathbf{r})\geq 1)&=1-\binom{nNWP(b)}{0}(1-p_{LC}(t,b|\mathbf{r})p_{ACC})^{nNWP(b)}\\&=1-(1-p_{LC}(t,b|\mathbf{r})p_{ACC})^{nNWP(b)} \qquad \text{(Eq. B.2.4-3)}\\&=1-(1-f_{LC}(t,b|\mathbf{r})p_{ACC})^{nNWP(b)}\end{aligned}$$

Rockfall in the lithophysal tuff can occur for events with PGV as low as 0.274 m/s (SNL 2007 [DIRS 176828], Eq. 6.7-1), is strongly correlated with PGV, and accumulates due to multiple events. The extent of collapse depends also on the bulking factor of the collapsed rubble (SNL 2007 [DIRS 176828], Section 6.7.1). As collapse rubble accumulates in the drift, the static load on the drip shields increases, and drip shields become more susceptible to failure during subsequent seismic loading. At full (100%) collapse, drip shield plate failure may occur with a small probability, for seismic events with PGV as low as 2.44 m/s (neglecting corrosion thinning of the plates) corresponding to annual recurrence frequency of 4.518×10^{-7} yr^{-1} (SNL 2007 [DIRS 176828], Tables 6-3 and 6-36). With less collapse (e.g. 50%; same source, Table 6-36) the probability is smaller and the intensity of the required seismic event is greater. In summary, there is a small probability that drip shield failure can occur from seismic loading under drift collapse rubble, which depends on the presence of enough rubble, which may accumulate during a single seismic event or multiple seismic events over time.

To address the recursive complexity of conditions leading to drip shield rupture in the lithophysal tuff, a Monte Carlo simulation approach, implemented in Mathcad, was used to estimate λ_L as it appears in Eq. B.2.4-5 (Output DTN: MO0712PBANLNWP.000, file: *Lith Probability of DS Failure.xmcd*). This analysis is described in detail in Section B.2.4.1.

Denote by $NLC(t,b\,|\,\mathbf{r})$ the random variable that counts the number of waste packages in the target group in percolation bin *b* in locations that have localized corrosion conditions at or after time *t*, in epistemic realization $\mathbf{r}$. The random variable $NLC(t,b\,|\,\mathbf{r})$ can be represented with a binomial distribution with probability $f_{LC}(t,b\,|\,\mathbf{r})$, so

$$\begin{aligned}P(NLC(t,b\,|\,\mathbf{r}) \geq 1)) &= 1 - \binom{nNWP(b)}{0}\left(1 - f_{LC}(t,b\,|\,\mathbf{r})p_{ACC}\right)^{nNWP(b)} \\ &= 1 - \left(1 - f_{LC}(t,b\,|\,\mathbf{r})p_{ACC}\right)^{nNWP(b)}\end{aligned} \qquad \text{(Eq. B.2.4-4)}$$

Because λ_L is defined to be the frequency of events that fail drip shields in the lithophysal region, and this failure can occur only once, the calculation only accounts for one event that causes failure of drip shields in the lithophysal unit within 10,000 years. Dividing the interval [0, 10,000 years] into intervals of length Δt with endpoints $t_0 = 0$, t_1, …, $t_M = 10{,}000$. The probability that the event occurs in one interval $[t_k, t_{k+1}]$ is

$$\lambda_L \Delta t \cdot e^{(-\lambda_L t_k)}$$

So the probability that the event occurs in the interval $[t_k, t_{k+1}]$ which results in one or more waste packages affected by localized corrosion is

$$\lambda_L \Delta t \cdot e^{(-\lambda_L t_k)} P(NLC(t,b\,|\,\mathbf{r}) \geq 1)$$

Finally, the probability that seismic events in 10,000 years cause one or more waste packages in the lithophysal part of percolation bin *b* to be affected by localized corrosion is given by

$$P(NLC(b\,|\,\mathbf{r}) \geq 1) = \int_0^{10{,}000} \lambda_L e^{(-\lambda_L s)} P(NLC(s,b\,|\,\mathbf{r}) \geq 1)\,ds \qquad \text{(Eq. B.2.4-5)}$$

And the probability that no waste package is affected by the combination of drip shield failure by lithophysal rockfall and localized corrosion in 10,000 years is given by

$$P(NLC = 0\,|\,\mathbf{r}) = \prod_{b=1}^{5}\left(1 - P(NLC(b\,|\,\mathbf{r}) \geq 1)\right) \qquad \text{(Eq. B.2.4-6)}$$

The epistemic uncertainty in localized corrosion, represented by $\mathbf{r}$, results in a distribution of values for $P(NLC = 0\,|\,\mathbf{r})$.

This analysis was implemented for a target group of 400 naval SNF waste packages (336 in the lithophysal tuff), yielding a mean probability of 3.0×10^{-5} that one or more naval packages will be affected by Mode 4D in 10,000 years. This is an illustrative calculation that does not reflect the full detail of the screening justifications for criticality processes for naval SNF.

B.2.4.1 Monte Carlo Analysis of Seismic Drip Shield Failure Mode 4

This analysis generates the parameter λ_L, the frequency of seismic events that rupture drip shields in the lithophysal tuff. This case is specific to the lithophysal tuff, because drift collapse of sufficient extent to cause rupture of the drip shield during a seismic event can only occur there. This analysis is used as input to the probabilistic analysis of Mode 4D for waste package failure (Section B.2.4).

In addition the probability of drip shield rupture from seismic loading with drift collapse is considered to be independent of its location anywhere within the lithophysal tuff.

Notation

n = Number of multiple seismic events simulated over 10,000 years.

E = The rockfall volume (m^3/meter of drift) required for complete drift collapse.

Development

The following process is implemented in Mathcad (Output DTN: MO0712PBANLNWP.000, file: *Lith Probability of DS Failure.xmcd*).

1. Given an annual exceedance frequency equal to λ(0.219 m/sec) DTN: MO0703PASDSTAT.001 [DIRS 183148], file *Lith Rubble Abstraction.xls*, worksheet *Data for Bounded Hazard* that represents events that can produce nonzero rockfall, use the Poisson Distribution to determine the probability of n events occurring in 10,000 years, where n ranges from 1 to 15.

2. Calculate the conditional probability that drip shield failure occurs given that n events have occurred in 10,000 years. This conditional probability is determined by synthetic sampling of 100,000 or more realizations. For each realization perform step A below, then for each event in the realization, perform steps B and C.

   A. For each realization, sample for E, the volume of rockfall required for complete drift collapse, by sampling a uniform distribution from 30 to 120 m^3/m.

   B. For the first event in a realization, sample the annual exceedance frequency over a range corresponding to the range of PGV from 0.219 m/s to 4.07 m/s, and determine the PGV from the hazard curve. Use the PGV and a second, independent random number to determine if non-zero rockfall occurs, then independently sample the gamma distribution to determine the rockfall volume associated with that event. Calculate the fraction of drift collapse (FD) by dividing the rockfall volume by E.

Given that PGV and the FD are known for this event, it is possible to determine whether drip shield failure has occurred, by calculating the probability from the interpolation function in Table 1-2 of DTN: MO0703PASEISDA.002 [DIRS 183156]). The random number used to determine if rockfall occurs is compared to the table value to determine if drip shield failure has occurred. If drip shield failure occurs, then the process stops. If drip shield failure has not occurred then proceed to the next step.

C. Perform the same calculation for the second, and subsequent events (up to *n* if drip shield failure does not occur). New random numbers are generated for each event. Test for drip shield failure at each event. If drip shield failure occurs, then stop.

D. For multiple realizations, compile the conditional probability of drip shield failure for *n* events, where *n* ranges from 1 to 15.

3. The results from Step 1 give the probabilities for $n = 1, 2, ...15$. The results from Step 2 give the conditional probability of drip shield failure. The dot product of these two vectors then gives the expected value for the probability P of drip shield failure in 10,000 years. The parameter λ_L, representing the frequency of seismic events that cause rupture to the drip shield in the lithophysal region is estimated by $\lambda_L = \frac{P}{10{,}000}$.

Inherent Conservatisms

The estimate of 3.0×10^{-5} provided by Equation B.2.4-6 for the probability that one or more naval SNF waste packages experiences water ingress by Mode 4D in 10,000 years after repository closure is a reasonable estimate of this value. The calculation relies on the conservative assumptions made in describing the effects of seismic ground motion on drip shields (SNL 2007 [DIRS 176828]) and the model for initiation of localized corrosion (SNL 2007 [DIRS 178519]). No additional conservative assumptions are made in this analysis.

Uncertainty in Results

The results computed from Equation B.2.4-6 reflect aleatory uncertainty in the number and nature of seismic events that can occur in 10,000 years after repository closure as well as the spatial location of navy SNF waste packages within the repository. These aleatory uncertainties are addressed by the calculation of λ_L, the mean frequency of events that cause drip shield failure, and in Equation B.2.4-1, which yields the mean number of navy SNF waste packages in the lithophysal tuff. The principal epistemic uncertainties that affect this calculation are the occurrence and composition of seepage waters and the processes that lead to initiation of localized corrosion on Alloy 22. These uncertainties are represented by the use of sample elements (realizations) $\mathbf{r}$, which result in a distribution of results from Equation B.2.4-6. Because the probability of localized corrosion initiation is uncertain and is highly variable between sample elements (see analysis results in Ouput DTN: MO0712PANLNNWP.000, file: *Nonlith LC Calculation Rev03.xmcd*), the distribution of results from Equation B.2.4-6 is significantly influenced by a few sample elements in which localized corrosion is highly probable. Thus, the distribution of results from Equation B.2.4-6 is highly skewed, causing the mean of this distribution to be much larger than its median value.

B.2.4.2 Probability of Early Rockfall Sufficient to Cause Elevated waste Package Temperatures and Then Failure by Localized Corrosion

This section considers drift collapse occurring in the lithophysal rock zone during the initial thermal period after closure of the repository. The rubble from seismic events could accumulate on and around the drip shield and act as a thermal blanket for the waste packages. This would result in increased waste package temperatures relative to nominal conditions (without drift collapse).

This calculation quantifies the probability that seismic activity during the first *T* years of the repository causes lithophysal rockfall sufficient to cause a thermal blanket effect in waste package temperature (300°C or more), which could alter waste forms in the target population of waste packages. Subsequent to this occurring one or more of the waste packages of that population could fail due to DS failure followed by seepage induced localized corrosion of the waste package outer barrier. This calculation is bounding in that the probability of localized corrosion is set to one if drip shield failure occurs.

The thermal influence of a collapsed drift on waste package temperatures is discussed in the *Postclosure Analysis of the Range of Design Thermal Loadings* (SNL 2008 [DIRS 179962], Section 6.5.1). In the case of drift collapse, the probability of waste package temperatures exceeding 300 degrees C is low right after repository closure and peaks at about 25 years after closure then continues to decrease (SNL 2008 [DIRS 179962], Section 6.5.1) to a small value after 80 years. For purposes of discussion in this calculation, the value of *T* is selected at 80 years.

This calculation is implemented in MathCad and provided in Output DTN: MO0712PBANLNWP.000, file *Probability of Thermal Blanket and Localized Corrosion.xmcd*.

This calculation file is developed so that an impact to waste forms occurs if lithophysal rockfall equals or exceeds 7.5 m^3/m at any time in the first 80 years. The basis for establishing the 7.5 m^3/m volume is presented in DTN: MO0709HOTWASTE.000 (SNL 2007 [DIRS 184821], Folder: *Drift Collapse*, File: *Worksheet in Seismic Consequence Analysis.xls*, Worksheet: *P10L Peak T vs Vol. LKT*). This worksheet presents a chart of the relationship of waste package temperature with the volume of rockfall at various times after repository closure. The analysis was performed with the 10th percentile thermal properties set for the rock mass. Use of the 10th percentile values maximizes the temperature increase with the lowest amount of rockfall and is thus conservative for this application. The selected rockfall volume of 7.5 m^3/m provides a minimum volume for which a waste package temperature reaches 300°C. The use of the minimum rockfall volume will result in an overestimate of the probability of an increased temperature that could affect the waste form and is thus conservative.

This calculation first computes the probability that a seismic event occurs in the first *T*= 80 years sufficient to cause at least 7.5 m^3/m of lithophysal rockfall. This event has two outcomes: 1) the DS fails due to this first event; 2) the DS does not fail because of this first event. If the DS does not fail, the calculation considers the probability that subsequent seismic events may fail the DS.

Lithophysal rockfall may occur if the PGV exceeds 0.274 m/s as shown in DTN: MO0703PASEISDA.002, [DIRS 183156], Equation 1-1. Events at this PGV occur with a frequency approximately 2.5×10^{-4} yr^{-1} as determined from the Seismic Hazard Curve in DTN: MO0703PASDSTAT.001 ([DIRS 183148] Workbook: *Lith Rubble Abstraction.xls*, Worksheet: *Data for Bounded Hazard*).

The probability of exactly one seismic event is based on the standard (Poisson) formulation (Hahn and Shapiro 1967 [DIRS 146529], Equation 4-9) for events that occur randomly over T years with a given rate, $\Delta\lambda$ per year:

$$P(1 \mid \Delta\lambda, T) = T\Delta\lambda^{-\Delta\lambda T} \qquad \text{(Eq. B.2.4-7)}$$

From the bounded hazard curve the exceedance frequency which corresponds to the PGV at which there is a nonzero probability of rockfall is 2.5×10^{-4} per year. The probability that one event occurs in T=80 years with PGV exceeding 0.274 m/s is given by:

$$2.5\times10^{-4}\,Te^{(-2.5\times10^{-4}T)} = 0.020 \qquad \text{(Eq. B.2.4-8)}$$

The probability that two or more events occur within T=80 years with PGV exceeding 0.274 m/s is approximately:

$$1-e^{(-2.5\times10^{-4}T)}-2.5\times10^{-4}\,Te^{(-2.5\times10^{-4}T)} = 2.0\times10^{-4} \qquad \text{(Eq. B.2.4-9)}$$

Because the outcome when considering two or more events is small relative to the probability for a single event, the calculation can consider the rockfall from only a single event as long as T is relatively small (compared to the 10,000-year time frame). Given that a seismic events occurs with PGV of v, the expected volume of lithophysal rockfall is given by:

$$E\left(V\left(v\right)\right) = P_{RF}\left(v\right) \times \mu\left(v'\right) \qquad \text{(Eq. B.2.4-10)}$$

where $P_{RF}(v) = \min[1.0, \max(0, 1.288 \cdot v - 0.353)]$ (DTN: MO0703PASEISDA.002 [DIRS 183156], Eq. 1-1) and $v' = \max\left(v, 0.4\right)$, and $\mu\left(v'\right) = 20.307\left(v'\right)^2 - 18.023v' + 4.0102$ (DTN: MO0703PASEISDA.002 [DIRS 183156], Equations 1-2 and 1-3) is the mean or expected rockfall volume. Table B-2 provides results for the evaluation of Equation B.2.4-10.

Table B-2. Expected Rockfall Volumes for Various PGV Values

PGV (v) (m/s)	$P_{RF}(v)$	$E(V(v))$ **(m^3)**
0.4	0.1622	0.008129
0.5	0.291	0.021956
0.6	0.4198	0.212805
0.7	0.5486	0.737609
0.8	0.6774	1.753301
0.9	0.8062	3.416813
0.95	0.8706	4.540542
1	0.935	5.885077
1.05	0.9994	7.470033
1.1	1	8.75637
1.2	1	11.62468

Source: DTN: Output DTN: MO0712PBANLNWP.000, file: *Probability of Thermal Blanket and Localized Corrosion.xmcd*.

From Table B-2, approximately 7.5 m^3/m occurs for events with PGV of about 1.05 m/s. From *Seismic Damage Abstractions For TSPA Compliance Cas*e (DTN MO0703PASEISDA.002 [DIRS 183156], Table 1-2, $FD_{LITH.}$=1.0 cases), DS failure can occur when PGV exceeds 1.05 m/s. For simplicity, this calculation considers one seismic event occurring in the first *T* years with PGV of at least 1.05 m/s, and that the rockfall from this event is sufficient to cause a thermal blanket effect. Moreover, this calculation is conservative by considering the rockfall from the first event is sufficient to impose the maximum static load on the drip shield, therefore, the fraction of the drift filled (FD) by rockfall from the first event is set to 1. This is conservative because the volume of rockfall required to impose the maximum static load on the drip shield is uncertain and is described by a uniform distribution ranging between 30 m^3/m and 120 m^3/m (SNL 2007 [DIRS 176828], Section 6.7.1.5).

To compute the probability of DS failure, DS corrosion can be neglected as inconsequential, so the DS thickness may be assumed to be 15mm. For each seismic event, the seismic consequences abstraction assumes that the PGV of the event, the occurrence of rockfall and the occurrence of drip shield failure are correlated. However, the volume of rockfall is independent of these correlated values (PGV, etc.). The probability of DS failure given the occurrence of a seismic event with PGV exceeding 1.05 m/s is estimated to be 1.9×10^{-3}, as calculated by a Monte Carlo simulation (Output DTN: MO0712PBANLNWP.000 File: *Lith Probability of DS Failure Rev01.xmcd)*

The probability that a seismic event with PGV exceeding 1.05 m/s occurs in the first *T* years is $\left(9.96\times10^{-6}\right)\times T$ (DTN: MO0703PASEISDA.002 [DIRS 183156], Table 1-1). Given that a seismic event with PGV exceeding 1.05 m/s occurs in the first *T* years, two outcomes are possible: 1) the DS fails due to the seismic event; 2) the DS does not fail due to the seismic event. The probability that the DS fails is $\lambda_1 = 1.9\times10^{-3}$ as previously stated, and the probability that DS failure does not occur is the compliment which is 0.998.

If the DS does not fail due to the event that occurs in the first *T* years, the DS could fail from a subsequent seismic event where the dynamic load on the DS is increased due to the rockfall from the first seismic event. The calculation of the probability of DS failure from a subsequent seismic event is simplified by the conservative assumption that the rockfall from the first event is sufficient to impose the maximum static load on the drip shield. In terms of Table 1-2 of (DTN: MO0703PASEISDA.002 [DIRS 183156]), the fraction of drift filled by the rockfall from the first event is set to 1. This assumption is conservative because the volume of rockfall required to impose the maximum static load on the drip shield is uncertain and is described by a uniform distribution ranging between 30 m^3/m and 120 m^3/m as presented in the Seismic *Consequence Abstraction* (SNL 2007 [DIRS 176828], Section 6.7.1.5).

The frequency of seismic events that cause failure of the DS after the drift is filled with rubble is $\lambda_2 = 4.42\times10^{-8}\,yr^{-1}$ as shown in Output DTN: MO0712PBANLNWP.000, file: *Lith Probability of DS Failure FD EQ1 Rev01.xmcd*. This probability is obtained in the same manner as the probability of seismic drip shield failure for Mode 4 presented in Section B.2.4.1 except that the two-way interpolation presented in DTN: MO0703PASEISDA.002 ([DIRS 183156], Table 1-2) is changed to a one-way interpolation with the fraction of the drift filled with rockfall set to one, (i.e., FD=1).

Thus, the probability that a seismic event occurs in the first *T* years resulting in a thermal blanket effect with subsequent drip shield failure, and that one or more of the target WPs in the lithophysal region of the repository experiences water ingress is bounded by

$$\begin{aligned}
P &= P(seismic\,event\,in\,T\,yr)\times\left[\begin{array}{l}\left(\begin{array}{l}P(DS\ fails\ from\ first\,event)\\ \times P(water\,ingress\,after\ first\,event)\end{array}\right)\\ +\left(\begin{array}{l}P(DS\,does\,not\ fail\ from\ first\,event)\\ \times P(DS\ fails\,before\,10{,}000\,yr\ from\,later\,event)\\ \times P(water\,ingress\,after\,DS\ failure)\end{array}\right)\end{array}\right]\\
&\le \left(T\times9.96\times10^{-6}\right)\times\left[\begin{array}{l}\left(1.9\times10^{-3}\right)\times1\\ +(0.998)\times\left(\left(4.42\times10^{-8}\right)\times(10{,}000-T)\right)\times1\end{array}\right]\\
&= \left\{\begin{array}{ll}1.86\times10^{-6} & if\ T=80\\ 6.95\times10^{-6} & if\ T=300\end{array}\right\}
\end{aligned}$$

(Eq. B.2.4-11)

This calculation is provided in Output DTN: MO0712PBANLNWP.000, file *Probability of Thermal Blanket and Localized Corrosion.xmcd.*

Inherent Conservatisms

The estimate of 6.95×10^{-6} (associated with *T* = 300 years)provided by Equation B.2.4-11 is a bounding estimate of the probability of water ingress into one or more of the target waste packages after seismic events during the first 300 years after repository closure have caused rockfall sufficient to alter waste by thermal blanket effects. This bounding estimate results from several conservative assumptions: first, that any seismic event with PGV exceeding 1.05 m/s results in rockfall sufficient to completely fill the drift (an unlikely result, see Table B2.4-1); second, that subsequent to drip shield failure, the WPOB also fails without uncertainty; and third, that if rockfall occurs, then all WP in the target population are subject to the thermal blanketing effects. In actuality, WPOB failure would depend probabilistically on the occurrence of early failure, seismic damage or localized corrosion, the models for which entail significant uncertainty (as discussed in the analyses for Modes 2D, 3D and 4D). In addition, WP temperatures show wide variability between spatial locations in simulations of the repository (SNL 2008 [DIRS 184433], Section 6.3.13), so it is possible that no WP in the target group would experience temperatures sufficient to cause adverse changes in the waste. These simplifying and conservative assumptions combine to yield a bounding estimate from Equation B.2.4-11. It should also be noted that this calculation relies on the conservative assumptions made in describing the effects of seismic ground motion on drip shields (SNL 2007 [DIRS 176828]).

Uncertainty in Results

The results computed from Equation B.2.4-11 reflect aleatory uncertainty in the number and nature of seismic events that can occur in 10,000 years after repository closure. These aleatory uncertainties are addressed by the calculation of $\lambda_1 = 1.9 \times 10^{-3}$, and in the calculation of $\lambda_2 = 4.42 \times 10^{-8}\ yr^{-1}$, the frequency of events that result in drip shield failure after the drift is filled with rubble. The spatial location of navy SNF waste packages within the repository is addressed by means of a conservative assumption. In addition, the epistemic uncertainties that could affect the performance of the waste package outer barrier after drip shield failure have also been addressed by means of conservative assumptions. Because of this treatment, Equation B.2.4-11 yields a bounding value rather than a distribution of results.

APPENDIX C
QUALIFICATION OF DATA

APPENDIX C
QUALIFICATION OF DATA

C.1 QUALIFICATION OF EXTERNAL SOURCE DATA

This section presents planning and documentation for the data qualification of the unqualified external source data used as direct input for this analysis. Data qualification is performed in accordance with SCI-PRO-005, *Scientific Analyses and Calculations*, and a facsimile of the Data Qualification Plan is included at the end of this appendix. The intent of the qualification process is to qualify the data for use only within this report.

C.2 QUALIFICATION METHODS SELECTED

Two methods were selected for qualification, as outlined in Attachment 3 of SCI-PRO-001, *Qualification of Unqualified Data*:

> **Method 1**, equivalent QA program, is used for reports from DOE and its contactors that describe fuel and associated material characteristics (DOE 2004 [DIRS 170071]). The rationale for using this method is that the QA programs for the reports can be traced, while all other methods are largely inapplicable; typically these reports cite older, one-of-a-kind records from decommissioned facilities.
>
> **Method 5**, technical assessment, is used for one data source (Wheatley 2007 [DIRS 181533]). The rationale for using this method is that documentation or proof of proper data acquisition is unavailable for review. For Method 5, one "actions to be taken" from SCI-PRO-001 is considered: (a) Determination that the employed methodology is acceptable.

Qualification process attributes used in the equivalent QA program of the external source is selected from the list provided in Attachment 4 of SCI-PRO-001, which represent the acceptance criteria used to determine if the data are qualified. Process attributes used specifically for data qualification in this report are:

1. *The extent to which the data demonstrate the properties of interest (e.g., physical, chemical, geologic, mechanical);*
2. *Qualifications of personnel or organizations generating the data are comparable to qualification requirements of personnel generating similar data under an approved program that supports the YMP License Application process or post closure science.*

Qualification process attributes used in the technical assessment of the external source is selected from the list provided in Attachment 4 of SCI-PRO-001, which represent the acceptance criteria used to determine if the data are qualified. Process attributes used specifically for data qualification in this report are:

1. *Qualifications of personnel or organizations generating the data are comparable to qualification requirements of personnel generating similar data under an approved program that supports the YMP License Application process or post closure science;*

2. *The extent to which the data demonstrate the properties of interest (e.g., physical, chemical, geologic, mechanical);*

3. *Prior peer or other professional reviews of the data and their results.*

C.2.1 Qualification of External Data Source DOE 2004 [DIRS 170071]

This report gives dimensions and characteristics for DOE and DSNF canisters and internals. Method 1, Equivalent QA Program (Attachment 3, SCI-PRO-001), was used to qualify the data. The following process attributes were used to assess these external data:

1. *The extent to which the data demonstrate the properties of interest (e.g., physical, chemical, geologic, mechanical)*

2. *Qualifications of personnel or organizations generating the data are comparable to qualification requirements of personnel generating similar data under an approved program that supports the YMP License Application process or post-closure science.*

This report gives the packaging strategies for the representative waste form groups evaluated for criticality safety. Therefore, criteria 1 is satisfied. The information for the report was gathered and assessed by the National Spent Nuclear Fuel Program. Golan (2004 [DIRS 182752]) reports that a 2004 audit found the National Spent Nuclear Fuel Program was satisfactorily implementing the QARD. Thus, criteria 2 is satisfied.

Based on the assessment made above, data qualification method 1 has been satisfied and data from DOE 2004 [DIRS 170071] are qualified for use as direct input for this analysis.

C.2.2 Qualification of External Data Source Wheatley 2007 [DIRS 181533]

The DOE-owned SNF waste forms that require plate type neutron absorber materials are mixed oxide (MOX) represented by Fast Flux Test Facility (FFTF) fuel, $UZrH_x$ represented by Training, Research, Isotopes, General Atomic (TRIGA) fuel, U/Th Oxide represented by Shippingport Light Water Breeder Reactor fuel, aluminum-based DOE-owned SNF represented by Advanced Test Reactor (ATR) fuel, and U-Zr/U-Mo represented by Enrico Fermi fuel (DOE 2004 DIRS 170071], Section 2.1.11). The absorber material for the Shippingport Light Water Breeder Reactor and Enrico Fermi SNF waste forms consists of a combination of both plates and shot and, thus, the absorber misload probability is considered insignificant. Thus, the MOX, ATR, and TRIGA waste forms are the only ones for which configurations with criticality potential have a non-trivial probability of absorber misload.

The external source of data used as direct input for this analysis is as follows:

- *Packaging Strategies for Criticality Safety for "Other" DOE Fuels in a Repository.* DOE/SNF/REP-090, Rev. 0 (DOE 2004 [DIRS 170071])

- Data for the DOE-owned SNF canister inventory from a journal article by Wheatley (2007 [DIRS 181533], p. 2) identified as follows*:

  MOX canister count = 128 + 15 = 143
  ATR canister count = 755 + 236 = 991
  TRIGA canister count = 89.

This results in a total of 1,223 canisters using absorber plate criticality control features

* Wheatley 2007 [DIRS 181533], Point Estimate column (rounded up).

The action taken to qualify the DOE-owned SNF inventory data from the journal article by Wheatley (2007 [DIRS 181533]) is from SCI-PRO-001, Attachment 3, Method 5(a) as follows:

Determination that the Employed Methodology is Acceptable

> A discussion and justification that the data collection methodology used was appropriate for the type of data under consideration (used appropriate equipment, typical of scientific and industry collection methods, etc.).

The following criteria were used to assess the external data from *Canister Counts for Criticality Analyses for DOE-owned SNF in the License Application* (Wheatley 2007 [DIRS 181533]):

1. The extent to which the data demonstrate the properties of interest (e.g., physical, chemical, geologic, mechanical)
2. The extent to which conditions under which the data were generated may partially meet the QA program that supports the YMP license application process or post closure science
3. Extent and reliability of the documentation associated with the data.

Justification for the appropriate use of data from: Wheatley 2007 [DIRS 181533]:

> The cited reference, Wheatley 2007 [DIRS 181533], was sent to the YMP by a manager from the National Spent Nuclear Fuel Program at the Idaho National Laboratory in support of the YMP postclosure criticality screening analysis, thus criterion 3 is satisfied. The reference contains inventory information abstracted from the DOE-owned SNF Spent Fuel Database that is maintained by the National Spent Nuclear Fuel Program, thus criteria 1 is satisfied. Triay (2007 [DIRS 184719]) reports that a 2007 audit found the National Spent Nuclear Fuel Program was satisfactorily implementing the QARD, thus criteria 2 is satisfied.

Based on the assessment made above, data qualification method 5 has been satisfied and data from Wheatley 2007 [DIRS 181533] are qualified for use as direct input for this analysis.

Data Qualification Plan

Complete only applicable items.

QA: QA

Page 1 of 1

Section I. Organizational Information

Qualification Title

Data Qualification for External Source Data used in CAL-DN0-NU-000002

Requesting Organization

Engineered Systems

Section II. Process Planning Requirements

1 List of Unqualified Data to be Evaluated

1) Wheatley, P.D. 2007. "Canister Counts for Criticality Analyses for DOE SNF in the License Application." Letter from P.D. Wheatley (INL) to R.M. Kacich (BSC) and M.K. Knowles (SNL), CCN 210126, June 20, 2007. ACC: LLR.20070627.0004. [DIRS 181533].

2) DOE (U.S. Department of Energy) 2004. *Packaging Strategies for Criticality Safety for "Other" DOE Fuels in a Repository.* DOE/SNF/REP-090, Rev. 0. Idaho Falls, Idaho: U.S. Department of Energy, Idaho Operations Office. ACC: MOL.20040708.0386. [DIRS 170071]

2. Type of Data Qualification Method(s) [Including rationale for selection of method(s) (Attachment 3) and qualification attributes (Attachment 4)]

Method 1, equivalent QA program, is used for reports from DOE and its contactors that describe fuel and associated material characteristics (DOE 2004 [DIRS 170071]. The rationale for using this method is that the QA programs for the reports can be traced, while all other methods are largely inapplicable; typically these reports cite older, one-of-a-kind records from decommissioned facilities.

Method 5, technical assessment, is used for one data source (Wheatley [DIRS 181533]). The rationale for using this method is that documentation or proof of proper data acquisition is unavailable for review. For Method 5, one "actions to be taken" from SCI-PRO-001 is considered: (a) Determination that the employed methodology is acceptable.

Qualification process attributes used in qualification of the external source is selected from the list provided in Attachment 4 of SCI-PRO-001, which represent the acceptance criteria used to determine if the data are qualified. Process attributes used specifically for data qualification in this report are:

1. Qualifications of personnel or organizations generating the data are comparable to qualification requirements of personnel generating similar data under an approved program that supports the YMP License Application process or post closure science;

2. The extent to which the data demonstrate the properties of interest (e.g., physical, chemical, geologic, mechanical);

3. Prior peer or other professional reviews of the data and their results;

3. Data Qualification Team and Additional Support Staff Required

John Scaglione (Data Qualification Chairperson); Charles Henkel

4. Data Evaluation Criteria

Were the personnel or organizations generating the data qualified and comparable to qualification requirements of personnel generating similar data under an approved program that supports the YMP License Application process or post closure science?

Does the data demonstrate the properties of interest (e.g., physical, chemical, geologic, mechanical)?

Has the data received a prior peer or other professional review?

5. Identification of Procedures Used

SCI-PRO-005 and SCI-PRO-001

6. Plan coordinated with the following known organizations providing input to or using the results of the data qualification

Engineered Systems

Section III. Approval

Qualification Chairperson Printed Name John M. Scaglione	Qualification Chairperson Signature	Date 2/18/2008
Responsible Manager Printed Name Cliff Howard	Responsible Manager Signature Cliff Howard	Date 2/18/2008

SCI-PRO-001.1-R1

Addendum Cover Page

Complete only applicable items.

QA: QA

1. Total Pages: 16

2. Addendum to (Title): Waste Package Flooding Probability Evaluation

3. DI (including Revision and Addendum No.):
CAL-DN0-NU-000002 REV 00C AD 01

	Printed Name	Signature	Date
4. Originator	John Scaglione		4/17/08
5. Checker	Charles Henkel	Cliff Howard for	4/19/08
6. QCS / Lead Lab QA Reviewer	Brian Mitcheltree		4/21/08
7. Responsible Manager / Lead	John Scaglione		4/21/08
8. Responsible Manager	Cliff Howard	Cliff Howard	4/21/08

9. Remarks

Cliff Hansen and John Case contributed to the development of the methodology presented in this addendum and the implementation of the methodology within the Mathcad files presented in Output DTN MO0803SUPPANWP.000.
Jason Groves assisted in the technical check of the calculation files provided in Output DTN: MO0803SUPPANWP.000.

Change History

10. Revision and Addendum No.	11. Description of Change
00A	Initial Issue
00B	Update Direct Inputs from Current Analyses, Develop Document in Accordance with SCI-PRO-005 Scientific Analyses and Calculations
00C	Revise calculations based on updated TSPA seepage rates and updated fault displacement data, Output DTN MO0802WPFLOODG.001 supersedes previous output DTN: MO0705WPFLOODG.000; Added discussions regarding hydraulic states internal to breached waste packages. New calculations added related combinatorial probability calculations related to drift collapse, drip shield collapse/rupture and localized corrosion;
00C AD 01	Addenda to supplement the bounding calculation documented in Section B.2.4.2, and Output DTN: MO0712PBANLNWP.000 Folder *4D* to provide a more detailed calculation for the probability of rockfall occurring within the first 300 years of repository closure and then being subject to localized corrosion.

INTENTIONALLY LEFT BLANK

CONTENTS

Page

1[a]. PURPOSE 1

2[a]. QUALITY ASSURANCE 1

3[a]. USE OF SOFTWARE 2

4[a]. INPUTS 2
  4.1[a] DIRECT INPUTS 2
  4.2[a] CRITERIA 3
  4.3[a] CODES, STANDARDS, AND REGULATIONS 3

5[a]. ASSUMPTIONS 3

6[a]. SCIENTIFIC ANALYSIS DISCUSSION 3

7[a]. RESULTS AND CONCLUSIONS 6

8[a]. INPUTS AND REFERENCES 7
  8.1[a] DOCUMENTS CITED 7
  8.2[a] CODES, STANDARDS, REGULATIONS, AND PROCEDURES 7
  8.3[a] SOURCE DATA, LISTED BY DATA TRACKING NUMBER 7
  8.4[a] OUTPUT DATA, LISTED BY DATA TRACKING NUMBER 8
  8.5[a] SOFTWARE CODES 8

INTENTIONALLY LEFT BLANK

FIGURES

Page

None.

TABLES

Page

Table 4-1[a].	Direct Inputs Used in Calculation..2

INTENTIONALLY LEFT BLANK

ACRONYMS

DIRS	document input reference system
DTN	data tracking number
FEPs	features, events, and processes
PGV	peak ground velocity
SNF	spent nuclear fuel
SNL	Sandia National Laboratories

INTENTIONALLY LEFT BLANK

1[a]. PURPOSE

The purpose of this addendum is to provide a supplemental calculation to the bounding calculation documented in Section B.2.4.2, and output data tracking number (DTN): MO0712PBANLNWP.000, folder: *4D* to provide a more detailed calculation for the probability of rockfall occurring within the lithophysal zone in the first 300 years of repository closure and then being subject to localized corrosion. The supplemental calculation expands the seismic event frequency range to evaluate any rockfall event as being capable of creating a thermal blanket effect in conjunction with a probability distribution that seepage through a failed drip shield will induce localized corrosion for at least one naval waste package. Therefore, this addendum is not intended to change what was done in the parent report, but merely to provide an additional calculation which is documented in output DTN: MO0803SUPPANWP.000.

This activity supports the evaluation of features, events, and processes (FEPs) that could lead to naval spent nuclear fuel (SNF) waste package criticality. The intended use of these results will be in performing assessments of conditions necessary for criticality.

The development of this report is consistent with Work Package S31013 specified in *Technical Work Plan for: Postclosure Criticality* (SNL 2007 [DIRS 178869], Table 1). Although the actual planning for an addendum is not specified in the technical work plan, this addenda is an additional calculation that falls within the scope described, therefore this calculation follows the approach outlined in the technical work plan (SNL 2007 [DIRS 178869], Section 2.1.4) where applicable.

The results presented in Section 7[a] apply specifically to naval SNF waste packages. For other types of waste packages the direct inputs and results would be different.

2[a]. QUALITY ASSURANCE

Development of this report has been determined to be subject to the Yucca Mountain Project quality assurance requirements as described in *Technical Work Plan for: Postclosure Criticality* (SNL 2007 [DIRS 178869], Section 8.1). Approved quality assurance procedures identified in the technical work plan (SNL 2007 [DIRS 178869], Section 4.1) have been used to conduct and document the activities described in this report. The technical work plan also identifies the methods used to control the electronic management of data (SNL 2007 [DIRS 178869], Section 8.4) during the calculation and documentation activities.

This report is prepared in accordance with SCI-PRO-004, *Managing Technical Product Inputs*, SCI-PRO-005, *Scientific Analyses and Calculations*, and TST-PRO-001, S*ubmittal and Incorporation of Data to the Technical Data Management System*.

3[a]. USE OF SOFTWARE

Mathcad Version 14 (STN: 611161-14.0-00), which is commercially available off-the-shelf software, was installed on a DELL OptiPlex GX745 personal computer running Microsoft Windows XP Professional and used in the preparation of this report. Mathcad is a problem-solving environment used in calculations and analyses to manipulate the inputs using standard mathematical expressions and operations. It is also used to tabulate and chart results. Standard functions of Mathcad are used. The inputs and results are documented in sufficient detail to allow an independent repetition of computations. Thus, Mathcad is used only as a worksheet and not as a software routine. Mathcad V. 14 is an exempt software product in accordance with IM-PRO-003, *Software Management*, Section 2. Thus, there are no known limitations on the outputs based on the selected software.

Inputs, outputs, and formulas used for the various Mathcad calculations are documented in Section 6[a]. The electronic files for the calculations may be found in output DTN: MO0803SUPPANWP.000. Note that if the Mathcad file is recalculated after opening, the seed may need to be set to the default value of 1 to generate identical results (i.e., *Seed(1)*).

4[a]. INPUTS

No change.

4.1[a] DIRECT INPUTS

Table 4-1[a] presents the direct inputs used to perform the evaluations of this addendum. The inputs provided are not intended to supersede or replace what is presented in the parent report, but provides what was used specifically in this addendum. Use of these data is justified, as they are extracted from qualified project sources and their application as documented in Section 6[a] and output DTN: MO0803SUPPANWP.000 is compatible with their developed purpose and limitations as described in Section 1[a].

Table 4-1[a]. Direct Inputs Used in Calculation

Input Description	Data Tracking Number/Source	Value
Base case time period that waste package surface temperature is above 200°C	SNL 2008 [DIRS 179962], Section 6.4.2.5, Figure 6.4.2-28	300 years
TSPA localized corrosion results used in Output DTN: MO0803SUPPANWP.000, file *Lith LC Calculation Rev06.xmcd*	DTN: MO0709TSPALOCO.000 [DIRS 182994], folder: *Additional_Information/LC_for_ Criticality*	*Lith_Fraction_LC_CSNF_Bin1.txt* *Lith_Fraction_LC_CSNF_Bin2.txt* *Lith_Fraction_ LC_CSNF_Bin3.txt* *Lith_Fraction_ LC_CSNF_Bin4.txt* *Lith_Fraction_ LC_CSNF_Bin5.txt*
Hazard curve relationship to exceedance frequency and PGV	DTN: MO0703PASDSTAT.001 [DIRS 185275], file: *Lith_Rubble_Abstraction.xls,* worksheet: *Data for Bounded Hazard*	See output DTN: MO0803SUPPANWP.000, file: *Thermal Blanket Effect in First T Years Rev01.xmcd*
Probability that a seismic event causes drip shield damage in lithophysal zone	DTN: MO0703PASEISDA.002 [DIRS 185278], Table 1-2	See output DTN: MO0803SUPPANWP.000, file: *Lith Probability of DS Failure For a Single Event Rev03.pdf*

Table 4-1[a]. Direct Inputs Used in Calculation (Continued)

Input Description	Data Tracking Number/Source	Value
PGV frequency for probability of nonzero rockfall in lithophysal zone	SNL 2007 [DIRS 176828], Section 6.7.1.1	$P_{rockfall} = MIN(1.0, MAX(0.0, (1.288)PGV - 0.353))$.
Regulatory limit for screening	10 CFR 63.114(d) [DIRS 180319]	One chance in 10,000 over 10,000 years

4.2[a] CRITERIA

No change.

4.3[a] CODES, STANDARDS, AND REGULATIONS

No change.

5[a]. ASSUMPTIONS

None used for this addendum.

6[a]. SCIENTIFIC ANALYSIS DISCUSSION

As indicated in Section 1[a], this addendum provides an additional calculation to what was issued with the parent report. Therefore, the following information should only be considered as additional information and not as superseding or replacing any of the information provided with the parent report.

This calculation quantifies the probability that rockfall (due to a seismic event) occurs during the first 300 years after repository closure and is followed by ingress of water into the waste package (e.g., through localized corrosion openings). Only drift collapse during the first 300 years after repository closure could lead to elevated waste package surface temperatures (>200°C) (SNL 2008 [DIRS 179962], Section 6.4.2.5, Figure 6.4.2-28). Temperatures below 200°C are not expected to result in any material thermal effects within the waste package.

This is calculation is performed by considering the following sequence:

1. A seismic event occurs within the first 300 years.
2. The seismic event produces rockfall.
3a. The rockfall causes drip shield collapse, or
3b. The rockfall does not result in drip shield collapse, and
3b1. A second seismic event occurs that will collapse the drip shield.
3b2. The waste package outer barrier fails due to the collapse of the drip shield and localized corrosion.

The calculation in 3a assumes that the waste package outer barrier fails from localized corrosion.

The probability that a seismic event causes rockfall in the lithophysal zone is given by *Seismic Consequence Abstraction* (SNL 2007 [DIRS 176828], Section 6.7.1.1):

$$P_{rockfall}(\nu) = \min(1.0, 1.288\nu - 0.353) \qquad \text{(Eq. 1[a])}$$

where

ν = PGV in m/s of the seismic event and
$P_{rockfall}(\nu)$ = probability of nonzero rockfall.

From Equation 1[a], the minimum PGV at which rockfall occurs is 0.274 m/s, which correlates to a frequency of occurrence of 2.51×10^{-4} per year (DTN: MO0703PASDSTAT.001 ([DIRS 185275], workbook: *Lith Rubble Abstraction.xls*, worksheet: *Data for Bounded Hazard*).

The probability that an event with PGV exceeding 0.274 m/s causes rockfall P_{RF} is derived from components of Equation 6.7-7 in *Seismic Consequence Abstraction* (SNL 2007 [DIRS 176828], Eq. 6.7-7), which is simplified to the following by assuming that the fraction of the drift filled with rockfall from the seismic event is equal to 1:

$$P_{RF} = \int_{\nu_{\min}}^{\nu_{\max}} P_{rockfall}(\nu) \left(\frac{d}{d\nu} \lambda(\nu) \frac{-1}{\lambda(\nu_{\min}) - \lambda(\nu_{\max})} \right) d\nu \qquad \text{(Eq. 2[a])}$$

where

ν = horizontal PGV in m/s
$\lambda = \lambda(\nu)$ = annual exceedance frequency on the bounded hazard curve for ν
$P_{rockfall}(\nu)$ is from Equation 1[a].

The $\nu_{\max}$ upper bound of the interpolation is established from the bounded hazard curve (DTN: MO0703PASDSTAT.001 [DIRS 185275], workbook: *Lith Rubble Abstraction.xls*, worksheet: *Data for Bounded Hazard*) where the frequency of occurrence equates to the regulatory limit of one chance in 10,000 over 10,000 years (10 CFR 63.114(d) [DIRS 180319]); so $\lambda(\nu_{\max}) = 1 \times 10^{-8}$ per year, which correlates to $\nu_{\max} = 4.07$ m/s. P_{RF} is calculated for in output DTN: MO0803SUPPANWP.000, file: *Thermal Blanket Effect in First T Years Rev01.xmcd* as 0.214.

The probability of a single seismic event with frequency λ in T years, $P(1 \mid \lambda, T)$, is approximated as follows:

$$P(1 \mid \lambda, T) = T \cdot \lambda(0.274) \qquad \text{(Eq. 3[a])}$$

Therefore, the probability that a seismic event with rockfall occurs within the first T years, P_E, is computed as follows:

$$P_E = T \cdot \lambda(0.274) \cdot P_{RF} \qquad \text{(Eq. 4[a])}$$

For T = 300 years, P_E = 0.0161 (output DTN: MO0803SUPPANWP.000, file: *Thermal Blanket Effect in First T Years Rev01.xmcd*).

Note that the rockfall event has two outcomes. The first outcome is (1) the drip shield fails due to the seismic event; and (2) the drip shield does not fail due to the seismic event.

To compute the probability of drip shield failure, drip shield corrosion can be neglected as inconsequential within 10,000 years, so the drip shield thickness may be assumed to be 15 mm and there is no thinning of the drip shield. For each seismic event, the seismic consequence abstraction assumes that the PGV of the event, the occurrence of rockfall and the occurrence of drip shield failure are correlated. The probability of drip shield failure given the occurrence of one seismic event that causes rockfall within the first T=300 years, $P(DSC|E)$, is estimated to be 3.59×10^{-4}, as calculated by a Monte Carlo simulation (output DTN: MO0803SUPPANWP.000, file: *Lith Probability of DS Failure For a Single Event Rev03.xmcd*).

If the drip shield does not fail due to the event that occurs in the first T years, the drip shield could fail from a subsequent seismic event where the dynamic load on the drip shield is increased due to the rockfall from the first seismic event.

As mentioned above the overall calculation is simplified by the conservative assumption that the rockfall from the first event is sufficient to impose the maximum static load on the drip shield. This is done by setting the fraction of the drift volume filled with rock to 1.0 after a seismic event has occurred, which will maximize the probability of drip shield failure from rockfall. The frequency of occurrence of seismic events that result in failure of the drip shield after the drift is filled with rubble, λ_D, is 4.42×10^{-8} per year (output DTN: MO0712PBANLNWP.000, folder: *4D*, file: *Lith Probability of DS Failure FD EQ1 Rev01.xmcd*). Using this frequency in *Lith LC Calculation Rev05.xmcd* from output DTN: MO0712PBANLNWP.000, folder: *4D* provides the probability of one or more of the target waste packages in the lithophysal region having water ingress over 10,000 years due to drip shield failure and localized corrosion of the waste package outer barrier, given that the drift volume is filled with rock from the seismic event that occurs in the first T = 300 years. This calculation is presented in output DTN: MO0803SUPPANWP.000, file: *Lith LC Calculation Rev06.xmcd.* This probability denoted as $P_L = 7.42 \times 10^{-5}$. A more detailed discussion presenting general information on notation and development of the probability distribution function for (1) rupture of the drip shield from seismic loading after drift collapse; and (2) resulting in breach of the waste package by seepage flow through the drip shield, and (3) localized corrosion of the waste package outer barrier is provided in Section B.2.4 of the parent report.

Two files from output DTN: MO0712PBANLNWP.000, folder: *4D – Lith LC Calculation Rev05.xmcd* and *Lith Probability of DS Failure.xmcd* have been modified for the calculation presented in this addendum and are provided in output DTN: MO0803SUPPANWP.000 as files *Lith LC Calculation Rev06.xmcd* and *Lith Probability of DS Failure for a Single Event Rev03.xmcd*, respectively. The technical modifications are discussed above. In addition to the technical modifications, an administrative update was made to two source DTNs within these files as follows: DTNs: MO0703PASDSTAT.001 [DIRS 185275] and MO0703PASEISDA.002 [DIRS 185278] were updated to reflect the latest DIRS identifiers, but the actual values used are the same for both sets of files.

7[a]. RESULTS AND CONCLUSIONS

The probabilities discussed in Section 6[a] are combined in output DTN: MO0803SUPPANWP.000, file: *Thermal Blanket Effect in First T Years Rev01.xmcd* to produce the total probability of water ingress resulting from the formation of a thermal blanket given that a seismic event occurs within the first T years as follows:

$$P = P_E\left[P(DSC \mid E) + (1 - P(DSC \mid E))P_L\right] \qquad \text{(Eq. 5[a])}$$

With the time period of interest set to 300 years, the total probability is 6.96×10^{-6}.

Inherent Conservatisms

The estimate of 6.96×10^{-6} is a conservative estimate of the probability of water ingress into one or more of the naval SNF waste packages after seismic events during the first 300 years after repository closure have caused rockfall sufficient to cause thermal blanket effects. This estimate results from several conservative modeling approximations: first, that if a seismic event fails the drip shield within 300 years, that the waste package outer barrier also fails (both structurally and as a seepage barrier) with certainty; second, that if the drip shield does not fail from a seismic event in 300 years, that sufficient rockfall has occurred to completely fill the drift (as discussed above); and third, that if rockfall occurs, then all waste packages in the target population are subject to the thermal blanketing effects. In actuality, waste package outer barrier failure isn't certain and depends probabilistically on the occurrence of localized corrosion which entails significant uncertainty (as discussed in the analyses for Modes 2D, 3D, and 4D of the parent report, Appendix B). In addition, waste package temperatures show wide variability between spatial locations in simulations of the repository (SNL 2008 [DIRS 184433], Section 6.3.13), so it is possible that no waste package in the target group would experience temperatures sufficient to cause adverse changes internal to the waste package.

Uncertainty in Results

The results computed from Equation 5[a] reflect aleatory uncertainty in the number and nature of seismic events that can occur in 10,000 years after repository closure. These aleatory uncertainties are addressed by the calculation of P_{RF}, the probability that a single seismic event with PGV exceeding 0.274 m/s causes rockfall, and in λ_D, the frequency of events that result in drip shield failure after the drift is filled with rubble. The principal epistemic uncertainties that affect this calculation are the occurrence and composition of seepage waters and the processes that lead to initiation of localized corrosion on Alloy 22. These uncertainties are represented by the use of sample elements (realizations), which result in a distribution of values for P_L. The value reported for P_L is the mean value estimated from the sample. Because the probability of localized corrosion initiation is uncertain and is highly variable between sample elements (see analysis results in output DTN: MO0712PBANLNWP.000, folder: *4D*, file: *Lith LC Calculation Rev05.xmcd*), the distribution of values for P_L is significantly influenced by a few sample elements in which localized corrosion is highly probable. Thus, the distribution of results from Equation 5[a] is highly skewed, causing the mean of this distribution to be much larger than its median value.

8[a]. INPUTS AND REFERENCES

8.1[a] DOCUMENTS CITED

176828 SNL (Sandia National Laboratories) 2007. *Seismic Consequence Abstraction.* MDL-WIS-PA-000003 REV 03. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20070928.0011.

178869 SNL 2007. *Technical Work Plan for: Postclosure Criticality.* TWP-EBS-MD-000018. REV 01. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20070206.0003.

184433 SNL 2008. *Multiscale Thermohydrologic Model.* ANL-EBS-MD-000049 REV 03 AD 02. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20080201.0003.

179962 SNL 2008. *Postclosure Analysis of the Range of Design Thermal Loadings.* ANL-NBS-HS-000057 REV 00. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20080121.0002.

8.2[a] CODES, STANDARDS, REGULATIONS, AND PROCEDURES

180319 10 CFR 63. 2007. Energy: Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada. Internet Accessible.

IM-PRO-003, *Software Management*.

SCI-PRO-004, *Managing Technical Product Inputs*.

SCI-PRO-005, *Scientific Analyses and Calculations*.

TST-PRO-001, S*ubmittal and Incorporation of Data to the Technical Data Management System*.

8.3[a] SOURCE DATA, LISTED BY DATA TRACKING NUMBER

185275 MO0703PASDSTAT.001. Statistical Analyses for Seismic Damage Abstractions. Submittal date: 03/17/2008.

185278 MO0703PASEISDA.002. Seismic Damage Abstractions for TSPA Compliance Case. Submittal date: 03/17/2008.

182994 MO0709TSPALOCO.000. TSPA Localized Corrosion Analysis. Submittal date: 09/13/2007.

8.4[a] OUTPUT DATA, LISTED BY DATA TRACKING NUMBER

MO0803SUPPANWP.000. Supplemental Probabilistic Analyses of Navy Waste Packages: 03/19/2008.

8.5[a] SOFTWARE CODES

None.