

INTENTIONALLY LEFT BLANK

EXECUTIVE SUMMARY

This analysis documents the screening analysis for postclosure criticality features, events, and processes (FEPs). It addresses the probability of criticality events resulting from degradation processes as well as disruptive events (i.e., seismic, igneous, and rockfall). Probability evaluations are performed utilizing the configuration generator model described in *Configuration Generator Model for In-Package Criticality*¹, a component of the methodology from *Disposal Criticality Analysis Methodology Topical Report*².

The total probability of criticality is compared against regulatory probability criterion established in 10 CFR 63.114(d)³ (less than one chance in 10,000 of occurring over 10,000 years). The total probability of criticality accounts for the evaluation of all potential critical configurations of all waste form and waste package combinations, both internal and external to the waste packages and for both steady-state and transient conditions.

Initially, *Screening Analysis of Criticality Features, Events, and Processes for License Application* was intended as a demonstration of the screening methodology and would utilize information for the 21-PWR with Absorber Plates Waste Package type only. However, in addition to the 21-PWR with Absorber Plates Waste Package, information is available to perform the screening analyses for the 12-PWR Long, 44-BWR, and 24-BWR waste package types. Where defensible, assumptions have been made for the evaluation of the 21-PWR with Control Rods and DOE SNF waste package types in order to perform a complete criticality screening analysis.

The inputs used to establish probabilities for this analysis report are based on information and data for the Total System Performance Assessment for the License Application (TSPA-LA), where available. Information and data for the Total System Performance Assessment for the Site Recommendation (TSPA-SR) are used where the TSPA-LA data are not available.

This analysis report will determine whether criticality will be included or excluded from the TSPA-LA. The results of this analysis will provide the technical basis for updating the TSPA-SR criticality screening analyses and decisions, previously documented in *Features, Events, and Processes: System-Level and Criticality*⁴. The updated criticality FEPs screening analysis will be prepared in accordance with the guidance specified in *The Enhanced Plan for Features,*

¹ BSC (Bechtel SAIC Company) 2003 [DIRS 165629]. *Configuration Generator Model for In-Package Criticality*. MDL-EBS-NU-000001 REV 01 ICN 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20030908.0004.

² YMP (Yucca Mountain Site Characterization Project) 2003 [DIRS 165505]. *Disposal Criticality Analysis Methodology Topical Report*. YMP/TR-004Q, Rev. 02. Las Vegas, Nevada: Yucca Mountain Site Characterization Office. ACC: DOC.20031110.0005.

³ 10 CFR 63 [DIRS 156605]. Energy: *Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada*. Readily available.

⁴ CRWMS M&O 2000 [DIRS 144180]. *Features, Events, and Processes: System-Level and Criticality*. ANL-WIS-MD-000019 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20010108.0012.

*Events, and Processes (FEPs) at Yucca Mountain*⁵ and supplemented by the KTI Letter Report *Response to Additional Information Needs on TSPA 2.05 and TSPA 2.06*.⁶

The total probability of criticality resulting from the criticality FEPs analyses documented in this report has a calculated probability below the regulatory probability criterion. Therefore, criticality can be excluded from the TSPA-LA evaluation.

⁵ BSC (Bechtel SAIC Company) 2002 [DIRS 158966]. *The Enhanced Plan for Features, Events, and Processes (FEPs) at Yucca Mountain*. TDR-WIS-PA-000005 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20020417.0385.

⁶ Freeze, G. 2003 [DIRS 165394]. *KTI Letter Report, Response to Additional Information Needs on TSPA 2.05 and TSPA 2.06*. REG-WIS-PA-000003 REV 00 ICN 04. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20030825.0003.

CONTENTS

	Page
1. PURPOSE	15
2. QUALITY ASSURANCE	17
3. USE OF SOFTWARE.....	19
3.1 QUALIFIED AND BASELINE SOFTWARE.....	19
3.1.1 MCNP.....	19
3.1.2 SAPHIRE	19
3.2 CONTROLLED SOFTWARE	20
3.2.1 EXCEL	20
3.2.2 Mathcad.....	20
4. INPUTS	21
4.1 DIRECT INPUTS	21
4.1.1 Data	21
4.1.2 Parameters	22
4.1.3 Technical Information	30
4.2 CRITERIA	32
4.3 CODES AND STANDARDS.....	36
5. ASSUMPTIONS	37
5.1 GENERAL CRITICALITY FEPS ANALYSIS ASSUMPTIONS	37
5.1.1 No Waste Package Corrosion Failures.....	37
5.1.2 Boron Loss in Commercial SNF Waste Packages	37
5.1.3 Waste Packages Emplaced As Designed.....	39
5.1.4 Corrosion Rate of Neutronit A978 Neutron Absorber Material.....	39
5.1.5 Boron Loss from Waste Packages with Absorber Plates	40
5.1.6 Degradation of Neutron Absorber Material in the 21-PWR with Control Rods Waste Package	40
5.1.7 Degradation of Neutron Absorber Material in the DOE SNF Waste Packages	41
5.2 SEISMIC CRITICALITY FEPS ANALYSIS ASSUMPTIONS.....	41
5.2.1 Seismic Damage to Drip Shield and Waste Package	41
5.2.2 Time of Water Ingress into a Damaged Waste Package	41
5.2.3 Major Assumptions in Supporting Calculations	42
5.3 ROCKFALL CRITICALITY FEPS ANALYSIS ASSUMPTIONS.....	44
5.4 IGNEOUS CRITICALITY FEPS ANALYSIS ASSUMPTIONS	44
5.4.1 System for Igneous Event Commercial SNF Criticality Analyses.....	44
5.4.2 Separation of Neutron Absorber Materials	44
5.4.3 System for Igneous Event DOE SNF Criticality Analyses	45
5.4.4 Critical Limit for Igneous Event Criticality Analyses.....	45
5.4.5 UO ₂ Density Used in Igneous Criticality Analyses.....	45
5.4.6 Magma Water Content	46

CONTENTS (Continued)

	Page
6. SCIENTIFIC ANALYSIS DISCUSSION	47
6.1 SCIENTIFIC APPROACH AND TECHNICAL METHODS	47
6.1.1 Criticality FEPs Origin and Identification.....	47
6.1.2 FEPs Screening Process	55
6.1.3 Background, Technical Information, and Literature Searches.....	56
6.1.4 Assumptions and Simplifications, Alternative Conceptual Models, and Consideration of Uncertainty in FEPs Screening.....	58
6.1.5 Alternative Approaches, Mathematical Formulations, and Units of Measure	58
6.1.6 Model and Software Issues for Previously Developed and Validated Models.....	58
6.1.7 Intended Use and Limitations.....	58
6.2 CRITICALITY FEPS SCREENING ANALYSIS MODEL	59
6.3 ANALYSIS OF BASE CASE CRITICALITY FEPS	66
6.3.1 Internal (In Situ) Criticality.....	67
6.3.2 External (Near-Field and Far-Field) Criticality.....	68
6.3.3 SAPHIRE Basic Event Probabilities	70
6.3.4 Base Case Criticality FEPs Analysis Results	80
6.4 ANALYSIS OF SEISMIC DISRUPTIVE EVENT CRITICALITY FEPS	80
6.4.1 Seismic Ground Motion Effects on In-Package Criticality Evaluations.....	82
6.4.2 SAPHIRE Basic Event Probability Modifications for Seismic Analysis.....	100
6.4.3 Seismic Criticality FEPs Analysis Results	102
6.4.4 Seismic Ground Motion Effects on Near-Field and Far-Field Criticality....	104
6.5 ANALYSIS OF ROCKFALL DISRUPTIVE EVENT CRITICALITY FEPS	104
6.5.1 Rockfall Drip Shield Failure Probability.....	104
6.5.2 Minimum Seepage Probability for Rockfall Disruptive Event	106
6.5.3 SAPHIRE Basic Event Probability Modifications for Rockfall Analysis ...	107
6.5.4 Rockfall Criticality FEPs Analysis Results.....	107
6.5.5 Rockfall External Criticality Probability.....	107
6.6 ANALYSIS OF IGNEOUS DISRUPTIVE EVENT CRITICALITY FEP	107
6.6.1 Igneous Intrusion Impacts on Waste Packages and Waste Forms	108
6.6.2 Configurations Resulting from Complete Waste Package Destruction	109
6.6.3 Complete Waste Package Destruction: Internal or Near-Field Criticality ...	110
6.7 CRITICALITY FEPS RESULTS	113
6.8 CRITICALITY FEPS SCREENING DECISIONS	115
6.8.1 FEP 2.1.14.15.0A Screening Discussion.....	115
6.8.2 FEP 2.1.14.16.0A Screening Discussion.....	117
6.8.3 FEP 2.1.14.17.0A Screening Discussion.....	119
6.8.4 FEP 2.2.14.09.0A Screening Discussion.....	122
6.8.5 FEP 2.1.14.18.0A Screening Discussion.....	125
6.8.6 FEP 2.1.14.19.0A Screening Discussion.....	127
6.8.7 FEP 2.1.14.20.0A Screening Discussion.....	130
6.8.8 FEP 2.2.14.10.0A Screening Discussion.....	133

CONTENTS (Continued)

	Page
6.8.9 FEP 2.1.14.21.0A Screening Discussion.....	136
6.8.10 FEP 2.1.14.22.0A Screening Discussion.....	137
6.8.11 FEP 2.1.14.23.0A Screening Discussion.....	140
6.8.12 FEP 2.2.14.11.0A Screening Discussion.....	143
6.8.13 FEP 2.1.14.24.0A Screening Discussion.....	146
6.8.14 FEP 2.1.14.25.0A Screening Discussion.....	148
6.8.15 FEP 2.1.14.26.0A Screening Discussion.....	150
6.8.16 FEP 2.2.14.12.0A Screening Discussion.....	152
7. CONCLUSIONS.....	157
7.1 SUMMARY.....	157
7.2 CRITICALITY FEPS SCREENING RECOMMENDATIONS FOR THE LICENSE APPLICATION.....	158
7.3 UNCERTAINTIES AND RESTRICTIONS.....	161
7.3.1 Restriction #1: This Screening Analysis Is a Draft Demonstration of the Screening Methodology.....	161
7.3.2 Restriction #2: Time-Dependent Corrosion Will Not be Available Until the TSPA-LA Is Performed.....	162
7.3.3 Restriction #3: Evaluation Does Not Account for Variations In Waste Package Design.....	162
7.3.4 Restriction #4: Assumptions Regarding Neutron Absorber Material Corrosion Rate and Retention in Waste Package.....	162
7.3.5 Restriction #5: Assumptions Regarding Igneous Event Configuration and External Critical Limit.....	162
7.3.6 Restriction #6: Evaluation Does Not Account for Condensation.....	163
7.4 ADDRESSING OF REQUIREMENTS AND CRITERIA.....	163
8. INPUTS AND REFERENCES.....	167
8.1 DOCUMENTS CITED.....	167
8.2 CODES, STANDARDS, REGULATIONS, AND PROCEDURES.....	173
8.3 SOURCE DATA, LISTED BY DATA TRACKING NUMBER.....	173
8.4 SOFTWARE CODES.....	174
9. ATTACHMENTS.....	175

INTENTIONALLY LEFT BLANK

FIGURES

	Page
6.2-1. Waste Form and Waste Package Types Proposed for Disposal at the Repository	61
6.2-2. Waste Package Type Event Tree	62
6.2-3. Event Tree for Processing Criticality FEPs Cases	63
6.2-4. Criticality FEPs Screening Analysis Event Tree	65
6.6-1. Criticality Calculations with Infinite System.....	113

INTENTIONALLY LEFT BLANK

TABLES

	Page
4.1-1. Stainless Steel Type 316 Corrosion Rate Data and 1.5 Times the Corrosion Rate.....	21
4.1-2. Mean Annual Exceedance Frequency and Corresponding Peak Ground Velocity.....	24
4.1-3. Lower-Bound Percent Damaged Area to Drip Shield Due to Seismic Event.....	24
4.1-4. Upper-Bound Percent Damaged Area to Drip Shield Due to Seismic Event.....	25
4.1-5. Defect Types to Consider for Waste Package and Drip Shield Performance.....	26
4.1-6. Available Emplacement Drift Length.....	27
4.1-7. Drift Emplacement Area by Geological Unit.....	27
4.1-8. Breakdown of 70,000 MTHM Emplacement Inventory by Waste Package Type.....	28
4.1-9. Configuration Generator Model Input Sources.....	29
4.1-10. Magma Composition Weight Percents.....	30
4.1-11. Technical Information Used to Calculate Amount of Boron Still Remaining Inside the Commercial SNF Waste Packages.....	31
4.1-12. Magma Composition Theoretical Densities.....	31
4.1-13. Elemental Composition of Magma with 0.5 Weight Percent Water.....	32
4.1-14. MCNP Input Data for Criticality FEPs Igneous Evaluations.....	32
4.2-1. Applicable Project Requirements.....	33
4.2-3. Acceptance Criteria for Uncertainty in Event Probability.....	35
5.1-1. Parameters Used to Calculate Amount of Boron Still Remaining Inside the Commercial SNF Waste Packages.....	38
6.1-1. Deleted Criticality FEPs per the Enhanced FEPs Plan.....	48
6.1-2. Changes to the Criticality FEPs per the Enhanced FEPs Plan.....	49
6.1-3. Listing of TSPA-LA Criticality Features, Events, and Processes.....	49
6.1-4. Criticality FEPs List to be Utilized in Criticality Screening Analysis.....	53
6.1-5. Corroborating Data, Models, Product Input or Technical Information.....	56
6.2-1. DOE SNF Intact Configuration Criticality Analysis References.....	60
6.3-1. Base Case Configurations: Internal (In Situ) Criticality FEPs.....	68
6.3-2. Base Case Configurations: External (Near-Field and Far-Field) Criticality FEPs.....	69
6.3-3. Base Case SAPHIRE Basic Event Assignment for Fault Tree MS-IC-1.....	70
6.3-4. SAPHIRE Basic Event Assignment for Fault Tree MS-IC-2.....	72
6.3-5. SAPHIRE Basic Event Assignment for Fault Tree MS-IC-3.....	75
6.3-6. SAPHIRE Basic Event Assignment for Fault Tree MS-IC-4.....	78
6.3-7. Per Waste Package Flooding Probabilities for Base Case Criticality FEPs.....	80
6.4-1. Seismic Disruptive Event Criticality FEPs.....	81
6.4-2. Weibull Parameters and Seepage Fraction (Lithophysal Zone).....	86
6.4-3. 21-PWR with Absorber Plates Waste Package Neutronit Degradation Parameters.....	88
6.4-4. 12-PWR Long Waste Package Neutronit Degradation Parameters.....	89
6.4-5. 44-BWR Waste Package Neutronit Degradation Parameters.....	90
6.4-6. 24-BWR Waste Package Neutronit Degradation Parameters.....	91
6.4-7. Weibull Parameters and Seepage Fraction (Nonlithophysal Zone).....	97
6.4-8. Seismic Base Case SAPHIRE Basic Event Assignment.....	100
6.4-9. Seismic Sensitivity Case SAPHIRE Basic Event Assignment.....	102

6.4-10.	Per Waste Package Flooding Probabilities for Seismic Base Case Criticality FEPs	102
6.4-11.	Per Waste Package Flooding Probabilities for Seismic Sensitivity Case Criticality FEPs.....	103
6.4-12.	Total Per Waste Package Flooding Probabilities for Seismic Criticality FEPs	103
6.5-1.	Rockfall Disruptive Event Criticality FEPs	104
6.5-2.	Per Waste Package Flooding Probabilities for Rockfall Criticality FEPs.....	107
6.6-1.	Igneous Disruptive Event Criticality FEPs	108
6.6-2.	Atom Densities of Magma with 0.5 Weight Percent Water.....	111
6.6-3.	Summary of Criticality Calculations with Infinite System	112
6.7-1.	Per Waste Package Flooding Probability per Waste Package Type	114
6.7-2.	Binomial Distribution Waste Package Flooding Probability	115
7.2-1.	Screening Decisions for Criticality FEPs.....	159
7.4-1.	Addressing Project Requirements	164
7.4-2.	Addressing Acceptance Criteria for Scenario Identification and Screening.....	165
7.4-3.	Addressing Acceptance Criteria for Uncertainty in Event Probability	166

ACRONYMS

BWR	boiling water reactor
DHLW	defense high-level (radioactive) waste
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FEPs	features, events, and processes
HLW	high-level (radioactive) waste
LA	License Application
MCNP	Monte Carlo N-Particle Transport Code System
MCO	multi-canister overpack
MGR	monitored geologic repository
MTHM	metric tons of heavy metal
NRC	U.S. Nuclear Regulatory Commission
PGV	peak ground velocity
PWR	pressurized water reactor
SNF	spent nuclear fuel
STN	Software Tracking Number
TSPA-LA	Total System Performance Assessment for the License Application
TSPA-SR	Total System Performance Assessment for the Site Recommendation
TSw	Topopah Spring welded hydrogeologic unit
WAPDEG	Waste Package Degradation computer code
YMP	Yucca Mountain Project

INTENTIONALLY LEFT BLANK

1. PURPOSE

The purpose and scope of this analysis report is to establish and justify the input parameters used in the screening analysis of postclosure criticality related features, events, and processes (FEPs) for use in the license application, to perform the screening analysis, and to document the analysis results. The results of the analysis are to be used to support criticality's inclusion into, or exclusion from, the Total System Performance Assessment for the License Application (TSPA-LA).

The analysis calculates the probability of criticality resulting from degradation processes (in-package and external) as well as disruptive events (i.e., seismic, igneous, and rockfall). Probability evaluations are performed utilizing the configuration generator model described in *Configuration Generator Model for In-Package Criticality* (BSC 2003 [DIRS 165629]), a component of the methodology from *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505]). The configuration generator model is utilized for the probability evaluation of the base case in-package degradation process, the seismic disruptive event and the rockfall disruptive event. Probability evaluations of the base case external processes and the igneous disruptive event are performed using analytical arguments. The probability analysis results are then compared to the regulatory probability criterion (10 CFR 63.114(d) [DIRS 156605]) for including or excluding FEPs from evaluation in the TSPA-LA. This comparison is the basis of the screening recommendation for the criticality FEPs.

The limitations of the analysis are:

- Only specific information and data for the 21-PWR with Absorber Plates, 12-PWR Long, 44-BWR, and 24-BWR waste package types were utilized. Assumptions (which require confirmation) were utilized to extend the probability evaluation to the 21-PWR with Control Rods and DOE SNF waste package types.
- To date, model reports necessary to support the criticality FEPs screening analysis have been developed and validated only for PWR commercial SNF. Therefore, it is not possible to extend these models to other waste forms (including BWR commercial SNF) and, at the same time, strictly adhere to the criticality analysis methodology outlined in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505]).
- The inputs used to establish probabilities for this analysis are based on information and data for the TSPA-LA, where available. Information and data for the Total System Performance Assessment for the Site Recommendation (TSPA-SR) are used where the TSPA-LA data are not available. In addition, modification of any of the TSPA-LA information used in the development of this analysis could necessitate an update to the criticality FEPs screening analysis.
- The current probability evaluation is extended only to the point of waste package flooding as developed in the configuration generator model. If necessary to gain further reductions in the total probability of criticality, it is possible to extend the evaluation

beyond this point to include the probability of configuration class formation and configuration class criticality potential.

The activity of developing this screening analysis is defined in *Technical Work Plan for: Risk and Criticality Department* (BSC 2003 [DIRS 165559]). There were no deviations from this plan.

2. QUALITY ASSURANCE

Technical Work Plan for: Risk and Criticality Department (BSC 2003 [DIRS 165559], Section 8) determined that the development of this analysis report and the associated activities are subject to *Quality Assurance Requirements and Description* (DOE 2003 [DIRS 162903]). This report contributes to the analysis and modeling used to support performance assessment. This analysis report investigates the performance of the following natural and engineered barriers that are important to waste isolation:

- Commercial Spent Nuclear Fuel Cladding
- DOE and Commercial Waste Packages
- Emplacement Drift Invert
- Drip Shield
- Saturated Zone (between the repository and the accessible environment)
- Surface Topography, Soils and Bedrock
- Unsaturated Zone above the Repository
- Unsaturated Zone below the Repository
- Waste Form

Although these barriers are categorized as “Safety Category” in *Q-List* (BSC 2003 [DIRS 165179]), the evaluations and conclusions do not directly impact the features important to safety, defined in AP-2.22Q, *Classification Analyses and Maintenance of the Q-List* [DIRS 164786]. The methods used to control the electronic management of data as required by AP-SV.1Q, *Control of the Electronic Management of Information* [DIRS 165687], are identified in *Technical Work Plan for: Risk and Criticality Department* (BSC 2003 [DIRS 165559], Section 8).

Also in accordance with *Technical Work Plan for: Risk and Criticality Department* (BSC 2003 [DIRS 165559], Table 1), development of this analysis was controlled by AP-SIII.9Q, *Scientific Analyses* [DIRS 164456].

INTENTIONALLY LEFT BLANK

3. USE OF SOFTWARE

3.1 QUALIFIED AND BASELINE SOFTWARE

3.1.1 MCNP

- Title: MCNP
- Version/Revision number: Version 4B2LV
- Software Tracking Number (STN): 30033-V4B2LV
- Status/Operating System: Qualified/HP-UX B.10.20
- Computer type: Hewlett Packard (HP) 9000 Series Workstations
- Computer processing unit number: CRWMS M&O Tag 700887

Input and output files for the various MCNP calculations are provided in Attachment VII. The MCNP software is: (1) appropriate for the application of k_{eff} calculations; (2) used only within the range of validation as documented throughout *MCNP-A General Monte Carlo N-Particle Transport Code* (Briesmeister 1997 [DIRS 103897]), *Software Qualification Report for MCNP Version 4B2, A General Monte Carlo N-Particle Transport Code* (CRWMS M&O 1998 [DIRS 102836]), *Software Code: MCNP* (CRWMS M&O 1998 [DIRS 154060]); and (3) obtained from Software Configuration Management in accordance with AP-SI.1Q, *Software Management* [DIRS 165023].

Input and output files for the MCNP calculations may be found in Attachment VII (a CD-ROM). The input files in Attachment VII allow an independent reproduction of the calculations.

3.1.2 SAPHIRE

- Title: SAPHIRE
- Version/Revision number: 7.18
- Software Tracking Number (STN): 10325-7.18-00
- Status/Operating System: Microsoft Windows 2000 Professional
- Computer Type: DELL Latitude C640 Laptop PC
- Computer processing unit number: CRWMS M&O Tag number 501215

The software code SAPHIRE V7.18 (BSC 2002 [DIRS 160873]) was used to develop and quantify event trees and fault trees in this analysis. SAPHIRE (Systems Analysis Programs for Hands-on Integrated Reliability Evaluations) is a state-of-the-art probabilistic risk analysis software program that utilizes an integrated event tree/fault tree methodology to develop and analyze the logical interactions that may occur between systems and components to determine the probability or frequency of an event's occurrence.

SAPHIRE is qualified software that was obtained from Software Configuration Management. It is appropriate for use in the present analysis, and is used only within its range of validation, in accordance with AP-SI.1Q [DIRS 165023].

The event trees, fault trees, and logic rules developed for the SAPHIRE calculations are documented in Attachment II. All of the electronic files necessary for the performance of the SAPHIRE calculation may be found in Attachment VII (a CD-ROM). The input files in Attachment VII allow an independent reproduction of the calculations.

3.2 CONTROLLED SOFTWARE

3.2.1 EXCEL

- Title: EXCEL
- Version/Revision number: Microsoft Excel 97 SR-2
- Status/Operating System: Microsoft Windows 2000 Professional
- Computer Type: DELL OptiPlex GX260 PC
- Computer processing unit number: CRWMS M&O Tag number 152855

Microsoft Excel for Windows, Version 97 SR-2, is used in this analysis to manipulate the inputs using standard mathematical expressions and operations. It is also used to tabulate and chart results. The user-defined formulas, inputs, and results are documented in sufficient detail to allow an independent repetition of computations. Thus, Microsoft Excel is used only as a worksheet and not as a software routine. Microsoft Excel 97 SR-2 is controlled under the Software Configuration Management, but is not required to be qualified as specified in Sections 2.1.1 and 2.1.6 of AP-SI.1Q [DIRS 165023].

Electronic files of the EXCEL calculations used in this analysis may be found in Attachment VII (a CD-ROM). The input files in Attachment VII allow an independent reproduction of the calculations.

3.2.2 Mathcad

- Title: Mathcad
- Version/Revision number: Mathsoft Engineering and Education, Inc. Mathcad 2001i Professional
- Status/Operating System: Microsoft Windows 2000 Professional
- Computer Type: DELL OptiPlex GX260 PC
- Computer processing unit number: CRWMS M&O Tag number 152369

Mathcad for Windows 2000, Version “2001i Professional,” is a problem-solving environment used in calculations and analysis. It is also used to tabulate and chart results. The user-defined expressions, inputs, and results are documented in sufficient detail to allow an independent repetition of computations. Thus, Mathcad is used as a worksheet and not as a software routine. Mathcad is controlled under the Software Configuration Management, but is not required to be qualified as specified in Sections 2.1.1 and 2.1.6 of AP-SI.1Q [DIRS 165023].

Input and output files for the various Mathcad calculations are documented in Attachments III, IV, and V. The electronic files of these calculations may be found in Attachment VII (a CD-ROM). The input files in Attachment VII allow an independent reproduction of the calculations.

4. INPUTS

4.1 DIRECT INPUTS

The following sections present the data, parameters, and technical information used to perform the criticality FEPs screening analysis.

4.1.1 Data

The following data were utilized in the development of this analysis. Use of these data is justified as they come from qualified project sources and their application is compatible with their developed purpose and limitations.

4.1.1.1 Corrosion Rate Data for Stainless Steel Type 316

The corrosion rate for Stainless Steel Type 316 was used to determine the corrosion rate for Neutronit A978. The corrosion rates for Stainless Steel Type 316 are from DTN: MO0401SPAMCRAE.000 ([DIRS 166801]). The Stainless Steel Type 316 corrosion rates based on J-13 well water are used to represent the corrosion rate of Neutronit A978. However, the corrosion rate for Neutronit A978 can be greater than Stainless Steel Type 316 because of the boron added; therefore, the corrosion rate will be enhanced by a factor of 1.5 (see Assumption 5.2.3). The corrosion rate data listed in Table 4.1-1, along with the corrosion rate data multiplied by the enhancement factor of 1.5, was used to fit a Weibull distribution. These data are used in Attachment V.

Table 4.1-1. Stainless Steel Type 316 Corrosion Rate Data and 1.5 Times the Corrosion Rate

SS Type 316 Corrosion Rates ^a ($\mu\text{m}/\text{yr}$)	1.5 times Stainless Steel Type 316 Corrosion Rates ($\mu\text{m}/\text{yr}$)
0.037	0.055
0.102	0.153
0.109	0.164
0.152	0.228
0.154	0.231
0.178	0.267
0.203	0.305
0.229	0.344
0.229	0.344
0.254	0.381
0.254	0.381
0.254	0.381
0.279	0.419

Source: ^a DTN: MO0401SPAMCRAE.000 ([DIRS 166801]), aqueous-316L.xls

4.1.2 Parameters

The following parameters were used to develop this analysis. Use of these parameters is justified because they come from qualified project sources and their application is compatible with their developed purpose and limitations.

4.1.2.1 Configuration Generator Model

This report utilizes the configuration generator model from *Configuration Generator Model for In-Package Criticality* (BSC 2003 [DIRS 165629], Attachment XII) to perform event tree / fault tree probability evaluations to support the criticality FEPs screening analysis. Information and parameters necessary to define the configuration generator model inputs are presented throughout Section 4.1. The configuration generator model inputs are developed and evaluated in Sections 6.3 through 6.5. Documentation of the configuration generator model used in the criticality FEPs screening analysis is provided in Section 6.2 and Attachment II.

4.1.2.2 Seepage Rate Information

The seepage rate is determined from the inputs discussed in the *Abstraction of Drift Seepage* (BSC 2003 [DIRS 165564], Section 6.7.1). The seepage flux is a function of three parameters: capillary strength (l/α) permeability (k), and adjusted percolation flux ($q_{perc,ff}$). The values for each these parameters will be discussed.

Capillary strength (l/α) is developed into two separate distributions, one to account for spatial variability and the second to account for uncertainty. The spatial variability follows a uniform distribution with a mean of 591 Pa, a lower bound of 402 Pa, and an upper bound of 780 Pa. The uncertainty ($\Delta l/\alpha$) is represented by a triangular distribution with a mean of 0.0 Pa, a lower bound of -105 Pa, and an upper bound of 105 Pa. These distributions are applicable for all geologic repository zones.

Permeability (k) is developed into two separate distributions, one to account for spatial variability and the other to account for uncertainty. The spatial variability for permeability was statistically analyzed using log-transformed data and found to follow a lognormal distribution (in log 10) (BSC 2003 [DIRS 165564], Section 6.6.2.1). The uncertainty (Δk) follows a triangular distribution. Depending on the geologic repository zone, there are different values for the lognormal distribution and the triangular distribution.

Lithophysal zone:

Lognormal distribution mean is -11.5 and standard deviation is 0.47 (in log 10).

Triangular distribution mean is 0.0, lower bound is -0.92, and upper bound is 0.92.

Nonlithophysal zone:

Lognormal distribution mean is -12.2 and standard deviation is 0.34 (in log 10).

Triangular distribution mean is 0.0, lower bound is -0.68, and upper bound is 0.68.

The percolation flux for the glacial transition climate used in this analysis is from DTN: LB0310AMRU0120.002 ([DIRS 166116]) and is based on the percolation in the repository area only (BSC 2003 [DIRS 165564], Figure 6.6-10). The percolation flux for the

glacial transition climate is described using three different scenarios (i.e., lower-bound, mean, and upper-bound), which are used in this analysis. The probability associated with the three different percolation flux scenarios are 0.24, 0.41, and 0.35 for the lower-bound, mean, and upper-bound, respectively (BSC 2003 [DIRS 165991], Section 7, Table 7-1). These probabilities are based on the glacial transition climate excluding the contingency area.

The final input for determining the seepage rate at the drift is the seepage rates, which are developed from lookup tables based on the three key parameters discussed above. The seepage rates are obtained through interpolation given a capillary strength (l/α), permeability (k), and adjusted percolation flux ($q_{perc,ff}$). The seepage rates are from DTN: LB0304SMDCREV2.002 ([DIRS 163687]) for nondegraded drifts and DTN: LB0307SEEPDRCL.002 ([DIRS 164337]) for degraded drifts. The seepage rates are adjusted to account for uncertainty, which follows a uniform distribution with a mean of 0.0, and lower-bound and upper-bound values of -1.7321 and 1.7321, respectively.

This information is used in Section 6.4.1.1.1 and Attachment IV.

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

The range of mean annual seismic exceedance frequencies is based on DTN: MO0308SPACALSS.002 [DIRS 164822], which follows a uniform distribution. The mean annual seismic exceedance frequency ranges from 10^{-8} to 10^{-4} per year. The time of occurrence of a seismic event ranges from repository closure to the performance period. This range is uniformly distributed from 1 year to 10,000 years (DTN: MO0308SPACALSS.002 [DIRS 164822]). This information is used in Section 6.4.1.1 and Attachment III.

4.1.2.4 Seismic Peak Ground Velocity

The horizontal peak ground velocity (PGV) is related to the mean annual seismic exceedance frequency. This relationship was developed in *Seismic Consequence Abstraction* (BSC 2003 [DIRS 161812], Section 6.4). The relationship between the PGV values and the mean annual seismic exceedance frequency was developed by scaling the PGV values at the monitored geologic repository (MGR) surface down to the drift. Based on this relationship scaled to the drift, the PGV values and their related mean annual seismic exceedance frequencies are listed in Table 4.1-2 (DTN: MO0308SPACALSS.002 [DIRS 164822]). This information is used in Section 6.4.1.1 and Attachment III.

Table 4.1-2. Mean Annual Exceedance Frequency and Corresponding Peak Ground Velocity

Mean Annual Exceedance Frequency (1/yr)	Peak Ground Velocity (m/s)
6.26×10^{-4}	0.159
2.78×10^{-4}	0.239
9.30×10^{-5}	0.398
1.84×10^{-5}	0.796
3.07×10^{-6}	1.59
2.28×10^{-7}	3.98
8.15×10^{-8}	5.57
2.60×10^{-8}	7.96
6.56×10^{-9}	11.9

Source: DTN: MO0308SPACALSS.002 [DIRS 164822]

4.1.2.5 Drip Shield Failure from Seismic Event

Damage to the drip shield can occur due to vibratory ground motion, which has the potential to allow advective flow to reach the waste package. The percent damaged area to the drip shield from a seismic event follows a uniform distribution. The lower bound of the uniform distribution for the percent damaged area is based on linear interpolation below a PGV value of 5.35 m/s and linear extrapolation for PGV values above 5.35 m/s. The lower bound values are shown in Table 4.1-3 (DTN: MO0308SPACALSS.002 [DIRS 164822]).

Table 4.1-3. Lower-Bound Percent Damaged Area to Drip Shield Due to Seismic Event

PGV Value (m/s)	Damaged Area to Drip Shield (percent)
0.00	0.0
2.44	0.0
5.35	10.0

Source: DTN: MO0308SPACALSS.002 [DIRS 164822]

The upper bound of the uniform distribution is also correlated to the PGV value. Table 4.1-4 provides the upper-bound percent damaged area of the drip shield based on PGV value. The upper-bound value can be interpolated for PGV values not directly listed. The input values (DTN: MO0308SPACALSS.002 [DIRS 164822]) are listed in Table 4.1-4.

Table 4.1-4. Upper-Bound Percent Damaged Area to Drip Shield Due to Seismic Event

PGV Value (m/s)	Damaged Area to Drip Shield (percent)
0.00	0.00
0.535	0.00
2.44	2.68
5.35	50.0
20.0	50.0

Source: DTN: MO0308SPACALSS.002 [DIRS 164822]

This information is used in Section 6.4.1.1 and Attachment III.

4.1.2.6 Drip Shield Failure from Seismically Induced Rockfall

Damage to a drip shield from seismically induced rockfall uses a log triangular distribution. The minimum percent damaged area of the drip shield is 0.001 and the maximum percent damaged area of the drip shield is 100 (DTN: MO0308SPACALSS.002 [DIRS 164822]). This information is used in Section 6.4.1.1 and Attachment III.

4.1.2.7 Waste Package Failure

Damage to the waste package can occur due to vibratory ground motion, which can allow the infiltration of advective flow. The percent damaged area to the waste package from a seismic event follows a uniform distribution. The minimum percent damaged area is 0.0 (DTN: MO0308SPACALSS.002) [DIRS 164822]. The upper bound of the uniform distribution for the percent damaged area of the waste package is correlated to the PGV value. This information is used in Section 6.4.1.1 and Attachment III.

4.1.2.8 Waste Package and Drip Shield Fabrication Error Probabilities

Waste package and drip shield fabrication and closure process error probabilities have been obtained from *Analysis of Mechanisms for Early Waste Package/Drip Shield Failure* (BSC 2003 [DIRS 164475]). The waste package and drip shield fabrication and closure process error probabilities used in this analysis are presented in Table 4.1-5 and have been obtained from Table 20 of *Analysis of Mechanisms for Early Waste Package/Drip Shield Failure* (BSC 2003 [DIRS 164475]).

The waste package information of Table 4.1-5 is used in Section 6.3.3.3.4 and the drip shield information is used in Section 6.3.3.2.5.

Table 4.1-5. Defect Types to Consider for Waste Package and Drip Shield Performance

Waste Package Defect Type	Evaluation of Probability per Waste Package
Weld flaws	See Table 11 thru Table 13 of BSC 2003 [DIRS 164475]
Improper heat treatment grouped with improper laser peening and waste package damaged by mishandling	Lognormal distribution: Median = 7.2×10^{-6} per waste package Mean = 2.8×10^{-5} per waste package error factor = 15 upper truncation value = 7.44213×10^{-3} per waste package
Drip Shield Defect Type	Main Characteristics
Weld flaws	Mean number of flaws: 4.1 per drip shield Mean size of flaw: 1.3 mm
Base metal flaws	See Table 18 of BSC 2003 [DIRS 164475]
Improper heat treatment	Mean probability: 1.3×10^{-5} per drip shield
Damage by mishandling	Mean probability: 4.8×10^{-7} per drip shield

Source: BSC 2003 [DIRS 164475], Table 20

It should be noted that one of the recommendations for modeling waste package damage due to improper heat treatment (grouped with improper laser peening and waste package damaged by mishandling) is to consider the entire waste package surface to be affected (BSC 2003 [DIRS 164475], Section 6.4.8). This information is used in Section 6.3.3.3.4.

Additionally, drip shield emplacement errors are calculated to be probable (BSC 2003 [DIRS 164475, Section 6.3.7), but do not result in an advective flow path through the drip shield and onto the waste package (BSC 2003 [DIRS 164475, Section 6.4.7). This information is used in Section 6.3.3.2.4.

4.1.2.9 Emplacement Drift Information

Emplacement drift information is required to perform the criticality rockfall disruptive event FEPs analysis (Section 6.5), as it is important to account for the total number of drip shields available and how many drip shields are emplaced in the two geological zones – lithophysal and nonlithophysal. The total number of drip shields to be emplaced can be estimated by dividing the total emplacement drift length by the average length of a drip shield. The lithophysal and nonlithophysal fractional areas can be calculated by dividing the emplacement drift area of both geological zones by the total drift area.

The total emplacement drift length can be calculated by summing the subtotals of the available emplacement drift lengths of each of the four panels presented in Tables 4 through 7 of *RDP/PA IED Subsurface Facilities* (BSC 2003 [DIRS 164490]). This information is summarized in Table 4.1-6 and the results used in Section 6.5.1. The drift emplacement area by geological unit is found in Table 9 of *Repository Design Project, Repository/PA IED Subsurface Facilities* IED (BSC 2003 [DIRS 164491]). This information is summarized in Table 4.1-7 and the results used in Sections 6.2 and 6.5.1.

Table 4.1-6. Available Emplacement Drift Length

Panel Number	Available Emplacement Drift Length (meters)	Reference
1	4,092	BSC 2003 [DIRS 164490], Table 4
2	18,850	BSC 2003 [DIRS 164490], Table 5
3	24,000	BSC 2003 [DIRS 164490], Table 6
4	17,003	BSC 2003 [DIRS 164490], Table 7
TOTAL	63,945	sum of rows 1 through 4

Source: BSC 2003 [DIRS 164490], Tables 4 through 7

Table 4.1-7. Drift Emplacement Area by Geological Unit

Geological Unit	Drift Emplacement Area (square meters)	Reference
Tptpul (lithophysal)	224,398	BSC 2003 [DIRS 164491], Table 9
Tptpmn (nonlithophysal)	616,003	BSC 2003 [DIRS 164491], Table 9
Tptpll (lithophysal)	4,013,268	BSC 2003 [DIRS 164491], Table 9
Tptpln (nonlithophysal)	129,483	BSC 2003 [DIRS 164491], Table 9
Total Lithophysal	4,237,666	sum of rows 1 and 3
Total Nonlithophysal	745,486	sum of rows 2 and 4
TOTAL	4,983,152	sum of rows 5 and 6

Source: BSC 2003 [DIRS 164491], Table 9

The average drip shield length is given as 5,805 mm (5.805 m) in *D&E / PA/C IED Interlocking Drip Shield and Emplacement Pallet* (BSC 2004 [DIRS 167309], Table 1). This value is used in Section 6.5.1.

4.1.2.10 Waste Package Population

Table 4.1-8 presents the percent breakdown of waste package by type for 70,000 metric tons of heavy metal (MTHM) currently proposed for disposal in the MGR. This information is obtained from *D&E/PA/C IED Typical Waste Package Components Assembly* (BSC 2004 [DIRS 167207], Table 11). It is used in Attachment II as the basis for the assignment of the basic event values for the waste form and waste package type fractions of event tree “WP_TYPE”.

Table 4.1-8. Breakdown of 70,000 MTHM Emplacement Inventory by Waste Package Type

Waste Package Design	Nominal Waste Package Inventory for LA	Nominal Waste Package Inventory for LA (%)
21-PWR with Absorber Plates	4299	38.4
21-PWR with Control Rods	95	0.8
12-PWR Long	163	1.5
44-BWR	2831	25.3
24-BWR	84	0.8
5-DHLW/DOE SNF Short (nonnaval spent nuclear fuel)	1147	10.3
5-DHLW/DOE SNF Long (nonnaval spent nuclear fuel)	2116 ^a	18.9
2-MCO/2-DHLW Long	149	1.3
Naval SNF Short	144	1.3
Naval SNF Long	156	1.4
Total	11184	100.0

Note: ^a includes waste package quantity for "5 HLW Long/1 DOE SNF Short" (31) and "5 HLW Long Only" (679) waste package configurations

Source: BSC 2004 [DIRS 167207, Table 11

4.1.2.11 Configuration Generator Model Input Parameters

Table 4.1-9 documents the input sources for the basic event input values used in the SAPHIRE probability calculations.

Table 4.1-9. Configuration Generator Model Input Sources

Event Tree Top Events	Basic Event Input Parameter	Reference Document(s)	Section Used
Sufficient water reaches drift MS-IC-1	Minimum seepage rate	<ul style="list-style-type: none"> • <i>Abstraction of Drift Seepage</i> (BSC 2003 [DIRS 165564], Section 6.7.1 and Figure 6.6-10) • <i>Analysis of Infiltration Uncertainty</i> (BSC 2003 [DIRS 165991], Section 7, Table 7-1) 	Sections 6.3, 6.4, and 6.5
Drip shield barrier penetration MS-IC-2	Drip shield failure due to stress corrosion cracking	<ul style="list-style-type: none"> • <i>Stress Corrosion Cracking of the Drip Shield, the Waste Package Outer Barrier, and the Stainless Steel Structural Material</i> (BSC 2003 [DIRS 161234], Section 6.3.7) 	Sections 6.3, 6.4, and 6.5
	Drip shield failure due to pitting and crevice corrosion	<ul style="list-style-type: none"> • <i>General Corrosion and Localized Corrosion of the Drip Shield</i> (BSC 2003 [DIRS 161236], Section 6.4.3) 	
	Drip shield failure due to emplacement error	<ul style="list-style-type: none"> • <i>Analysis of Mechanisms for Early Waste Package/Drip Shield Failure</i>, (BSC 2003 [DIRS 164475], Sections 6.3.7 and 6.4.7) 	
	Drip shield failure due to fabrication errors	<ul style="list-style-type: none"> • <i>Analysis of Mechanisms for Early Waste Package/Drip Shield Failure</i>, (BSC 2003 [DIRS 164475], Tables 11, 13, and 20) 	
	Drip shield failure due to floor heave	<ul style="list-style-type: none"> • <i>Engineered Barrier System Features, Events, and Processes</i> (BSC 2003 [DIRS 166464], Section 6.2.30) 	
	Drip shield failure due to thermal expansion	<ul style="list-style-type: none"> • <i>EBS Radionuclide Transport Abstraction</i> (BSC 2003 [DIRS 166466], Section 6.3.1.3) 	
	Drip shield failure due to rockfall	<ul style="list-style-type: none"> • <i>Seismic Consequence Abstraction</i> (BSC 2003 [DIRS 161812], Sections 6.6.2 and 6.6.1.1) 	
	Drip shield failure due to a seismic event	<ul style="list-style-type: none"> • <i>Seismic Consequence Abstraction</i> (BSC 2003 [DIRS 161812], Section 6.6.3) 	
Waste package barrier penetration MS-IC-3	Waste package failure due to a seismic event	<ul style="list-style-type: none"> • <i>Seismic Consequence Abstraction</i> (BSC 2003 [DIRS 161812], Section 6.6.3) 	Sections 6.3, 6.4, and 6.5
	Waste package failure due to fabrication errors	<ul style="list-style-type: none"> • <i>Analysis of Mechanisms for Early Waste Package/Drip Shield Failure</i>, (BSC 2003 [DIRS 164475], Tables 18 and 20 and Section 6.4.8) • <i>WAPDEG Analysis of Waste Package and Drip Shield Degradation</i> (BSC 2003 [DIRS 161317], Tables 46 and 47) 	

4.1.2.12 Magma Composition Parameters

The average composition of magma predicted to enter the MGR drifts is provided in Table 4.1-10. This information is used as input to the MCNP calculations presented in Attachment VII. The information contained in Table 4.1-10 was obtained from Table 6 of *Characterize Eruptive Processes at Yucca Mountain, Nevada* (BSC 2003 [DIRS 166407]).

Table 4.1-10. Magma Composition Weight Percents

Mineral	Wt. %
SiO ₂	48.50
TiO ₂	1.93
Al ₂ O ₃	16.74
Fe ₂ O ₃	1.74
FeO	8.90
MnO	0.17
MgO	5.83
CaO	8.60
Na ₂ O	3.53
K ₂ O	1.84
P ₂ O ₅	1.22

Source: BSC 2003 [DIRS 166407], Table 6

4.1.3 Technical Information

The following technical information was utilized in the development of this analysis and is justified, since it comes from approved sources and its application is compatible with its developed purpose and limitations.

4.1.3.1 Regulatory Probability Criterion

The following criterion has been utilized in the screening analysis as the basis for excluding criticality FEPs from TSPA-LA evaluations on low probability. This criterion is also the basis for some of the project performance assessment criteria listed in Table 4.2-1. The regulatory probability criterion is cited from 10 CFR Part 63 [DIRS 156605].

10 CFR 63.114 Requirements for Performance Assessment

Any performance assessment used to demonstrate compliance with 63.113 must:

- (d) Consider only events that have at least one chance in 10,000 of occurring over 10,000 years.

The regulatory probability criterion is used for the criticality FEPs screening decisions in Section 6.8.

4.1.3.2 Technical Information Used to Determine Boron Loss in the Commercial SNF Waste Packages

Except for the information obtained from D'Agostino and Stephens (1986 [DIRS 160320]), the technical information listed in Table 4.1-11 is required to calculate the amount of boron in the waste packages containing Neutronit plates. The sources for the required parameters are noted in Table 4.1-11. This information is utilized in Section 6.4.1.1.1, Tables 6.4-3 through 6.4-6, and Attachment V.

The information obtained from D'Agostino and Stephens (1986 [DIRS 160320]) is utilized in Attachment V for the performance of a statistical test to determine the acceptability of the Weibull distribution's fit of the Neutronit corrosion information.

Table 4.1-11. Technical Information Used to Calculate Amount of Boron Still Remaining Inside the Commercial SNF Waste Packages

Variable(s)	Description	Value	Source)
ρ_{316}	Stainless Steel Type 316N Grade density	8.00 g/cm ³	ASM 1980 [DIRS 104317], p. 34, Table 12
AW	Atomic Weight of boron	10.811 g/mol	Parrington et al. 1996 [DIRS 103896], p. 63
b_{wf}	Boron content in Neutronit	0.75 - 0.99 wt%	ASTM A 887-89 [DIRS 154062], Table 1, Type 304B3
		1.00 - 1.24 wt%	ASTM A 887-89 [DIRS 154062], Table 1, Type 304B4
		1.50 - 1.74 wt%	ASTM A 887-89 [DIRS 154062], Table 1, Type 304B6
n and α	5% significance level α for \sqrt{n} *D Case 3	10	D'Agostino and Stephens 1986 [DIRS 160320], Table 4.18, p. 148
		20	
		50	
		∞	

4.1.3.3 External Criticality Information

The uranium loading per fuel assembly used in the external criticality evaluations is 0.469 MTU (Punatar 2001 [DIRS 155635], Table 3-1). This value is appropriate as it is representative of a commercial SNF assembly's uranium loading. This information is used in Section 6.3.2.

4.1.3.4 Magma Composition Information

The theoretical density of the minerals comprising the magma predicted to enter the MGR drifts is given in Table 4.1-12. Atomic information for the elemental constituents of the magma composition is presented in Table 4.1-13. Sources for water and SNF information used in the igneous MCNP calculations are provided in Table 4.1-14. The MCNP calculations support Section 6.6 and the calculation inputs and outputs are contained in Attachment VII.

Table 4.1-12. Magma Composition Theoretical Densities

Mineral	Theoretical Density (g/cc) ^b
SiO ₂	2.32
TiO ₂	3.84
Al ₂ O ₃	3.965
Fe ₂ O ₃	5.24
FeO	5.70
MnO	5.46
MgO	3.58
CaO	3.38
Na ₂ O	2.27
K ₂ O	2.32
P ₂ O ₅	2.39

Source: Weast 1985 [DIRS 111561], pages B-68 through B-161

Table 4.1-13. Elemental Composition of Magma with 0.5 Weight Percent Water

Element	Molar Mass (g/mol) ^a	MCNP ID ^b
H	1.01	1001.50C
O	16.00	8016.50C
Si	28.09	14000.50C
Al	26.98	13027.50C
Fe	55.85	26000.55C
Mg	24.31	12000.50C
Ca	40.08	20000.50C
Na	22.99	11023.50C
K	39.10	19000.50C
Ti	47.87	22000.50C
P	30.97	15031.50C
Mn	54.94	25055.50C
Total	NA	NA

Sources: ^a Parrington et al. 1996 [DIRS 103896]

^b Briesmeister 1997 [DIRS 103897], Appendix G

Table 4.1-14. MCNP Input Data for Criticality FEPs Igneous Evaluations

Parameter Description	Value(s)	Units	Source of Value(s)
Fuel pellet radius	0.47	cm	DOE 1987 [DIRS 132333], p. 2A-34
Fuel pellet length	1.1	cm	DOE 1987 [DIRS 132333], p. 2A-34
Molar mass of U-235 U-238 O-16	235.043922 238.050785 15.9949146	g/mol	Parrington et al. 1996 [DIRS 103896]
Water theoretical density	1.0	g/cc	Batchelor 1967 [DIRS 103289], p. 596

4.2 CRITERIA

This section lists the criteria and requirements addressed by this analysis report. Table 4.2-1 lists the applicable project requirements from *Project Requirements Document* (Canori and Leitner 2003 [DIRS 166275]). Tables 4.2-2 and 4.2-3 list the applicable *Yucca Mountain Review Plan* (NRC 2003 [DIRS 163274]) acceptance criteria. Section 7.4 presents how these criteria and requirements have been addressed in this analysis.

Table 4.2-1. Applicable Project Requirements

Requirement Number and Title	Requirement Text	Rationale for Requirement
PRD-002/T-015 ^a ; Requirements for Performance Assessment	For complete requirement text, see 10 CFR 63.114 [DIRS 156605]	Regulation 10 CFR 63.114 [DIRS 156605] specifies technical requirements to be used in a performance assessment to demonstrate compliance to 10 CFR 63.113. It includes requirements for calculations, including data related to site geology, hydrology, and geochemistry; the need to account for uncertainties and variabilities in model parameters; the need to consider alternative conceptual models; and technical bases for inclusion or exclusion of specific features, events, and processes (FEPs); deterioration or degradation processes of engineered barriers; and all the models used in the performance assessment. The Performance Assessment organization is responsible for developing and using TSPA calculations, methods, models, and processes that comply with the requirements of this section.
PRD-002/T-034 ^b ; Limits on Performance Assessments	For complete requirement text, see 10 CFR 63.342 [DIRS 156605]	This section states that the license applicant's performance assessments should not include very unlikely FEPs, defined as those that are estimated to have less than one chance in 10,000 of occurring within 10,000 years of disposal. Furthermore, this section states that the performance assessments need not evaluate the impacts of sequences of FEPs with a higher chance of occurrence if the results of the earlier performance assessments would not be changed significantly. The Performance Assessment organization is responsible for incorporating these limits on performance assessments into its analytical models, methods, and activities.
PRD-013/T-016 ^c ; DOE SNF Canister Criticality Potential Postclosure	The methodology defined in the <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]) shall be used to demonstrate acceptable criticality control for canisters and the waste packages in which they are disposed.	This requirement specifies the method by which acceptable criticality control is demonstrated for the canisters and the waste packages for postclosure.
PRD-013/T-023 ^d ; Naval SNF Canister Criticality Potential Postclosure	The methodology defined in the NNPP addendum (Mowbray 1999 [DIRS 149585]) to the <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]) shall be used to demonstrate acceptable criticality control for canisters and the waste packages in which they are disposed.	The methodology in the NNPP addendum demonstrates the method by which acceptable postclosure criticality control is demonstrated for the waste packages with NNPP canisters. NNPP is directly responsible for completing the postclosure in-package criticality analysis for naval SNF waste packages and supplying the results to DOE. NNPP will also provide the results of the fissile material loss from waste packages source term calculations to the DOE for any out-of-package criticality analyses that may be needed.
PRD-013/T-038 ^e ; Disposable Commercial-Origin DOE SNF Canister Criticality Potential Postclosure	The methodology defined in the <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]) shall be used to demonstrate acceptable criticality control for canisters and the waste packages in which they are disposed.	The methodology in the Topical Report demonstrates the method by which acceptable postclosure criticality control is demonstrated for canisters and waste packages in a repository.

Source: Canori and Leitner 2003 [DIRS 166275]

- NOTES: ^a Requirement basis is 10 CFR 63.114 and 63.113 [DIRS 156605] & YMP-RD 3.3.4.19 (YMP 2001).
^b Requirement basis is 10 CFR 63.342 [DIRS 156605] (40 CFR 197.36 [DIRS 155238])
^c Requirement basis is WASRD 4.3.12.B (DOE 2002 [DIRS 158873])
^d Requirement basis is WASRD 4.4.13.B (DOE 2002 [DIRS 158873])
^e Requirement basis is WASRD 4.5.13.B (DOE 2002 [DIRS 158873])

Table 4.2-2. Acceptance Criteria for Scenario Identification and Screening

Acceptance Criteria Name	Description
<p>Acceptance Criterion 1: The Identification of a List of Features, Events, and Processes Is Adequate</p>	<p>(1)The Safety Analysis Report contains a complete list of features, events and processes, related to the geologic setting or the degradation, deterioration, or alteration of engineered barriers (including those processes that would affect the performance of natural barriers) that have the potential to influence repository performance. The list is consistent with the site characterization data. Moreover, the comprehensive features, events, and processes list includes, but is not limited to, potentially disruptive events related to igneous activity (extrusive and intrusive); seismic shaking (high-frequency-low-magnitude, and rare large-magnitude events); tectonic evolution (slip on existing faults and formation of new faults); climatic change (change to pluvial conditions); and criticality.</p>
<p>Acceptance Criterion 2: Screening of the List of Features, Events, and Processes Is Appropriate</p>	<p>(1) The U.S. Department of Energy has identified all features, events, and processes related to either the geologic setting or to the degradation, deterioration, or alteration of engineered barriers (including those processes that would affect the performance of natural barriers) that have been excluded;</p> <p>(2) The U.S. Department of Energy has provided justification for those features, events, and processes that have been excluded. An acceptable justification for excluding features, events, and processes is that either the feature, event, and process is specifically excluded by regulation; probability of the feature, event, and process (generally an event) falls below the regulatory criterion; or omission of the feature, event, and process does not significantly change the magnitude and time of the resulting radiological exposures to the reasonably maximally exposed individual, or radionuclide releases to the accessible environment; and</p> <p>(3) The U.S. Department of Energy has provided an adequate technical basis for each feature, event, and process, excluded from the performance assessment, to support the conclusion that either the feature, event, or process is specifically excluded by regulation; the probability of the feature, event, and process falls below the regulatory criterion; or omission of the feature, event, and process does not significantly change the magnitude and time of the resulting radiological exposures to the reasonably maximally exposed individual, or radionuclide releases to the accessible environment.</p>

Source: NRC 2003 [DIRS 163274], Section 2.2.1.2.1.3

Table 4.2-3. Acceptance Criteria for Uncertainty in Event Probability

Acceptance Criterion Number and Title	Description
<p>Acceptance Criterion 1: Events Are Adequately Defined</p>	<p>(1) Events or event classes are defined without ambiguity and used consistently in probability models, such that probabilities for each event or event class are estimated separately; and</p> <p>(2) Probabilities of intrusive and extrusive igneous events are calculated separately. Definitions of faulting and earthquakes are derived from the historical record, paleoseismic studies, or geological analyses. Criticality events are calculated separately by location.</p>
<p>Acceptance Criterion 2: Probability Estimates for Future Events Are Supported by Appropriate Technical Bases</p>	<p>(1) Probabilities for future natural events have considered past patterns of the natural events in the Yucca Mountain region, considering the likely future conditions and interactions of the natural and engineered repository system. These probability estimates have specifically included igneous events, faulting and seismic events, and criticality events.</p>
<p>Acceptance Criterion 3: Probability Model Support Is Adequate</p>	<p>(1) Probability models are justified through comparison with output from detailed process level models and/or empirical observations (e.g., laboratory testing, field measurements, or natural analogs, including Yucca Mountain site data). Specifically:</p> <p>(a) For infrequent events, the U.S. Department of Energy justifies, to the extent appropriate, proposed probability models with data from reasonably analogous systems. Analog systems should contain significantly more events than the Yucca Mountain system, to provide reasonable evaluations of probability model performance;</p> <p>(b) The U.S. Department of Energy justifies, to the extent appropriate, the ability of probability models to produce results consistent with the timing and characteristics (e.g., location and magnitude) of successive past events in the Yucca Mountain system; and</p> <p>(c) The U.S. Department of Energy probability models for natural events use underlying geologic bases (e.g., tectonic models) that are consistent with other relevant features, events, and processes evaluated, using Section 2.2.1.2.1.</p>
<p>Acceptance Criterion 4: Probability Model Parameters Have Been Adequately Established</p>	<p>(1) Parameters used in probability models are technically justified and documented by the U.S. Department of Energy. Specifically:</p> <p>(a) Parameters for probability models are constrained by data from the Yucca Mountain region and engineered repository system to the extent practical;</p> <p>(b) The U.S. Department of Energy appropriately establishes reasonable and consistent correlations between parameters; and</p> <p>(c) Where sufficient data do not exist, the definition of parameter values and conceptual models is based on appropriate use of other sources, such as expert elicitation conducted in accordance with appropriate guidance.</p>
<p>Acceptance Criterion 5: Uncertainty in Event Probability Is Adequately Evaluated</p>	<p>(1) Probability values appropriately reflect uncertainties. Specifically:</p> <p>(a) The U.S. Department of Energy provides a technical basis for probability values used, and the values account for the uncertainty in the probability estimates; and</p> <p>(b) The uncertainty for reported probability values adequately reflects the influence of parameter uncertainty on the range of model results (i.e., precision) and the model uncertainty, as it affects the timing and magnitude of past events (i.e., accuracy).</p>

Source: NRC 2003 [DIRS 163274], Section 2.2.1.2.2.3

4.3 CODES AND STANDARDS

The following codes have been cited in this analysis:

- 40 CFR 197 [DIRS 155238]. 2001. *Protection of Environment: Public Health and Environmental Radiation Protection Standards for Yucca Mountain, Nevada.*
- 10 CFR 63 [DIRS 156605]. Energy: *Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada.*

The following standards are applicable to criticality FEPs screening evaluations for the repository:

- ASM 1980 [DIRS 104317]. *Properties and Selection: Stainless Steels, Tool Materials and Special-Purpose Metals.* Volume 3 of *Metals Handbook.*
- ASTM A 887-89 [DIRS 154062] (Reapproved 2000) 2000. *Standard Specification for Borated Stainless Steel Plate, Sheet, and Strip for Nuclear Application.*

5. ASSUMPTIONS

5.1 GENERAL CRITICALITY FEPS ANALYSIS ASSUMPTIONS

5.1.1 No Waste Package Corrosion Failures

Assumption: It is assumed that the TSPA-LA results will show that there are no corrosion failures of the waste package before 10,000 years.

Rationale: Based on results from *WAPDEG Analysis of Waste Package and Drip Shield Degradation* (CRWMS M&O 2000 [DIRS 151566], Section 6.5.1 and BSC 2003 [DIRS 161317], Section 6.6.2, Figures 36, 37 and 48), the earliest failure due to waste package corrosion mechanisms (general corrosion, stress corrosion cracking, and localized corrosion) was beyond the 10,000-year performance period. However, these results cannot be referenced as they require confirmation by TSPA-LA (BSC 2003 [DIRS 161317], Section 1). If the environmental conditions of the TSPA-LA analysis do not exclude corrosion of the waste package, the probability evaluations of the criticality FEPs must be updated to account for the increased waste package damage area resulting from these failure mechanisms.

Confirmation Status: Confirmation of this assumption will be required when the waste package corrosion failure results from the TSPA-LA are available.

Use in the Analysis: This assumption is used in Sections 6.3.3 and 7.3.2.

5.1.2 Boron Loss in Commercial SNF Waste Packages

Assumption: It is assumed that the updated commercial SNF waste package design parameters will result in similar boron loss probability results as the previous design parameters.

Rationale: *Repository Design Project, RDP/PA IED Typical Waste Package Components Assembly (2)* (BSC 2003 [DIRS 163855]) has been superseded by *D&E/PA/C IED Typical Waste Package Components Assembly* (BSC 2004 [DIRS 167207]). However, *D&E/PA/C IED Typical Waste Package Components Assembly* (BSC 2004 [DIRS 167207]) does not contain the necessary information required to update the product output as utilized from DTN: MO0210MWDEXC01.008 ([DIRS 163531]), which is generated by *Boron Loss from CSNF Waste Packages* (BSC 2003 [DIRS 165890]). Revisions of the information obtained from *Boron Loss from CSNF Waste Packages* (BSC 2003 [DIRS 165890]) are necessary based on the updated information that is provided in *D&E/PA/C IED Typical Waste Package Components Assembly* (BSC 2004 [DIRS 167207]). Once *D&E/PA/C IED Typical Waste Package Components Assembly* (BSC 2004 [DIRS 167207]) is revised to incorporate the required information, a future revision of this analysis will reflect this new information.

The parameters listed in Table 5.1-1 reflect the previous waste package design and are used in this analysis to determine the amount of boron remaining in the waste packages containing Neutronit plates during degradation. The sources for the required parameters are noted in Table 5.1-1.

Table 5.1-1. Parameters Used to Calculate Amount of Boron Still Remaining Inside the Commercial SNF Waste Packages

Variable(s)	Description	Value	Source
21-PWR Absorber Plate Waste Package (Parameters used in Section 6.4.1.1.1, Table 6.4-3)			
SA	Surface area of Neutronit Plates	5.29E+05 cm ²	DTN: MO0210MWDEXC01.008 [DIRS 163531], spreadsheet "CSNF WP Model Abstraction.xls", sheet "Volumes and Surface Areas"
Vr	Void Volume of waste package	4,685 L	DTN: MO0210MWDEXC01.008 [DIRS 163531], spreadsheet "CSNF WP Model Abstraction.xls", sheet "Volumes and Surface Areas", referred to as "normalization factor" and "liters of void volume"
Fuel Basket A-Plate	8 plates per waste package	85,000 g	BSC 2003 [DIRS 163855], Table 2
Fuel Basket B-Plate	8 plates per waste package	85,000 g	
Fuel Basket C-Plate	16 plates per waste package	44,000 g	
12-PWR Absorber Plate Waste Package (Parameters used in Section 6.4.1.1.1, Table 6.4-4)			
SA	Surface area of Neutronit Plates	3.19E+05 cm ²	DTN: MO0309SPABRNAM.001 [DIRS 165892], spreadsheet "12 PWR Long WP.xls", sheet "Volumes and Surface Areas"
Vr	Void Volume of waste package	3,280 L	DTN: MO0309SPABRNAM.001 [DIRS 165892], spreadsheet "12 PWR Long WP.xls", sheet "Volumes and Surface Areas"
Fuel Basket A-Plate	4 plates per waste package	76,000 g	BSC 2003 [DIRS 163855], Table 8
Fuel Basket B-Plate	4 plates per waste package	76,000 g	
Fuel Basket C-Plate	16 plates per waste package	34,000 g	
44-BWR Absorber Plate Waste Package (Parameters used in Section 6.4.1.1.1, Table 6.4-5)			
SA	Surface area of Neutronit Plates	9.55E+05 cm ²	DTN: MO0309SPABRNAM.001 [DIRS 165892], spreadsheet "44 BWR WP.xls", sheet "Volumes and Surface Areas"
Vr	Void Volume of waste package	4,850 L	DTN: MO0309SPABRNAM.001 [DIRS 165892], spreadsheet "44 BWR WP.xls", sheet "Volumes and Surface Areas"
Fuel Basket A-Plate	4 plates per waste package	63,000 g	BSC 2003 [DIRS 163855], Table 3
Fuel Basket B-Plate	4 plates per waste package	63,000 g	
Fuel Basket C-Plate	16 plates per waste package	15,000 g	
Fuel Basket D-Plate	16 plates per waste package	44,000 g	
Fuel Basket E-Plate	16 plates per waste package	44,000 g	
24-BWR Absorber Plate Waste Package (Parameters used in Section 6.4.1.1.1, Table 6.4-6)			
SA	Surface area of Neutronit Plates	6.93E+05 cm ²	DTN: MO0309SPABRNAM.001 [DIRS 165892], spreadsheet "24 BWR WP.xls", sheet "Volumes and Surface Areas"
Vr	Void Volume of waste package	2,700 L	DTN: MO0309SPABRNAM.001 [DIRS 165892], spreadsheet "24 BWR WP.xls", sheet "Volumes and Surface Areas"
Fuel Basket A-Plate	4 plates per waste package	89,000 g	BSC 2003 [DIRS 163855], Table 9
Fuel Basket B-Plate	4 plates per waste package	89,000 g	
Fuel Basket C-Plate	8 plates per waste package	90,000 g	
Fuel Basket D-Plate	8 plates per waste package	90,000 g	
Fuel Basket E-Plate	16 plates per waste package	30,000 g	

Confirmation Status: Confirmation of this assumption will be required once *D&E/PA/C IED Typical Waste Package Components Assembly* (BSC 2004 [DIRS 167207]) is revised to incorporate the required waste package design information.

Use in the Analysis: This information is used in Tables 6.4-3 through 6.4-6 of Section 6.4.1.1.1 and Attachment III.

5.1.3 Waste Packages Emplaced As Designed

Assumption: It is assumed that the initial neutron absorber material mass and location and the waste package internal structural capabilities are as-designed.

Rationale: This assumption is necessary to account for the possibility that, through human error either during manufacturing or waste package loading, the waste package internals placed in the waste package may not be as-designed. An example of these human errors include selecting a 21-PWR with Control Rods Waste Package for the insertion of commercial SNF intended to be placed into a 21-PWR with Absorber Plates Waste Package. This would result in the waste package basket containing no neutron absorber material. Although the possibility exists that the waste package will not be emplaced as designed, it is not possible at this time to assess the probability of its occurrence.

Confirmation Status: Removal of this assumption cannot occur until the probability that a waste package will be emplaced in a not as-designed condition is calculated. Performance of this calculation cannot occur until the manufacturing processes and surface facility procedures for selecting, loading, closing and emplacing the waste packages are established.

Use in the Analysis: This assumption is used in Sections 6.3.3 and 7.3.3.

5.1.4 Corrosion Rate of Neutronit A978 Neutron Absorber Material

Assumption: It is assumed that the corrosion rate of the Neutronit A978 neutron absorber material is not in excess of 1.5 times that of Stainless Steel Type 316.

Rationale: Although no numerical corrosion rates are presented in the literature available from the manufacturer of Neutronit A978 (Kügler 1997 [DIRS 134327]), the information that is available does state that Neutronit A976 has a corrosion resistance similar to Stainless Steel Type 321. However, the repository currently plans to utilize Neutronit A978 for the manufacturer of neutron absorber baskets in most commercial SNF waste packages (only the 21-PWR with Control Rods Waste Package does not contain Neutronit in its basket assembly design). Neutronit A978 is similar to a stainless steel type that contains molybdenum. Stainless steel alloys containing molybdenum, such as Stainless Steel Type 316, have a higher corrosion resistance than stainless steel types that do not contain molybdenum, such as Stainless Steel Type 321. It is reasonable to expect, therefore, that Neutronit A978 would have a corrosion rate similar to that of Stainless Steel Type 316. For uncertainty considerations, the stainless steel 316 corrosion rate is increased by 50 percent for use in Neutronit A978 degradation evaluations.

Confirmation Status: This assumption requires confirmation through testing.

Use in the Analysis: This assumption is used in Section 6.4.1, Section 7.3.4, and Attachment III.

5.1.5 Boron Loss from Waste Packages with Absorber Plates

Assumption: It is assumed that up to 90 percent of the boron can be removed from a degraded waste package with absorber plates containing typical PWR fuel assemblies without a criticality concern. It is further assumed that up to 50 percent of the boron can be removed from a degraded waste package with absorber plates containing typical BWR fuel assemblies without a criticality concern.

Rationale: Since the corrosion rate of the basket component materials not carrying boron (i.e., carbon steel) are greater than the material carrying boron (i.e., stainless steel), corrosion products will accumulate faster than boron is lost. These corrosion products will displace water (a neutron moderator) and reduce the criticality potential of the degraded waste package. The percentages are estimates based on preliminary scoping analyses of when the boron loss effect will exceed the corrosion product build-up effect. The difference in allowable boron loss rates between the PWR and BWR waste packages is due to the BWR SNF assemblies being disposed of with their channels. These channels inhibit the accumulation of corrosion products within the assembly matrix.

Confirmation Status: This assumption requires confirmation by analysis.

Use in the Analysis: This assumption is used in Section 6.4.1, Section 7.3.4, and Attachment III.

5.1.6 Degradation of Neutron Absorber Material in the 21-PWR with Control Rods Waste Package

Assumption: It is assumed that the neutron absorber material in the 21-PWR with Control Rods Waste Package will not degrade during the performance period.

Rationale: The 21-PWR with Control Rods Waste Package is designed for PWR commercial SNF having a higher assembly k_{∞} than is acceptable for placement in the 21-PWR with Absorber Plates Waste Package. The 21-PWR with Control Rods Waste Package uses zirconium clad, boron carbide (B_4C) control rods for reactivity control (CRWMS M&O 1997 [DIRS 100224], Section 7.3.2). These control rods are inserted into each assembly guide tube location. The zirconium cladding of the control rods is the same as the Zircaloy used for the manufacture of fuel rod cladding. Under normal conditions, Zircaloy-clad fuel rods will be intact beyond the performance period because Zircaloy cladding is highly resistant to corrosion (Hillner et al. 1998 [DIRS 100455], Abstract). Because the zirconium cladding of the control rods will be unirradiated and will be thicker than the fuel rod cladding, its durability and corrosion resistance is expected to be even greater than that of the Zircaloy cladding of the fuel rods. In addition, because the zirconium control rod cladding is thicker and because the controls are protected by the fuel assembly guide tubes, it is unlikely the control rod cladding will be damaged during seismic events. Therefore, it is assumed that the neutron absorber materials of the 21-PWR with Control Rods Waste Package cannot be flushed from the waste package during the performance period.

Confirmation Status: This assumption requires confirmation by analysis.

Use in the Analysis: This assumption is used in Sections 6.3.3, 6.4.1, 7.3.1, and 7.3.4.

5.1.7 Degradation of Neutron Absorber Material in the DOE SNF Waste Packages

Assumption: It is assumed that the loss rate of the neutron absorber material from the DOE standardized SNF canisters contained in the DOE SNF waste package types is no greater than that of the 21-PWR with Absorber Plates Waste Package.

Rationale: The current design of the DOE-standardized SNF canisters (e.g., CRWMS M&O 2000 [DIRS 151742] or CRWMS M&O 2000 [DIRS 147650]) is for the inclusion of neutron absorber materials contained in a material (Alloy 22) with long term performance characteristics (i.e., low corrosion rate) that are greater than that of the neutron absorber materials contained in the material (Stainless Steel Type 316) of the 21-PWR with Absorber Plates Waste Package (DTN: MO0401SPAMCRAE.000 [DIRS 166801]).

Confirmation Status: This assumption requires confirmation by analysis.

Use in the Analysis: This assumption is used in Sections 6.3.3, 7.3.1 and 7.3.4.

5.2 SEISMIC CRITICALITY FEPS ANALYSIS ASSUMPTIONS

5.2.1 Seismic Damage to Drip Shield and Waste Package

Assumption: It is assumed that all seismically induced damage is located on the top of the drip shield and waste package.

Rationale: Damage at the top of the drip shield and waste package allows advective flow to penetrate the waste package and create a bathtub configuration. Bathtub configurations are the most critical because commercial SNF assemblies are in a core-like geometry and, with no neutron absorber materials present, have near-ultimate neutron moderation. This assumption is conservative.

Confirmation Status: This assumption does not require further confirmation by testing, design, or analysis.

Use in the Analysis: This assumption is used in Sections 6.3.3 and 6.4.1.

5.2.2 Time of Water Ingress into a Damaged Waste Package

Assumption: It is assumed that water can not penetrate a damaged commercial SNF waste package prior to 700 years after closure of the repository.

Rationale: This assumption is used in order to determine the start of a time period for advective flow into a damaged commercial SNF waste package to degrade and flush out the Neutronit. Advective flow into a damaged waste package is assumed improbable prior to 700 years after repository closure due to the dryout of the drift from the thermal pulse (BSC 2003 [DIRS 166463], Table 6.3-5).

Confirmation Status: This assumption does not require further confirmation by testing, design, or analysis.

Use in the Analysis: This assumption is used in Section 6.3.2, Section 6.4.1 and Attachment III.

5.2.3 Major Assumptions in Supporting Calculations

The following are major assumptions that are listed in the supporting documents. A synopsis of the assumptions is listed here for brevity. For more detailed information, refer to the referenced document.

5.2.3.1 Supporting Assumptions used by *Seismic Consequence Abstraction* (BSC 2003 [DIRS 161812], Section 5)

The following assumptions from *Seismic Consequence Abstraction* (BSC 2003 [DIRS 161812], Section 5) are important to the development of the damaged area(s) of the drip shield and waste package along with calculations used in the seismic probability calculation.

- 1) The affected area(s) where the residual stress from mechanical damage exceeds the residual stress of the barrier is assumed to have failed as a barrier to flow and transport. The rationale is based on using this residual stress threshold as the failure criterion. This is a nonmechanistic criterion because detailed calculations of the actual rates of general corrosion, stress corrosion cracking, or localized corrosion are not being used to determine the actual failure time after a seismic event. Rather, it is acknowledged the potential exists for one or several of these processes to occur with such rapidity that the entire damaged area ceases to function as an effective barrier to flow and transport.
- 2) Seismic events occur in a random manner, following a Poisson process. The rationale for this assumption (the behavior of the earth is generally random [Poisson process]) is the underlying assumption in all probabilistic hazard analyses. In other words, all earthquakes are considered as independent events with regard to magnitude, time, and location. Although there may be cases where sufficient data and information exists to depart from this assumption, the Poisson process is generally an effective representation of nature and represents a compromise between the complexity of natural processes, availability of information, and sensitivity of results of engineering relevance.
- 3) No damage occurs to EBS components until the repository experiences ground motions larger than those for the 10^{-4} per year annual exceedance frequency. Damage to EBS components from vibratory ground motion is assumed to become nonzero between 10^{-4} and 10^{-5} per year annual exceedance frequencies. The rationale for this assumption is based on structural analyses performed at vibratory ground motions for an annual exceedance frequency of 5×10^{-4} per year. These results showed no residual stresses greater than the residual stress of the barriers. The confirmation of this assumption has an associated TBV (TBV-5106) (BSC 2003 [DIRS 161812], Section 5.1).
- 4) The fault displacement hazard curves for the Pagany Wash and Sevier Wash faults are identical to the fault displacement hazard curve for the Drill Hole Wash fault. The

rationale is based on: (1) the Drill Hole Wash fault provides the best field data for the three faults; (2) none of the faults suggest displacement in Quaternary alluvial terraces (the scale of the cumulative vertical displacement is less than 5 to 10 meters); (3) the total fault length is similar for the three faults; and (4) previous geologic studies have consolidated the three faults based on similar characteristics. Therefore, the three faults can be treated in a similar manner with regard to the potential seismic hazard.

- 5) The derivation of the mean dose formula is assumed to be a function of the time of occurrence and the amplitude of the PGV for the seismic hazard. The dose time histories for the reasonably maximally exposed individual at time (τ) from a seismic event occurring at a time (t) prior to τ depends only on the time of occurrence of the event and on PGV at the waste emplacement drifts associated with the seismic event. The rationale for this assumption is based on the simplification of the mathematical equation, which derives the mean dose calculation.
- 6) These supporting calculations include several major assumptions not directly used in the abstraction process, but noteworthy enough to deserve repeating here.
 - (a) The structural response calculations for the waste package and drip shield incorporate assumptions for structural thickness and for material properties for Alloy 22 and of Titanium Grade 7. The thicknesses of the drip shield plates and the waste package outer shell have been reduced by 2 mm in these calculations to represent the potential degradation of these structures by general corrosion over the first 10,000 years after repository closure. The material properties of Alloy 22 and of Titanium Grade 7 have been evaluated at an elevated temperature (150°C) that provides conservative values for mechanical properties over most (97 percent) of the 10,000-year duration.
 - (b) Rockfall calculations for the lithophysal and nonlithophysal zones also make several key assumptions. In the lithophysal zone, block size distribution is assumed to be a function of the inter-lithophysal fracture density and the lithophysae spacing. This assumption is relevant to the abstraction process because it limits the potential damage to the drip shield from tunnel collapse in the lithophysal zone, as discussed in Section 6.6.2 of *Seismic Consequence Abstraction* (BSC 2003 [DIRS 161812]).

5.2.3.2 Supporting Assumptions used by *Abstraction of Drift Seepage* (BSC 2003 [DIRS 165564], Section 5)

There are two primary assumptions listed in *Abstraction of Drift Seepage* (BSC 2003 [DIRS 165564], Section 5). These assumptions are important to the development of the seepage parameters used in the seepage development.

- 1) The first assumption discusses the capillary diversion depending upon the difference in capillary strength ($1/\alpha$) between the interior of the drift and the rock surrounding the drift. This assumption assumes capillary strength of the rubble rock material for a collapsed drift to be 100 Pa. The rationale for this assumption is based on the porosity of the rubble rock material being much greater than that of intact rock, because of the large voids between chunks of fragmented rock. The resulting capillary strength of the rubble-

filled drift is therefore, much weaker than that of the intact surrounding rock. The value of 100 Pa is therefore chosen as a conservative, nonzero value to represent the effective capillary strength of the rubble-filled drift with an air gap forming at the ceiling.

- 2) The second assumption discusses thermal-hydrological simulations for collapsed drifts requiring knowledge about the thermal hydraulic properties of the rubble rock material filling the drift. The thermal conductivity is set to that of air; the heat capacity is set to zero. The interface area between void continuum and the fragmented rock continuum, important for the fluid and heat exchange between the two media, is estimated from a simple geometry model, calculating the surface area of spherical rock blocks with a 0.1-m diameter. The contact area for flow and heat transport between individual rock fragments was assumed to follow two alternative cases. The two cases are a geometric interface area between grid elements reduced by a factor of $(1-0.231)$ where 0.231 refers to the volume fraction of the voids in the rubble material and one-half of this value.

Its rationale states that the thermal hydraulic properties of the lithophysal matrix rock are appropriate for the fragmented rock blocks, because they are formed from chunks of lithophysal matrix rock that fell into the drift. In addition, a sensitivity analysis was conducted with a one order of magnitude variation to permeability. That analysis demonstrated that the general conclusions for seepage abstraction are not affected by this parameter variation. The two cases showed similar results.

5.3 ROCKFALL CRITICALITY FEPS ANALYSIS ASSUMPTIONS

No additional assumptions are required to evaluate the rockfall disruptive event criticality FEP.

5.4 IGNEOUS CRITICALITY FEPS ANALYSIS ASSUMPTIONS

5.4.1 System for Igneous Event Commercial SNF Criticality Analyses

Assumption: It is assumed that the system modeled for an igneous event criticality is infinite. The waste form utilized is 5 weight percent enriched uranium-235 commercial SNF pellets and is surrounded by a cubic lattice of magma, which serves as the neutron moderator.

Rationale: This is a conservative approach because (1) an infinite system experiences zero neutron leakage; (2) 5 weight percent is the current upper limit for commercial SNF enrichment (BSC 2003 [DIRS 165732], Section 6); and (3) the fuel pellet is completely surrounded by a neutron moderator.

Confirmation Status: This assumption does not require confirmation by testing, design, or analysis.

Use in the Analysis: This assumption is used in Section 6.6.2.

5.4.2 Separation of Neutron Absorber Materials

Assumption: For commercial SNF, it is assumed that the fissile material becomes separated from the neutron absorber material following the destruction of the waste package by igneous

intrusion. This assumption will be utilized even though there is no identified mechanism during an igneous event by which this separation would occur.

Rationale: This is a conservative approach. The loss of the neutron absorber will increase the criticality potential (i.e., the neutron multiplication factor) of the system.

Confirmation Status: This assumption does not require confirmation by testing, design, or analysis.

Use in the Analysis: This assumption is used in Section 6.6.2.

5.4.3 System for Igneous Event DOE SNF Criticality Analyses

Assumption: It is assumed that configurations formed due to igneous events in or out of waste packages containing DOE SNF canisters will not result in the formation of critical systems.

Rationale: Igneous events will not result in critical configurations due to the limited magma moderation (less than 0.5 weight percent water), the less than optimum geometrical configurations that will be formed, and the mixing of neutron absorbers and fissile materials.

Confirmation Status: This assumption requires confirmation by analysis.

Use in the Analysis: This assumption is used in Sections 6.6.3 and 7.3.5.

5.4.4 Critical Limit for Igneous Event Criticality Analyses

Assumption: It is assumed that the critical limit for configurations formed due to igneous events in or out of commercial SNF waste packages is higher than 0.82.

Rationale: The lowest calculated k_{eff} value for the solution benchmark experiments evaluated in *Summary Report of Laboratory Critical Experiment Analyses Performed for the Disposal Criticality Analysis Methodology* (CRWMS M&O 1999 [DIRS 157731], Section 4.2) is higher than 0.96. Using appropriate benchmark experiments (mainly solution) for configurations formed due to igneous events and the methodology to be developed in the external criticality model report is expected to result in the calculation of a critical limit well above 0.82.

Confirmation Status: This assumption requires confirmation by analysis.

Use in the Analysis: This assumption is used in Sections 6.6.3 and 7.3.5.

5.4.5 UO₂ Density Used in Igneous Criticality Analyses

Assumption: It is assumed that the UO₂ density for MCNP calculations is 10.41 g/cc, which is 95 percent of the theoretical density of 10.96 g/cc (DTN: MO9906RIB00048.000 [DIRS 147618]).

Rationale: Using a UO₂ fractional density is common practice.

Confirmation Status: This assumption does not require further confirmation by testing, design, or analysis.

Use in the Analysis: This assumption is used in Section 6.6.2.

5.4.6 Magma Water Content

Assumption: It is assumed that the magma water content is 0.5 weight percent at a temperature of 1150°C.

Rationale: Magma water content is presented as an assumption in *Igneous Intrusion Impacts on Waste Package and Waste Form* (BSC 2003 [DIRS 165002], Section 5.1.2), and discussed in detail in *Characterize Eruptive Processes at Yucca Mountain, Nevada* (BSC 2003 [DIRS 166407], Section 6.3.2.2).

Confirmation Status: This assumption does not require further confirmation by testing, design, or analysis.

Use in the Analysis: This assumption is used in Section 6.6.2.

6. SCIENTIFIC ANALYSIS DISCUSSION

The following sections discuss the criticality FEPs analyses. Section 6.1 discusses the methods and approach used for the FEPs process as it applies to the criticality FEPs, as well as changes in the criticality FEPs from the TSPA-SR to the TSPA-LA FEPs list. Section 6.1 of this analysis report identifies the source of the criticality FEPs, describes the FEPs screening process, and provides documentation related to consideration of generic issues such as uncertainty, alternative conceptual models, and model and software issues. Section 6.2 discusses the SAPHIRE model used to establish the technical basis for the criticality FEPs screening, other than the FEPs related to igneous events which is presented in Section 6.6. The SAPHIRE model summarized in Section 6.2 was developed specifically for this purpose in *Configuration Generator Model for In-Package Criticality* (BSC 2003 [DIRS 165629]) and is consistent with the TSPA approach to satisfy the regulatory probability criterion and performance objectives. Additionally, these analyses are also appropriate because they address the NRC's acceptance criteria in *Yucca Mountain Review Plan* (NRC 2003 [DIRS 163274]) as previously discussed in Section 4.2, which are applicable to the FEPs discussions provided in Sections 6.3 through 6.8 of this analysis report. Section 6.3 provides the details and results of the base case criticality FEPs screening analysis. Section 6.4 provides the details and results of the seismic disruptive event criticality FEPs screening analysis. Section 6.5 provides the details and results of the rockfall disruptive event criticality FEPs screening analysis. Section 6.6 provides the details and results of the igneous disruptive event criticality FEPs screening analysis. Section 6.7 summarizes the results of Sections 6.3 through 6.6. Section 6.8 provides the screening discussions for the criticality FEPs.

6.1 SCIENTIFIC APPROACH AND TECHNICAL METHODS

The methods and approach for FEPs screening for TSPA-LA are provided in generic form in *The Enhanced Plan for Features, Events, and Processes (FEPs) at Yucca Mountain* (BSC 2002 [DIRS 158966]) and KTI Letter Report *Response to Additional Information Needs on TSPAI 2.05 and TSPAI 2.06* (Freeze 2003 [DIRS 165394]). The YMP has chosen to satisfy the regulatory probability criterion and performance objectives by adopting a FEP analysis and scenario development process. The first step of the FEP analysis process is the identification of the FEPs potentially relevant to the performance of the MGR. A review of FEPs analysis and scenario development in other radioactive waste disposal programs is provided in Section 2 of *The Enhanced Plan for Features, Events, and Processes (FEPs) at Yucca Mountain* (BSC 2002 [DIRS 158966]) and includes a discussion of alternative FEP identification lists and scenario development processes. Regardless of the specific approach chosen to perform the screening, the screening process is, in essence, a comparison of the FEP against the regulatory probability criterion and performance objectives specified in 10 CFR 63.114(d), (e), and (f) [DIRS 156605] regarding the inclusion or exclusion of FEPs into the TSPA-LA evaluation.

6.1.1 Criticality FEPs Origin and Identification

The development of a comprehensive list of FEPs potentially relevant to postclosure performance of the potential Yucca Mountain repository is an ongoing, iterative process based on site-specific information, design, and regulations. The approach for developing an initial list

of FEPs in support of TSPA-LA was documented in Freeze et al. (2001 [DIRS 154365]). The initial FEPs list contained 328 FEPs, of which 176 were included in TSPA-SR models (CRWMS M&O 2000 [DIRS 153246], Tables B-9 through B-17). Each FEP was assigned a unique YMP FEP database number, based on the Nuclear Energy Agency (NEA 1992 [DIRS 100479]) categories. The database number is the primary method for identifying FEPs, and consists of an eight-digit number having a format *x.x.xx.xx.xx*. A similar numbering system is used for the TSPA-LA FEPs list to provide a unique identifier for each FEP. In general, TSPA-SR FEPs with numbers ending in .00 were converted to TSPA-LA FEPs with numbers ending in “.0A”. New TSPA-LA FEPs (created when splitting TSPA-SR FEPs) are further designated with a sequential suffix (.0B, .0C, etc.) to ensure traceability.

Twenty-two of the TSPA-SR FEPs in the YMP FEPs database (Freeze et al. 2001 [DIRS 154365]) were identified as criticality related, two of which were redundant and subsequently deleted. The remaining 20 FEPs form the initial TSPA-LA criticality FEPs list. Table 6.1-1 lists the two deleted FEPs.

Table 6.1-1. Deleted Criticality FEPs per the Enhanced FEPs Plan

TSPA-SR FEP Number	TSPA-SR FEP Name	TSPA-SR FEP Description	Basis for Deletion From TSPA-LA
2.1.14.01.00	Criticality in waste and EBS	Nuclear criticality refers to a self-sustaining fission chain reaction that requires a sufficient concentration and localized (critical) mass of fissionable isotopes (e.g., U-235, Pu-239). Thermal criticality requires the additional presence of neutron-moderating materials (e.g., water) in a suitable geometry. Fast criticality can occur without moderator, but generally requires a much larger critical mass than thermal criticality. Criticality can be prevented by the presence of neutron absorbing elements (e.g., boron, gadolinium). Within the waste and EBS, a critical mass may occur within the waste package (in situ) or out of the waste package and in the drift (near-field). This FEP aggregates all mechanisms for in situ and near-field criticality into a single category. Specific processes that could produce criticality are discussed in FEPs 2.1.14.03.00 through 2.1.14.08.00 (for in situ) and in FEPs 2.1.14.09.00 through 2.1.14.14.00 (for out-of-container).	FEP Deleted. Redundant to other 2.1.14.0x.0A TSPA-LA FEPs.
2.2.14.01.00	Critical assembly forms away from repository	Nuclear criticality requires a sufficient concentration and localized (critical) mass of fissile isotopes (e.g., U-235, Pu-239) and also the presence of neutron-moderating materials (e.g., water) in a suitable geometry. Criticality is liable to be damped by the presence of neutron absorbing isotopes (e.g., Pu-240). Far-field criticality can occur if fissile material is transported away from the repository and then a critical mass accumulates in the presence of water. This FEP aggregates all mechanisms for far-field criticality into a single category. Specific processes that could produce far-field criticality are discussed in FEPs 2.2.14.02.00 through 2.2.14.08.00.	FEP Deleted. Redundant to other 2.1.14.0x.0A TSPA-LA FEPs.

Source: Freeze et al. 2001 [DIRS 154365], Appendix B

Additionally, the description of TSPA-SR FEP 2.1.14.14.00 was expanded for TSPA-LA to address multiple disruptive criticality initiating events (seismic, igneous, and rockfall). For TSPA-SR, this FEP only addressed an igneous initiating event. This change is shown in Table 6.1-2.

Table 6.1-2. Changes to the Criticality FEPs per the Enhanced FEPs Plan

TSPA-SR FEP Number	TSPA-SR FEP Name, and Description ^a	TSPA-LA FEP Number, Name, and Description	Basis of Change for TSPA-LA ^b
2.1.14.14.00	<p>Out-of-package criticality, fuel/magma mixture</p> <p>Interaction between fuel and magma dilutes fissile material, excludes water, and minimizes its return. For criticality to occur, neutron absorbers must also be removed.</p>	<p>2.1.14.14.0A – Criticality resulting from disruptive events</p> <p>Nuclear criticality refers to a self-sustaining fission chain reaction that requires sufficient concentration and localized (critical) mass of isotopes (e.g., U-235, Pu-239). This can include thermal criticality, which requires the additional presence of neutron-moderating materials (e.g., water) in a suitable geometry. Fast criticality can occur without moderator, but generally requires a much larger critical mass than thermal criticality. The repository will house a variety of nuclear waste types and configurations (e.g., CSNF and DSNF). A disruptive event such as seismic ground motion, rockfall, or igneous intrusion could lead to damaged packages and allow water (a moderator) to enter the packages. They could also lead to destruction of the internal configuration of the packages; release and distribution of the waste exterior to package; or in the case of an igneous intrusion drastically change the chemical environment and/or mix with the waste. Thereby, disruptive events could be a criticality initiating event.</p>	<p>This FEP was expanded to include all disruptive criticality initiating events, not just an igneous intrusion resulting in a fuel magma mixture.</p>

Source: ^a Freeze et al. 2001 [DIRS 154365], Appendix B

^b DTN: MO0307SEPFEPS4.000 [DIRS 164527]

An initial criticality FEPs list for TSPA-LA was then developed based on the deletion and expansion of individual FEPs as discussed above. The initial TSPA-LA criticality FEPs have been documented in *LA FEP List* (DTN: MO0307SEPFEPS4.000 [DIRS 164527]) and are listed in Table 6.1-3.

Table 6.1-3. Listing of TSPA-LA Criticality Features, Events, and Processes

FEP Number	FEP Name	FEP Description
2.1.14.02.0A	Criticality in situ, nominal configuration, top breach	The waste package internal structures and the waste form remain intact (nominal configuration). There is a breach near the top of the waste package, which allows water to collect in the waste package. Criticality then occurs in situ.
2.1.14.03.0A	Criticality in situ, WP internal structures degrade faster than waste form, top breach	The waste package internal structures degrade, but not the waste form. There is a breach near the top of the waste package, which allows standing water to collect in the waste package. Significant amounts of the neutron absorber are flushed out the top of the waste package and criticality occurs in situ.
2.1.14.04.0A	Criticality in situ, WP internal structures degrade at same rate as waste form, top breach	The waste package internal structures degrade at the same rate as the waste form. There is a breach near the top of the waste package, which allows water to collect in the waste package. Significant amounts of the neutron absorber are flushed out the top of the waste package. A slurry with insufficient neutron absorbing material forms at the waste package bottom and criticality occurs in situ.

Table 6.1-3. Listing of TSPA-LA Criticality Features, Events, and Processes (Continued)

FEP Number	FEP Name	FEP Description
2.1.14.05.0A	Criticality in situ, WP internal structures degrade slower than waste form, top breach	The waste package internal structures degrade slower than waste form. There is a breach near the top of the waste package, which allows water to collect in the waste package. The waste form degrades, separating from the neutron absorbers. A slurry forms at the waste package bottom and criticality occurs in situ.
2.1.14.06.0A	Criticality in situ, waste form degrades in place and swells, top breach	The waste package internal structures remain intact while the waste form degrades. There is a breach near the top of the waste package, which allows water to collect in the waste package. The waste form degrades in place, but swells into a more reactive configuration, which may overwhelm the in-place neutron absorbing material. Criticality occurs in situ.
2.1.14.07.0A	Criticality in situ, bottom breach allows flow through WP, fissile material collects at bottom of WP	There is a breach at the bottom of the waste package, which does not allow water to collect in the waste package. Moderation is provided by water retained in clay or hydrated metal corrosion products accumulating in the bottom of the waste package with the fissile material. Significant amounts of the neutron absorber are either flushed from the waste package or remain distributed throughout the waste package, while fissile material collects at bottom of the waste package. Criticality occurs in situ.
2.1.14.08.0A	Criticality in situ, bottom breach allows flow through WP, waste form degrades in place	There is a breach at the bottom of the waste package, which does not allow water to collect in the waste package. Moderation is provided by water trapped in the clay or oxides. The waste form degrades in place and the neutron absorbing material mobilizes away from the waste form. Criticality occurs in situ.
2.1.14.09.0A	Near-field criticality, fissile material deposited in near-field pond	Fissile material-bearing solution or intact fissile material is deposited in a near-field pond. Fissile material may migrate due to bottom-only breach of cask or due to massive structural failure of waste package. Near-field criticality can result if fissile material geometry represents critical configuration and sufficient water is present in pond.
2.1.14.10.0A	Near-field criticality, fissile solution flows into drift low point	Near-field criticality results when fissile material-bearing solution flows into a drift low point. The poison has already been separated from the solution carrying the fissile material, either due to retention in intact components within the waste package or prior removal by flow-through leaching within the waste package.
2.1.14.11.0A	Near-field criticality, fissile solution is adsorbed or reduced in invert	Near-field criticality results from fissile solution adsorbed or reduced in invert (concrete and crushed tuff). The geometry of the invert allows zonal precipitation (under the influence of gravity) wherein the fissile and non fissile species may precipitate at different places within the invert.
2.1.14.12.0A	Near-field criticality, filtered slurry or colloidal stream collects on invert surface	Near-field criticality results when slurry or colloidal stream is filtered (i.e., neutron absorbers are removed) by waste package corrosion products and collect on top of invert surface.
2.1.14.13.0A	Near-field criticality associated with colloidal deposits	Near-field criticality could result from colloids deposited in fractured or degraded concrete, from colloids filtered in the invert, or from colloids deposited in dead-ends of stress-relief cracks in the surrounding tunnel.

Table 6.1-3. Listing of TSPA-LA Criticality Features, Events, and Processes (Continued)

FEP Number	FEP Name	FEP Description
2.1.14.14.0A	Criticality resulting from disruptive events	Nuclear criticality refers to a self-sustaining fission chain reaction that requires sufficient concentration and localized (critical) mass of isotopes (e.g., U-235, Pu-239). This can include thermal criticality, which requires the additional presence of neutron-moderating materials (e.g., water) in a suitable geometry. Fast criticality can occur without moderator, but generally requires a much larger critical mass than thermal criticality. The repository will house a variety of nuclear waste types and configurations (e.g., CSNF and DSNF). A disruptive event such as seismic ground motion, rockfall, or igneous intrusion could lead to damaged packages and allow water (a moderator) to enter the packages. They could also lead to destruction of the internal configuration of the packages; release and distribution of the waste exterior to package; or in the case of an igneous intrusion drastically change the chemical environment and/or mix with the waste. Thereby, disruptive events could be a criticality initiating event.
2.2.14.02.0A	Far-field criticality, precipitation in organic reducing zone in or near water table	Fissile material is transported to an organic reducing zone and precipitates in a geometrically favorable configuration in or near water table.
2.2.14.03.0A	Far-field criticality, sorption on clay/zeolite in TSbv	Fissile material is transported to Topopah Spring unit where it sorbs onto the clays and zeolites of the basal vitrophyre in a geometrically favorable configuration.
2.2.14.04.0A	Far-field criticality, precipitation caused by hydrothermal upwell or redox front in the saturated zone	Fissile material is transported to the saturated zone where it encounters hydrothermal upwelling or a redox front and precipitates in a geometrically favorable configuration in the saturated zone.
2.2.14.05.0A	Far-field criticality, precipitation in perched water above TSbv	Fissile material is transported to the perched water above the Topopah Spring basal vitrophyre, where chemical change causes it to precipitate in a geometrically favorable configuration.
2.2.14.06.0A	Far-field criticality, precipitation in fractures of TSw rock	Fissile material is transported to Topopah Spring welded unit where it precipitates in a geometrically favorable configuration within the fractures.
2.2.14.07.0A	Far-field criticality, dryout produces fissile salt in a perched water basin	Fissile material is transported to a perched water basin. Dryout (evaporation exceeds infiltration) of the basin and the solution containing fissile material results in a fissile salt in a geometrically favorable configuration in the basin.
2.2.14.08.0A	Far-field criticality associated with colloidal deposits	Far-field criticality could result from colloids deposited in clays/zeolites in TSbv or deposited in perched water above the relatively impermeable TSbv.

DTN: MO0307SEPFEPS4.000 [DIRS 164527]

Subsequent to their documentation in *LA FEP List* (DTN: MO0307SEPFEPS4.000 [DIRS 164527]), the initial criticality FEPs for TSPA-LA were re-evaluated. To facilitate the TSPA-LA screening analysis, the criticality FEPs were reclassified for greater clarification and transparency into the following categories:

1. Base Case (Nominal Scenario Class) FEPs
 - A. Internal to the Waste Package
 1. Intact Configuration
 2. Degraded Configurations
 - B. External to the Waste Package
 1. Near-Field Configurations
 2. Far-Field Configurations
2. Seismic Disruptive Event FEPs
 - A. Internal to the Waste Package
 1. Intact Configuration
 2. Degraded Configurations
 - B. External to the Waste Package
 1. Near-Field Configurations
 2. Far-Field Configurations
3. Rockfall Disruptive Event FEPs
 - A. Internal to the Waste Package
 1. Intact Configuration
 2. Degraded Configurations
 - B. External to the Waste Package
 1. Near-Field Configurations
 2. Far-Field Configurations
4. Igneous Disruptive Event FEPs
 - A. Internal to the Waste Package
 1. Intact Configuration
 2. Degraded Configurations
 - B. External to the Waste Package
 1. Near-Field Configurations
 2. Far-Field Configurations

The “Internal to the Waste Package” degraded configuration FEPs encompass the configuration classes identified in Figures 3-2a and 3-2b of *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505]). Figure 3-2a defines in-package bathtub configuration classes (hole at top of waste package and waste package flooded). Figure 3-2b defines in-package flow-through configuration classes (hole at top and bottom of waste package and water flowing through and over waste package internals and waste form).

The “External to the Waste Package” near-field configuration FEPs encompass the degraded configuration classes identified in Figure 3-3a of *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505]) and the far-field configuration FEPs encompass the configuration classes of Figure 3-3b. The near-field environment is defined as external to the waste package and inside the drift wall (including any drift liner and the invert). The far-field environment is defined as the area beyond the drift wall (i.e., in the host rock of the repository).

Table 6.1-4 presents the revised list of 16 criticality FEPs for TSPA-LA that resulted from this reclassification. Because the revised list of 16 criticality FEPs and the initial list of 20 criticality FEPs (refer to Table 6.1-3) were derived from the configuration classes identified in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505], Figures 3.2a, 3.2b, 3.3a, and 3.3b), the revised list completely replaces and supercedes the initial list. Table 6.1-4 provides a cross-reference to confirm that all of the initial criticality FEPs have been incorporated into the revised list of criticality FEPs for TSPA-LA.

Table 6.1-4. Criticality FEPs List to be Utilized in Criticality Screening Analysis

FEP Number	FEP Name	FEP Description	Cross-Reference to Initial LA FEP List
Base Case FEPs			
2.1.14.15.0A	In-package criticality (intact configuration)	The waste package internal structures and the waste form remain intact. A breach (or breaches) in the waste package allow(s) water to either accumulate or flow-through the waste package. Criticality then occurs in situ. In-package criticality resulting from disruptive events is addressed in separate FEPs.	2.1.14.02.0A
2.1.14.16.0A	In-package criticality (degraded configurations)	The waste package internal structures and the waste form degrade. A critical configuration (sufficient fissile material and neutron moderator, lack of neutron absorbers) develops and criticality occurs in situ. Potential in situ critical configurations are defined in Figures 3.2a and 3.2b of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]). In-package criticality resulting from disruptive events is addressed in separate FEPs.	2.1.14.03.0A 2.1.14.04.0A 2.1.14.05.0A 2.1.14.06.0A 2.1.14.07.0A 2.1.14.08.0A
2.1.14.17.0A	Near-field criticality	Near-field criticality occurs when fissile material-bearing solution from the waste package is transported into the drift and the fissile material is precipitated into a critical configuration. Potential near-field critical configurations are defined in Figure 3.3a of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]). In-package criticality resulting from disruptive events is addressed in separate FEPs.	2.1.14.09.0A 2.1.14.10.0A 2.1.14.11.0A 2.1.14.12.0A 2.1.14.13.0A
2.2.14.09.0A	Far-field criticality	Far-field criticality occurs when fissile material-bearing solution from the waste package is transported beyond the drift and the fissile material is precipitated into a critical configuration. Potential far-field critical configurations are defined in Figure 3.3b of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]). In-package criticality resulting from disruptive events is addressed in separate FEPs.	2.2.14.02.0A 2.2.14.03.0A 2.2.14.04.0A 2.2.14.05.0A 2.2.14.06.0A 2.2.14.07.0A 2.2.14.08.0A

Table 6.1-4. Criticality FEPs List to be Utilized in Criticality Screening Analysis (Continued)

FEP Number	FEP Name	FEP Description	Cross-Reference to Initial LA FEP List
Seismic Disruptive Event FEPs			
2.1.14.18.0A	In-package criticality resulting from a seismic event (intact configuration)	The waste package internal structures and the waste form remain intact either during or after a seismic disruptive event. A breach (or breaches) in the waste package allow(s) water to either accumulate or flow-through the waste package. Criticality then occurs in situ.	2.1.14.14.0A
2.1.14.19.0A	In-package criticality resulting from a seismic event (degraded configurations)	Either during, or as a result of, a seismic disruptive event, the waste package internal structures and the waste form degrade. A critical configuration develops and criticality occurs in situ. Potential in situ critical configurations are defined in Figures 3.2a and 3.2b of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]).	
2.1.14.20.0A	Near-field criticality resulting from a seismic event	Either during, or as a result of, a seismic disruptive event, near-field criticality occurs when fissile material-bearing solution from the waste package is transported into the drift and the fissile material is precipitated into a critical configuration. Potential near-field critical configurations are defined in Figure 3.3a of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]).	
2.2.14.10.0A	Far-field criticality resulting from a seismic event	Either during, or as a result of, a seismic disruptive event, far-field criticality occurs when fissile material-bearing solution from the waste package is transported beyond the drift and the fissile material is precipitated into a critical configuration. Potential far-field critical configurations are defined in Figure 3.3b of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]).	
Rockfall Disruptive Event FEPs			
2.1.14.21.0A	In-package criticality resulting from rockfall (intact configuration)	The waste package internal structures and the waste form remain intact either during or after a rockfall event. A breach (or breaches) in the waste package allow(s) water to either accumulate or flow-through the waste package. Criticality then occurs in situ.	2.1.14.14.0A
2.1.14.22.0A	In-package criticality resulting from rockfall (degraded configurations)	Either during, or as a result of, a rockfall event, the waste package internal structures and the waste form degrade. A critical configuration develops and criticality occurs in situ. Potential in situ critical configurations are defined in Figures 3.2a and 3.2b of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]).	
2.1.14.23.0A	Near-field criticality resulting from rockfall	Either during, or as a result of, a rockfall event, near-field criticality occurs when fissile material-bearing solution from the waste package is transported into the drift and the fissile material is precipitated into a critical configuration. Potential near-field critical configurations are defined in Figure 3.3a of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]).	

Table 6.1-4. Criticality FEPs List to be Utilized in Criticality Screening Analysis (Continued)

FEP Number	FEP Name	FEP Description	Cross-Reference to Initial LA FEP List
2.2.14.11.0A	Far-field criticality resulting from rockfall	Either during, or as a result of, a rockfall event, far-field criticality occurs when fissile material-bearing solution from the waste package is transported beyond the drift and the fissile material is precipitated into a critical configuration. Potential far-field critical configurations are defined in Figure 3.3b of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]).	
Igneous Disruptive Event FEPs			
2.1.14.24.0A	In-package criticality resulting from an igneous event (intact configuration)	The waste package internal structures and the waste form remain intact either during or after an igneous disruptive event. A breach (or breaches) in the waste package allow(s) water to either accumulate or flow-through the waste package. Criticality then occurs in situ.	2.1.14.14.0A
2.1.14.25.0A	In-package criticality resulting from an igneous event (degraded configurations)	Either during, or as a result of, an igneous disruptive event, the waste package internal structures and the waste form degrade. A critical configuration develops and criticality occurs in situ. Potential in situ critical configurations are defined in Figures 3.2a and 3.2b of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]).	
2.1.14.26.0A	Near-field criticality resulting from an igneous event	Either during, or as a result of, an igneous disruptive event, near-field criticality occurs when fissile material-bearing solution from the waste package is transported into the drift and the fissile material is precipitated into a critical configuration. Potential near-field critical configurations are defined in Figure 3.3a of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]).	
2.2.14.12.0A	Far-field criticality resulting from an igneous event	Either during, or as a result of, an igneous disruptive event, far-field criticality occurs when fissile material-bearing solution from the waste package is transported beyond the drift and the fissile material is precipitated into a critical configuration. Potential far-field critical configurations are defined in Figure 3.3b of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]).	

6.1.2 FEPs Screening Process

The first step in the FEP analysis process, described in Section 6.1.1, was the identification of FEPs. The second step in the FEP analysis process is the screening of each FEP against the project screening criteria. The NRC requires the consideration and evaluation of FEPs as part of the performance assessment activities. More specifically, the NRC regulations allow the exclusion of FEPs from the TSPA if they can be shown to be of low probability or of low consequence. The specified criteria can be summarized in the form of two FEP screening statements as follows.

1. The event has at least one chance in 10,000 of occurring over 10,000 years (10 CFR 63.114(d) [DIRS 156605]).

2. The magnitude and time of the resulting radiological exposure to the reasonably maximally exposed individual, or radionuclide release to the accessible environment, would be significantly changed by its omission (10 CFR 63.114(e) and (f) [DIRS 156605]).

Additionally, the Acceptance Criteria in *Yucca Mountain Review Plan* (NRC 2003 [DIRS 163274], Section 2.2.1.2.1.3) requires evaluating FEPs based on the regulations. This criterion can be summarized in the form of a third FEP screening statement.

3. The FEP is not excluded by regulation.

Evaluating FEPs against these screening statements may be done in any order. If there are affirmative conditions for all three screening criteria, the FEP is “Included” in the TSPA-LA model. If there is a negating condition in any of the three screening criteria, the FEP is “Excluded” from the TSPA-LA model.

The approach taken in this analysis is to evaluate the probability of the criticality FEPs based on the interactions between the natural and engineered barrier systems over the performance period to determine if this event can be excluded from evaluation in the TSPA-LA based on low probability of occurrence.

6.1.3 Background, Technical Information, and Literature Searches

Data and technical information sources used for the FEPs evaluation are cited within each FEP discussion, and use of this information and data has been documented per YMP procedural requirements. Where possible, the technical information used in this analysis report to support the screening decisions was obtained from controlled source documents and references using the appropriate document identifiers or records system accession numbers. Sources of such data include, but are not limited to, analyses, models, technical reports, and other YMP documents and databases. As needed, alternative and corroborative information and data were obtained from literature searches of peer-reviewed journals, other widely recognized scientific periodicals, results of review of YMP documents by external organizations, and other appropriate sources such as technical handbooks and textbooks. A listing of the corroborating data, models, product input, or technical information used to support the criticality FEPs screening decisions are provided in Table 6.1-5.

Table 6.1-5. Corroborating Data, Models, Product Input or Technical Information

Reference Description	Reference Sections Used	Section Used in	Input Description
<i>Evaluation of Codisposal Viability for MOX (FFTF) DOE-Owned Fuel</i> (CRWMS M&O 1999 [DIRS 125206])	Entire	Table 6.2-1	Reference to FFTF criticality evaluations
<i>Evaluation of Codisposal Viability for UzrH (TRIGA) DOE-Owned Fuel</i> (CRWMS M&O 2000 [DIRS 147650])	Entire	Table 6.2-1	Reference to TRIGA criticality analyses
<i>Evaluation of Codisposal Viability for HEU Oxide (Shippingport PWR) DOE-Owned Fuel</i> (CRWMS M&O 2000 [DIRS 147651])	Entire	Table 6.2-1	Reference to Shippingport PWR criticality analyses
<i>21-PWR Waste Package with Absorber Plates Loading Curve Evaluation</i> (BSC 2003 [DIRS 166610])	Entire	Section 6.2	Reference to loading curve analyses

Table 6.1-5. Corroborating Data, Models, Product Input or Technical Information (Continued)

Reference Description	Reference Sections Used	Section Used in	Input Description
<i>Evaluation of Codisposal Viability for U-Zr/U-Mo Alloy (Enrico Fermi) DOE-Owned Fuel (CRWMS M&O 2000 [DIRS 151742])</i>	Entire	Table 6.2-1	Reference to Enrico Fermi criticality analyses
<i>Evaluation of Codisposal Viability for Th/U Oxide (Shippingport LWBR) DOE-Owned Fuel (CRWMS M&O 2000 [DIRS 151743])</i>	Entire	Table 6.2-1	Reference to Shippingport LWBR criticality analyses
<i>Evaluation of Codisposal Viability for U-Metal (N Reactor) DOE-Owned Fuel (CRWMS M&O 2001 [DIRS 154194])</i>	Entire	Table 6.2-1	Reference to N Reactor criticality analyses
<i>Yucca Mountain Science and Engineering Report (DOE 2002 [DIRS 155943])</i>	Table 3-3	Section 6.6	Percentage of MTHM by waste package design
	Section 4.3.3.2.1	Section 6.6	Possibility of criticality due to an igneous event
<i>Evaluation of Codisposal Viability for Melt and Dilute DOE-Owned Fuel (BSC 2001 [DIRS 157733])</i>	Entire	Table 6.2-1	Reference to Melt and Dilute criticality analyses
<i>Evaluation of Codisposal Viability for Th/U Carbide (Fort Saint Vrain HTGR) DOE-Owned Fuel (BSC 2001 [DIRS 157734])</i>	Entire	Table 6.2-1	Reference to Fort St. Vrain criticality analyses
<i>External Accumulation of Fissile Material from DOE Co-Disposal Waste Packages (BSC 2002 [DIRS 159913])</i>	Section 5.2.2	Section 6.3.2	Plume description cited to support conclusions.
<i>44 BWR Waste Package Loading Curve Evaluation (BSC 2001 [DIRS 161125])</i>	Entire	Section 6.2	Reference to loading curve analyses
<i>Disposal Criticality Analysis Methodology Topical Report (YMP 2003 [DIRS 165505])</i>	Section 3.3	Sections 6.2 and 6.3	Master Scenario List
<i>Criticality Model Report (BSC 2003 [DIRS 165733])</i>	Section 6.2.1	Section 6.2	Definition of criticality limit
	Entire	Sections 6.2 and 6.3	Reference to criticality model
<i>WAPDEG Analysis of Waste Package and Drip Shield Degradation (CRWMS M&O 2000 [DIRS 151566])</i>	Section 6.5.1	Section 6.3.3.3.2	Waste package failure due to pitting and crevice corrosion
<i>WAPDEG Analysis of Waste Package and Drip Shield Degradation (CRWMS M&O 2000 [DIRS 151566])</i>	Entire	Section 6.3.3.4	Formation and generation of bathtub configurations
<i>WAPDEG Analysis of Waste Package and Drip Shield Degradation (BSC 2003 [DIRS 161317])</i>	Section 6.6.2 and Figures 36, 37, and 38	Sections 6.3.3.2.1, 6.3.3.3.1, 6.3.3.3.3, and 6.3.3.3.4	General corrosion failure of the waste package and drip shield and stress corrosion cracking failure of the waste package
<i>Geochemistry Model Abstraction and Sensitivity Studies for the 21 PWR CSNF Waste Packages (BSC 2002 [DIRS 160638])</i>	Sections 4.1.2.1 and 4.1.2.2	Section 6.3.2	Information on the retention and release of fissile material from a degraded waste package
<i>Characterize Framework for Igneous Activity at Yucca Mountain, Nevada (BSC 2003 [DIRS 163769])</i>	Table 22	Sections 6.2 and 6.6	Annual frequency of an intrusive igneous event
<i>Igneous Intrusion Impacts on Waste Package and Waste Form (BSC 2003 [DIRS 165002])</i>	Section 1	Section 6.6.1	Igneous impacts on waste package in Zone 1 and Zone 2; Zone 2 impacts due to volatile gases
	Sections 6.5.2 and 6.7.2	Sections 6.6.1 and 6.6.2	
<i>Thermodynamics (Wark 1983 [DIRS 157283])</i>	Table A-12	Section 6.6.3	Saturation temperature at 7.5 MPa

6.1.4 Assumptions and Simplifications, Alternative Conceptual Models, and Consideration of Uncertainty in FEPs Screening

The generic assumptions used in the FEPs screening for the criticality FEPs are provided in Section 5, along with their rationale, confirmation status, and where used in this document.

Specific guidance and criteria for the consideration of alternative conceptual models (and their relationship to FEPs) and the treatment of uncertainty are provided in Section 5 and Appendices A and C of *Scientific Processes Guidelines Manual* (BSC 2002 [DIRS 160313]). Alternative conceptual models and uncertainty issues are addressed in supporting documentation cited as part of the FEPs evaluation.

6.1.5 Alternative Approaches, Mathematical Formulations, and Units of Measure

Alternative approaches to the configuration generator model used to perform most of the FEP screening arguments are discussed in *Configuration Generator Model for In-Package Criticality* (BSC 2003 [DIRS 165629]). The current approach was selected because its results are more transparent.

In general, FEPs screening involves the comparison of the probability of occurrence of some feature, event, or process to some threshold level of probability, or some other threshold measure that defines the onset of consequence to repository performance. Mathematical and numerical formulations typically are used to define the measure of the FEP of interest (e.g., development of the seismic hazard curves) and its probability of occurrence. Any mathematical formulations, equations, or algorithms used in the criticality FEP evaluations are discussed in the appropriate section.

Depending on the criticality FEPs being evaluated, the units of measure of the source information may vary. In all cases, the units as they appeared in the cited source are provided to allow traceability, and metric equivalents, if necessary, are provided in parentheses for consistency and transparency.

6.1.6 Model and Software Issues for Previously Developed and Validated Models

The configuration generator model used to determine the probability of potentially critical configurations for the FEPs screening analysis uses the SAPHIRE code. The validation of the model is discussed in a separate model report (BSC 2003 [DIRS 165629]). The SAPHIRE code is discussed in Section 3.1.2.

6.1.7 Intended Use and Limitations

The intended use of this analysis report is to provide criticality FEPs screening information for the project-specific FEPs database, and to promote traceability and transparency regarding FEPs disposition. This analysis report presents the source documentation to provide the technical basis, and to provide the supporting arguments for exclusion of criticality FEPs from the TSPA-LA model. Accordingly, this analysis report may be of use to reviewers during the licensing review process.

6.2 CRITICALITY FEPS SCREENING ANALYSIS MODEL

The criticality FEPS screening analysis utilizes the event tree/fault tree process model developed in *Configuration Generator Model for In-Package Criticality* (BSC 2003 [DIRS 165629], Attachment XII) for the evaluation of the overall probability of criticality. The configuration generator model identifies the possible pathways required for the development of internal waste package configuration classes (degraded or otherwise), evaluates the probability of occurrence for the configuration classes, and provides the configuration class associated parameter ranges to determine the criticality potential of each configuration class. Although currently only validated for application with 21-PWR with Absorber Plates Waste Packages, the methods provided in this model are considered to be applicable to all waste forms and waste package types with adequate justification.

In addition, as documented, the configuration generator model allows for a probability evaluation of the potentially critical configurations to be performed at several points during the development of the configuration classes. The first logical point of evaluation would be the probability that water will enter a failed waste package and the waste package would remain in a flooded condition during the postclosure performance period (i.e., during the first 10,000 years after the permanent closure of the repository). This is a logical evaluation point because unless water enters and floods the waste package, the waste package internals cannot degrade and allow the neutron absorber material to be removed from the waste package. The loss of neutron absorber materials and the presence of a neutron moderator are required to achieve an in-package criticality during the postclosure performance period.

The second logical evaluation point is the probability of configuration class formation. These configuration classes are defined by the Master Scenario List in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505], Section 3.3) and are discussed in Section 6.2 of *Configuration Generator Model for In-Package Criticality* (BSC 2003 [DIRS 165629]). These configuration classes, representing waste package flooded and flow-through configurations, represent the physical characteristics of the waste package, waste package internals, and waste forms that are possible during the waste package/waste form degradation processes. It should be noted that the criticality FEPS were derived from the configuration classes defined by the Master Scenario List in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505], Section 3.3). It is necessary to degrade the waste package/waste form in some manner to achieve a potentially critical configuration. This is because intact, fully loaded, fully flooded waste package conditions are precluded from achieving criticality by design to satisfy a preclosure operations requirement that the MGR provide means to ensure criticality control during SNF/HLW handling operations, including waste package loading (Siddoway 2003 [DIRS 163904], Requirement 1.1.6-4). If this requirement is satisfied, in situ criticality in an intact configuration (criticality FEPS 2.1.14.15.0A, 2.1.14.18.0A, 2.1.14.21.0A, or 2.1.14.24.0A) cannot occur.

It has been previously demonstrated that through loading curve analyses for the 21-PWR with Absorber Plates and the 44-BWR waste package types that an intact, fully flooded waste package configuration cannot achieve criticality (BSC 2003 [DIRS 166610] and BSC 2001 [DIRS 161125], respectively). To satisfy Requirement 1.1.6-4 (Siddoway 2003 [DIRS 163904]), similar analyses must be performed for the remaining commercial SNF waste packages.

Analyses have also been previously performed for eight of the nine representative DOE SNF waste forms that demonstrate subcriticality of these waste package types for intact, fully flooded conditions. The references for these analyses are listed in Table 6.2-1.

Table 6.2-1. DOE SNF Intact Configuration Criticality Analysis References

DOE SNF Representative Waste Form	Intact Configuration Criticality Analysis Reference
1. Fast Flux Test Facility (FFTF)	CRWMS M&O 1999 [DIRS 125206]
2. Training, Research, Isotopes, General Atomics (TRIGA)	CRWMS M&O 2000 [DIRS 147650]
3. N Reactor	CRWMS M&O 2001 [DIRS 154194]
4. Shippingport PWR	CRWMS M&O 2000 [DIRS 147651]
5. Shippingport LWBR	CRWMS M&O 2000 [DIRS 151743]
6. Fort St. Vrain	BSC 2001 [DIRS 157734]
7. Melt and Dilute	BSC 2001 [DIRS 157733]
8. Enrico Fermi	CRWMS M&O 2000 [DIRS 151742]
9. Three Mile Island II	Not available.

The final logical evaluation point is to assess the criticality probability for each configuration class. Using the criticality model (BSC 2003 [DIRS 165733]) and the configuration class characteristics defined by the configuration generator model, detailed criticality analyses are performed to determine the effective neutron multiplication factor (k_{eff}) for the range of parameters associated with each configuration class. If the calculated k_{eff} is below a prescribed critical limit (BSC 2003 [DIRS 165733], Section 6.2.1) for the entire range of parameters, the configuration class has no criticality potential. If the calculated k_{eff} is above a prescribed critical limit for some or all of the range of parameters, then the probability of achieving these parameter ranges is assessed. The probability of achieving these parameter ranges is the configuration class's criticality probability.

It is the intent of the criticality FEPs screening analysis to perform a probability evaluation of only the potential for water to enter the waste package and maintain a flooded condition during the postclosure performance period. The portions of the configuration generator event tree/fault tree process model to be exercised in this analysis are as follows.

The first event tree developed in the configuration generator model defines the fractional breakdown of the waste forms and waste package types proposed for disposal in the repository. This event tree (Figure 6.2-1) has been modified slightly to indicate the fraction of total waste package inventory for each waste package type, including naval waste package types. The updated inventory fractions are based on the information provided in Table 4.1-8. Although the Naval Nuclear Propulsion Program is responsible for assessing criticality potential of the naval waste package types in accordance with an addendum (Mowbray 1999 [DIRS 149585]) to *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505]), these waste package types are presented on this event tree for completeness.

Waste Package Fraction	Waste Form Type Percentages by Originator	Waste Form Sub-Type Percentages	Waste Package Type Percent Breakdown						
WP	WP-SOURCE	WP-IND	WP-TYPE	#	END-STATE-NAMES	FRACTION			
Waste Package Fraction	Commercial CSNF (66.8% of total inventory)	PWR (40.7% of total inventory)	21-PWR Absorber Plate (38.4% of total inventory)	1	21PWR-AP-WP	3.840E-001			
			21-PWR Control Rod (0.8% of total inventory)	2	21PWR-CR-WP	8.000E-003			
			12-PWR Long (1.5% of total inventory)	3	12PWR-WP	1.500E-002			
			BWR (26.1% of total inventory)	44-BWR (25.3% of total inventory)	4	44BWR-WP	2.53E-001		
				24-BWR (0.8% of total inventory)	5	24BWR-WP	8.000E-003		
			DOE SNF (30.5% of total inventory)	DOE Long (10.3% of total inventory)	DOE Short (18.9% of total inventory)	6	DOE-LONG-WP	1.030E-001	
					DOE Short (18.9% of total inventory)	7	DOE-SHORT-WP	1.890E-001	
					DOE MCO (1.3% of total inventory)	8	DOE-MCO-WP	1.300E-002	
					Naval SNF (2.7% of total inventory)	Naval Short (1.3% of total inventory)	9	NAVAL-SHORT-WP	1.300E-002
						Naval Long (1.4% of total inventory)	10	NAVAL-LONG-WP	1.400E-002

Source: Criticality FEPs Analysis SAPHIRE Model (Attachment VII)

Figure 6.2-1. Waste Form and Waste Package Types Proposed for Disposal at the Repository

Eight commercial and DOE SNF waste package types (Figure 6.2-1) have been utilized as the initiating event in a new event tree, which only transfers to another event tree that directs the evaluation of a waste package’s criticality potential resulting from the four criticality FEPs cases. An example of the “Waste Package Type” event tree is presented in Figure 6.2-2. The “Waste Package Type” event tree of Figure 6.2-2 automatically transfers to a third event tree. The transfer is indicated by the “T” after the event tree sequence number in the “#” column. The “CASE” end state name in the “END_STATE_NAMES” column of this event tree indicates the name of the event tree to which the transfer occurs.

The “CASE” event tree is presented in Figure 6.2-3. This event tree directs the evaluation of the four criticality FEPs cases — (1) Base Case, (2) Seismic Disruptive Event, (3) Rockfall Disruptive Event, and (4) Igneous Disruptive Event. These cases are represented as branches in the event tree top event FEP. As shown in Figure 6.2-3, the Igneous Disruptive Event ends in an “OK” end state that indicates SAPHIRE processing and no further event tree/fault tree evaluation of this initiating event is performed. An evaluation of the igneous disruptive event is provided in Section 6.6 of this report. The probabilities of occurrence assigned to each of the four basic events representing these four criticality FEPs cases are as follows:

FEP_BASECASE = 1.000E-000 (always possible)
 FEP_SEISMIC = 1.000E-000 (always possible)
 FEP_ROCKFALL = 1.000E-000 (always possible)
 FEP_IGNEOUS = 1.700E-004 (event frequency of 1.7E-8/year × 10,000 years)
 (BSC 2003 [DIRS 163769], Table 22)

Initiate Evaluation of 21-PWR with Absorber Plates Waste Package Type			
WP01-21-PWR-AP	<PASS>	#	END_STATE_NAMES
		1 T	CASE

Source: Criticality FEPs Analysis SAPHIRE Model (Attachment VII)

Figure 6.2-2. Waste Package Type Event Tree

The seismic disruptive event has been assigned a value of 1.0 because the probability of its occurrence is integral to the calculation of the minimum required seepage. This calculation is documented in Section 6.4 and Attachments III-V. Assigning the seismic disruptive event a value other than 1.0 would result in double counting of the probability of its occurrence. The rockfall disruptive event also has been assigned a value of 1.0. Rockfall is the result of natural drift degradation phenomena and is expected to occur throughout the postclosure period without any predictable frequency. The evaluation of the rockfall disruptive event is presented in Section 6.5. The rockfall disruptive event is differentiated from rockfall that may occur during a seismic disruptive event. Damage resulting from seismic induced rockfall is accounted for in the Section 6.4.

Incoming Waste Package Type Identifier	FEPs Initiating Event	Rock Type of Drift			
IE1	FEP	DRIFT	#		END-STATE
WP Type	Base Case Probability = 1.0	Nonlithophysal (15%)	1 T		FEPS
		Lithophysal (85%)	2 T		FEPS
	Seismic Disruptive Event Probability = 1.0	Nonlithophysal	3 T		FEPS
		Lithophysal	4 T		FEPS
	Rock Fall Disruptive Event Probability = 1.0	Nonlithophysal	5 T		FEPS
		Lithophysal	6 T		FEPS
	Igneous Disruptive Event Probability = 1.7E-4		7		OK

Source: Criticality FEPs Analysis SAPHIRE Model (Attachment VII)

Figure 6.2-3. Event Tree for Processing Criticality FEPs Cases

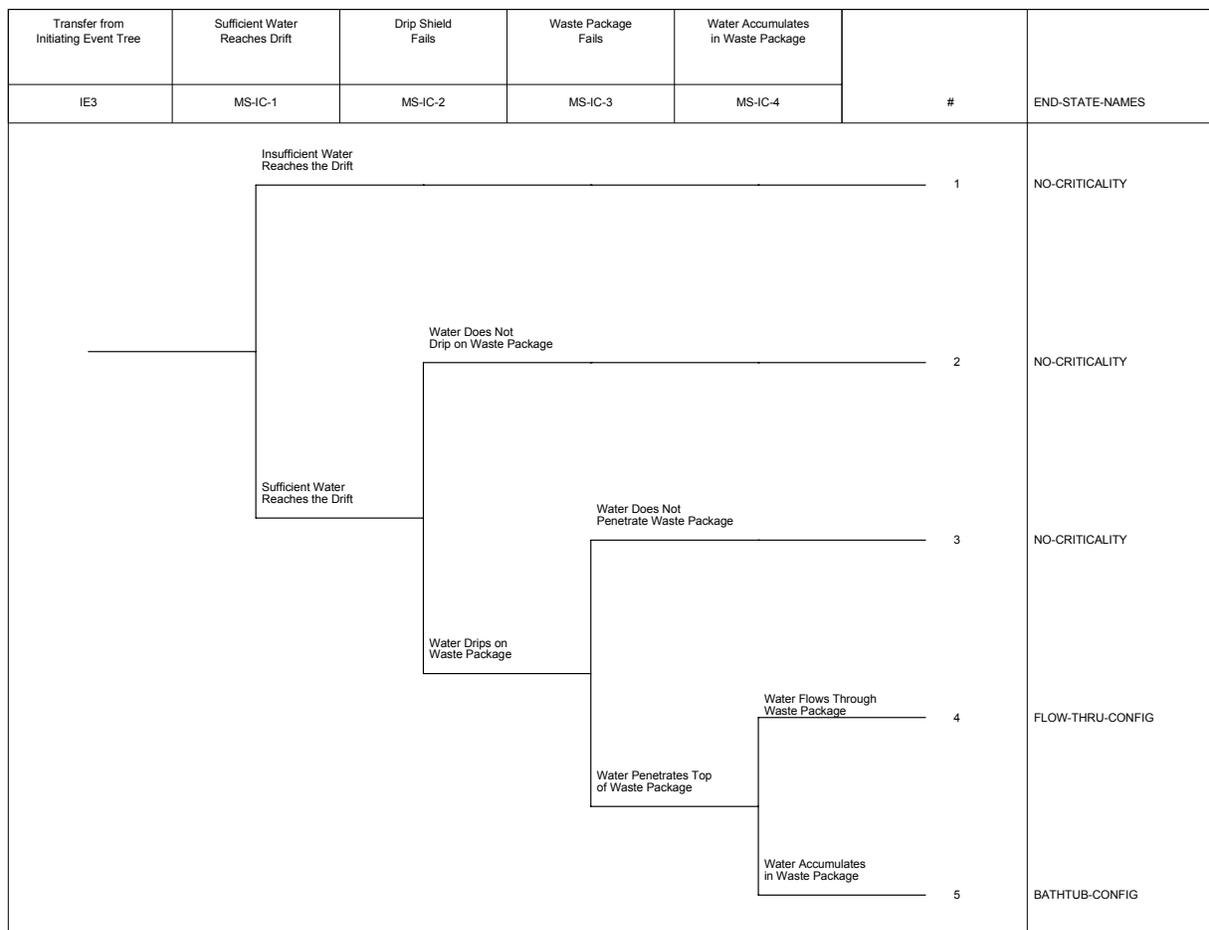
A second top event, DRIFT, is presented in the “CASE” event tree of Figure 6.2-3. This top event splits the evaluation between the two geological zones of the drifts – lithophysal and nonlithophysal. Based on total drift area information (BSC 2003 [DIRS 164491], Table 9), of the 4,983,152 m² of total emplacement drift, 745,486 m² reside in the nonlithophysal geological zone. This results in a top event split fraction of 0.15 for nonlithophysal (745,486/4,983,152) and 0.85 for lithophysal. These values are applied to the event tree evaluation by setting the probability of basic event DRIFT to 0.85. As will be discussed in Sections 6.4 (seismic disruptive event criticality FEPs) and 6.5 (rockfall disruptive event criticality FEPs), it is important to distinguish between the two geological units during rockfall impact evaluations.

The “CASE” event tree of Figure 6.2-3 automatically transfers to a fourth event tree. The transfer is indicated by the “T” after the first six event tree sequence numbers in the “#” column. The “FEPS” end state name in the “END-STATE” column of this event tree indicates the name of the event tree to which the transfer occurs. The “FEPS” event tree (shown in Figure 6.2-4) performs the probability evaluation for water ingress into a waste package, waste package flooding, and maintenance of a flooded configuration (i.e., bathtub) for the duration of the postclosure performance period.

As presented in Figure 6.2-4, only four top events are necessary to define the processes to assess the probability of the formation of a waste package bathtub configuration. The purpose of the first top event (MS-IC-1) is to evaluate the probability of the water flux necessary to penetrate a waste package in order to degrade waste package internals and remove the neutron absorber material (creating a potentially critical configuration) reaching the drift. If sufficient water reaches the drift, then top event MS-IC-2 is queried. However, if sufficient water does not reach the drift (i.e., the branching goes up), then the analysis ends at this point because there is not sufficient water to create a potentially critical configuration.

Top event MS-IC-2 evaluates the probability that, given sufficient water flux in the drift, the drip shield is failed in such a manner to allow water to pass through to the waste package. If the drip shield is not failed, then the analysis is halted as indicated by the up branch of this top event. However, if the drip shield is failed and sufficient water is allowed to pass through, then top event MS-IC-3 is queried.

Top event MS-IC-3 evaluates the probability that, given sufficient water flux passes through the drip shield, the waste package is failed in such a manner to allow the water to enter in sufficient quantity to support the generation of a potentially critical configuration. If the waste package is not failed, then the analysis is halted. However, if the waste package is failed and sufficient water is allowed to pass through, then top event MS-IC-4 is queried.



Source: Criticality FEPs Analysis SAPHIRE Model (Attachment VII)

Figure 6.2-4. Criticality FEPs Screening Analysis Event Tree

Top event MS-IC-4 evaluates the probability that, given sufficient water flux passes into the waste package, water accumulates in the waste package for a sufficient duration to allow for the degradation of the waste package internals and the removal of the neutron absorbing materials, creating a potentially critical configuration. The accumulation and retention of water in the waste package is referred to as a bathtub configuration. It is also possible for sufficient water to enter the waste package, but the water does not accumulate. Rather, a breach in the waste package bottom could allow for water to flow out. This condition is referred to as a flow-through configuration. The waste package internals could degrade under such conditions and the neutron absorber materials removed, but there would be insufficient water retained in the waste package to allow for neutron moderation, a necessary component to support in-package criticality. The analysis is halted at this point.

Another possible configuration is one in which a breach in the top and bottom of the waste package exists, but that the bottom hole is much smaller than the top hole, so more water can enter the waste package through the top than can exit through the bottom. This configuration is not explicitly considered in this analysis because the low seepage rates predicted in the repository would preclude this configuration from occurring and because the bottom breach

would rapidly ablate due to accelerated corrosion resulting from the pressurized flow through the bottom hole. In addition, this waste package configuration can be considered a subset of the bathtub configuration.

If any of the first three top events branch upward (nonoccurrence of the event), the analysis stops because the conditions required to achieve a potentially critical configuration are not met. This is noted in the END-STATE-NAMES column through the assignment of the “NO-CRITICALITY” end state. The evaluation of top event MS-IC-4 results in the generation of two end states indicating the probability of generating a waste package bathtub configuration (end state BATHTUB-CONFIG) or a waste package flow through configuration (end state FLOW-THRU-CONFIG).

Each of the top events of Figure 6.2-4 is supported with fault trees. In turn, each fault tree is quantified through the evaluation of logic that defines the relationship between dependent and independent events (referred to as basic events). The supporting fault trees are presented in Attachment II, Figures II-5 through II-8. Sections 6.3 through 6.5 quantify the fault tree basic events for the three criticality FEP cases evaluated using SAPHIRE (i.e., Base Case, Seismic Disruptive Event, and Rockfall Disruptive Event), respectively.

6.3 ANALYSIS OF BASE CASE CRITICALITY FEPS

This screening analysis of the base case postclosure criticality FEPS is based on the probability that sufficient water to degrade and subsequently flush out the neutron absorber material reaches the waste form during the period of performance (10,000 years after repository closure).

For a criticality event to occur, the proper combination of materials (neutron moderators, neutron absorbers, fissile) and geometric configuration must exist. A critical system for the geological repository is defined as one having an effective neutron multiplication factor (k_{eff}), larger than the critical limit. The critical limit is the value of k_{eff} at which a system (configuration of fissile material) is considered critical as characterized by statistical tolerance limits (BSC 2003 [DIRS 165733], Section 6.2.1).

All base case (i.e., nominal scenario class, no disruptive events) postclosure criticality FEPS, internal and external, require water infiltration to degrade the waste package internals. Neutron absorber material loss and a flooded waste package condition for neutron moderation is the most likely scenario that could result in a potentially critical configuration in any of the in situ criticality FEPS. External criticality FEPS (near-field and far-field) also require the separation of neutron absorber materials from the waste form, transport of fissile material from the waste package, and accumulation of the fissile material within the drift invert or beyond.

Water, silica, and carbon are the only potential moderating materials for internal and external configurations. Water is the most effective neutron-moderating material, which can enter the waste package as percolation flow or be present in the pores of the rock. Silica is present in appreciable quantities in the high-level radioactive waste glass canisters and in the rock. Silica can also be introduced into the waste package through precipitation from the percolation flow. Carbon is present in only limited amounts in select DOE SNF types and, therefore, has a limited impact on the potential for criticality. The loading of the DOE-standardized SNF canisters, the

design of the basket structure inside the canisters, and the addition of neutron absorbers take into account the presence and effect of glass in DOE SNF codisposal waste packages. Silica from the high-level radioactive waste glass canisters has no impact on the potential for criticality in DOE SNF codisposal waste packages. Silica is a much less effective moderator than water and its introduction into commercial SNF waste packages will displace water and effectively reduce the reactivity of the system, thus reducing the potential for criticality.

In addition, criticality without water infiltration is unlikely for the geologic repository because the waste package is designed such that a criticality event in an intact waste package configuration is not possible (refer to intact waste package configuration discussion in Section 6.2).

Some of the DOE SNF waste forms are highly enriched and could potentially support unmoderated (fast) criticality if (1) the (fissile) material is concentrated beyond its design concentration in the waste form and (2) the neutron absorber materials are removed. Concentration of the fissile material beyond its design concentration could result from either waste form degradation or a disruptive event. However, removal of the neutron absorber materials from a DOE SNF waste package would require a breach of the waste package and a removal mechanism. The most likely neutron absorber material removal mechanism is through water infiltration resulting in degradation of the waste package internal components, the dissolution of the neutron absorber material, and flushing of the material from the waste package.

6.3.1 Internal (In Situ) Criticality

Water entering a failed waste package may occur from two primary pathways: (1) water dripping from the drift crown, and (2) water dripping from the underside of the drip shield due to evaporation and condensation. The first pathway can occur if the drip shield fails to divert dripping water from the drift crown into a failed waste package. The second pathway can occur if water vapor condenses on the underside of the drip shield and falls onto and enters a failed waste package. Only the first pathway is discussed for top event MS-IC-1 in Section 6.3.3.1 as the model for calculating the quantity of condensation available to enter a failed waste package is not yet available. The availability of water, drip shield and waste package failure, and the formation of a bathtub configuration are associated with top events MS-IC-1, MS-IC-2, MS-IC-3 and MS-IC-4 of the criticality FEPs screening analysis event tree.

The internal criticality FEPs probability analysis is performed only to the point of waste package flooding because a flooded waste package is necessary to obtain appreciable degradation of the waste package internals for the removal of the neutron absorber materials and to provide effective neutron moderation. The intact, fully flooded configuration of FEPs 2.1.14.15.0A, 2.1.14.18.0A, 2.1.14.21.0A, and 2.1.14.24.0A has been discussed previously in Section 6.2. Criticality is precluded by design for this configuration. Table 6.3-1 presents the list of base case internal (in situ) criticality FEPs.

Table 6.3-1. Base Case Configurations: Internal (In Situ) Criticality FEPs

FEP Number	FEP Name	FEP Description
2.1.14.15.0A	In-package criticality (intact configuration)	The waste package internal structures and the waste form remain intact. A breach (or breaches) in the waste package allow(s) water to either accumulate or flow-through the waste package. Criticality then occurs in situ. In-package criticality resulting from disruptive events is addressed in separate FEPs.
2.1.14.16.0A	In-package criticality (degraded configurations)	The waste package internal structures and the waste form degrade. A critical configuration (sufficient fissile material and neutron moderator, lack of neutron absorbers) develops and criticality occurs in situ. Potential in situ critical configurations are defined in Figures 3.2a and 3.2b of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]). In-package criticality resulting from disruptive events is addressed in separate FEPs.

Source: Table 6.1-4

6.3.2 External (Near-Field and Far-Field) Criticality

The probability of external criticality is less than the probability of water entering a failed waste package. If the probability of water entering a failed waste package (in either a bathtub or flow-through configuration) during the performance period is calculated to be below the regulatory probability criterion (less than one chance in 10,000 of occurring over 10,000 years (10 CFR 63.114(d) [DIRS 156605]), then the probability of an external criticality would be even lower. This is because, in addition to the events evaluated to calculate the probability of water entering a failed waste package, the probability of the following events must be considered for external criticality:

- Waste form degradation over the performance period;
- Separating the fissile materials from the degraded waste form;
- Removing the fissile materials from the waste package;
- Accumulating sufficient fissile material into a potentially critical configuration in the near-field or far-field environments; and
- Having sufficient neutron moderator available.

The base case external criticality FEPs are presented in Table 6.3-2. The external FEPs define criticality configurations that begin with source terms resulting from the transport of fissile materials from the waste package in a form (either as solutes, colloids, or slurry of fine particulate) that can be transported into the drift invert (near-field) and beyond (far-field).

Table 6.3-2. Base Case Configurations: External (Near-Field and Far-Field) Criticality FEPs

FEP Number	FEP Name	FEP Description
2.1.14.17.0A	Near-field criticality	Near-field criticality occurs when fissile material-bearing solution from the waste package is transported into the drift and the fissile material is precipitated into a critical configuration. Potential near-field critical configurations are defined in Figure 3.3a of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]). In-package criticality resulting from disruptive events is addressed in separate FEPs.
2.2.14.09.0A	Far-field criticality	Far-field criticality occurs when fissile material-bearing solution from the waste package is transported beyond the drift and the fissile material is precipitated into a critical configuration. Potential far-field critical configurations are defined in Figure 3.3b of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]). In-package criticality resulting from disruptive events is addressed in separate FEPs.

Source: Table 6.1-4

Retention and release of key isotopes from degrading commercial SNF waste packages is discussed in *Geochemistry Model Abstraction and Sensitivity Studies for the 21 PWR CSNF Waste Packages* (BSC 2002 [DIRS 160638], Sections 4.1.2.1 and 4.1.2.2). The process of determining external criticality potential starts with a source term, which is the waste package effluent water containing soluble radionuclides including fissile material. A significant fraction of the fissile material in the source term can be precipitated in the near-field and far-field by mixing the effluent water with diverted water at near-neutral pH levels that has flowed around the drift. This requires a simultaneous large flow rate around the waste package and a nominal flow rate through the waste package.

The results of *Geochemistry Model Abstraction and Sensitivity Studies for the 21 PWR CSNF Waste Packages* (BSC 2002 [DIRS 160638]) show that the commercial SNF waste form is very durable being well protected by the Zircaloy cladding and very insoluble in the relatively weak chemistry of commercial SNF waste packages. Assuming an early waste package failure results in an advective flow path into the waste package, it is expected that a very insignificant amount (less than 0.5 percent) of the uranium and plutonium in commercial SNF waste packages will be released into solution and removed from the waste package during the performance period. This release value is applicable to either bathtub or flow-through waste package configurations. In addition, this result was calculated assuming that up to 10 percent of the fuel is exposed (failed) at the time of waste package breach. If 100 percent fuel exposure is assumed, the waste package is predicted to fill with corrosion products in less than 1,000 years, thereby preventing the migration of fissile material external to the waste package.

Based on 0.469 MTU per assembly (Punatar 2001 [DIRS 155635], Table 3-1), 0.5 percent corresponds to less than 50 kg of low enriched uranium (less than 5 weight percent uranium-235) for a fully loaded 21-PWR waste package. Due to the large plume (both in depth and volume) associated with the accumulation of uranium-oxide fuels in the near-field and far-field environments (BSC 2002 [DIRS 159913], Section 5.2.2) and the presence of tuff throughout the accumulation zone, 50 kg of low enriched uranium cannot form a critical configuration in the external environment.

6.3.3 SAPHIRE Basic Event Probabilities

The criticality FEPs screening analysis is an application of the *Configuration Generator Model for In-Package Criticality* (BSC 2003 [DIRS 165629]). Potential critical configurations are a result of waste package bathtub configurations in which the waste package internals degrade faster than the waste form and the neutron absorber material is flushed from the waste package.

The four events and processes required to achieve a bathtub configuration are listed as top events in Figure 6.2-3. These four events are: (1) the probability that sufficient seepage flux is available to degrade the waste package internals and flush out the neutron absorber materials (top event MS-IC-1); (2) the probability of drip shield failure (top event MS-IC-2); (3) the probability of waste package failure (top event MS-IC-3); and (4) the probability of achieving and maintaining a bathtub configuration during the performance period (top event MS-IC-4).

Each of these top events is quantified by a corresponding fault tree. Figures of these fault trees are provided in Attachment II (Figures II-5 through II-8). Each fault tree has several basic events connected by logic gates to accurately account for the relationships between the events in order to calculate the probability of occurrence of that top event. The following sections present the justification of the probability assignments to the basic events necessary to evaluate the base case internal criticality FEPs.

6.3.3.1 Top Event MS-IC-1

Water reaching the drift is an important factor in waste package degradation and criticality potential. It is associated with top event MS-IC-1 of the criticality FEPs analysis event tree (Figure II-4) and its associated fault tree inputs (Figures II-5). Two parameters characterize the seepage into the emplacement drifts – the seepage fraction (location within the drifts that see seepage) and the seepage flux rate (the volume of water entering the drift on an annual basis). The process for evaluating these parameters is presented in Attachment IV. The seepage evaluation incorporates the seepage fraction parameter into the calculation of determining the probability of achieving the minimum (or greater) seepage flux required. The seepage basic event and its value used to quantify fault tree MS-IC-1 is presented in Table 6.3-3. The justification for its value assignment is discussed in the Section 6.3.3.1.1.

Table 6.3-3. Base Case SAPHIRE Basic Event Assignment for Fault Tree MS-IC-1

Input Data Description	Input Data Probability (per waste package for all waste package types)	Justification
Sufficient water (infiltrate/condensate) reaches drift by 10,000 years BE-SEEPAGE-10K	0.0	Section 6.3.3.1.1 Assumption 5.1.6 Assumption 5.1.7

6.3.3.1.1 Minimum Seepage Flux

The seepage flux rate entering the drift is based on the Weibull distributions calculated in Attachment IV. This seepage flux is independent of both the waste form and waste package. Therefore, the seepage flux can be used for all waste forms being analyzed and are applicable for all waste forms configuration classes.

Although the seepage rate into the drift is the same for all waste forms, the probability values assigned to the minimum required seepage for the various waste forms will differ. This is because these probabilities are determined from the requirement that the seepage rates be sufficient to permit the development of particular configuration classes (degradation of the waste package internals and removal of the neutron absorber materials from the waste package) within a specified time (i.e., 10,000 years). The minimum required seepage rate is also dependent upon the size and location of the flow path from the drift overhead into the waste package. This requires evaluation of drip shield and waste package failure mechanisms and their resulting failure areas. For the calculation of the minimum required seepage, the neutron absorber materials present in the evaluated waste packages are at their specified design mass (Assumption 5.1.3).

The probability of having sufficient seepage into a waste package is based on many factors (time step of interest, breach size of the drip shield and waste package, evaporation rate, and condensation rate), all of which play an important part in determining the probability of the seepage flux.

However, the probability of attaining the minimum seepage flux for the base case criticality FEPs is calculated to be zero because the probability of drip shield failure is determined to be zero for base case conditions (refer to Sections 6.3.3.2). For base case criticality FEPs, this result is applicable for all waste form/waste package types. Basic event BE-SEEPAGE-10K in the MS-IC-1A fault tree will be utilized for all waste package types and will be assigned a value of 0.0.

6.3.3.2 Top Event MS-IC-2

Water passing through the drip shield to the waste package is an important factor in waste package degradation and criticality and is associated with top event MS-IC-2 of the criticality FEP analysis event tree (Figure II-4) and its associated fault tree (Figure II-6). Water can reach the waste package along two primary pathways – water dripping from the drift crown through a failed drip shield and water dripping from the underside of a drip shield due to evaporation/condensation. The first pathway can occur if the dripping water from the drift overhead passes through a failed area on the drip shield onto the waste package. The second pathway can occur if water condenses on the underside of a drip shield and falls onto the waste package. However, as discussed previously in Section 6.3.1, evaporation and condensation are not considered in this evaluation as the TSPA-LA condensation model is not yet available.

Water pathways through the drip shield can be created by corrosion and/or gaps caused by the drip shield response to events such as seismic activity and emplacement errors. Drip shield failures can be categorized as being caused by either time-dependent or time-independent mechanisms. Corrosion failure mechanisms are time-dependent and may be active or inactive during the performance evaluation period.

Time-independent drip shield failure mechanisms are defined as those failure mechanisms that can occur randomly from the time of initial emplacement. Drip shield emplacement errors, rockfall, or seismic events are types of time-independent failure mechanisms that can potentially result in immediate creation of an advective pathway through the drip shield. In certain cases,

such as fabrication errors, the failure mechanism is an initiator that exacerbates corrosion (a time-dependent mechanism).

The drip shield failure mechanisms identified in *Configuration Generator Model for In-Package Criticality* (BSC 2003 [DIRS 165629], Figures II-2 and II-3) are discussed in the remainder of this section. The intent of these discussions is to justify the basic event probability values used in the evaluation of the base case criticality FEPs. Drip shield failure is defined as those drip shield damage mechanisms that can result in an advective flow path through the drip shield and onto the waste package surface. Drip shield failure could be the result of a crack in the drip shield surface or from the catastrophic failure of the complete drip shield. As will be discussed, not all drip shield damage results in the failure of the drip shield's primary function.

The drip shield failure basic event probability values are presented in Table 6.3-4. The list of failure mechanisms developed for the configuration generator model is based on the available information from TSPA-SR. It should be noted that drip shield failure due to floor heave identified in *Configuration Generator Model for In-Package Criticality* (BSC 2003 [DIRS 165629], Figure II-2) is not considered in this analysis. Floor heave was discredited as a drip shield failure mechanism in *Engineered Barrier System Features, Events, and Processes* (BSC 2003 [DIRS 166464], Section 6.2.30). The BE-DS-FLOOR-HEAVE basic event has therefore been removed from the MS-IC-2 fault tree.

Table 6.3-4. SAPHIRE Basic Event Assignment for Fault Tree MS-IC-2

Input Data Description	Input Data Probability (per drip shield for all waste package types)	Justification
Drip shield degrades due to general corrosion within 10,000 years. BE-DS-GENCOR-10K	0.0	Section 6.3.3.2.1
Drip shield degrades due to crevice corrosion within 10,000 years (form of localized corrosion). BE-DS-CREVICE-10K	0.0	Section 6.3.3.2.2
Drip shield degrades due to pitting corrosion within 10,000 years (form of localized corrosion). BE-DS-PITTING-10K	0.0	Section 6.3.3.2.2
Drip shield degrades due to stress corrosion cracking within 10,000 years. BE-DS-SCC-10K	0.0	Section 6.3.3.2.3
Drip shield emplacement error. BE-DS-EMPLACEMENT	0.0	Section 6.3.3.2.4
Drip shield fails due to fabrication error (early failure). BE-DS-FABRICATION	0.0	Section 6.3.3.2.5
Drip shield fails due to thermal expansion. BE-DS-THERM-EXPAN	0.0	Section 6.3.3.2.6
Drip shield failure due to seismic event. BE-DS-SEISMIC	0.0	Section 6.3.3.2.7
Drip shield failure due to rockfall of sufficient size. BE-DS-ROCK-FALL	0.0	Section 6.3.3.2.8

6.3.3.2.1 General Corrosion Failure of the Drip Shield

This is a time-dependent drip shield failure mechanism. As stated in *WAPDEG Analysis of Waste Package and Drip Shield Degradation* (BSC 2003 [DIRS 161317], Section 6.6.2 and

Figure 37), the earliest failure of the drip shield due to general corrosion does not occur until after 10,000 years (approximately 47,500 years). However, these results cannot be referenced as they require confirmation by TSPA-LA (BSC 2003 [DIRS 161317], Section 1).

It is assumed that TSPA-LA will show there are no general corrosion failures of the drip shield before 10,000 years (Assumption 5.1.1) and, therefore, the probability of drip shield failure due to general corrosion during the performance period is zero. The probability of basic event BE-DS-GENCOR-10K is, therefore, set to 0.0.

6.3.3.2.2 Localized Corrosion Failure of the Drip Shield

This is a time-dependent drip shield failure mechanism. As discussed in Section 6.3.3.2.5, drip shield fabrication errors can result in localized corrosion. *General Corrosion and Localized Corrosion of the Drip Shield* (BSC 2003 [DIRS 161236], Section 6.4.3) states that “Localized corrosion of Titanium Grade 7 would not initiate in a repository-relevant environment...” Therefore, the probabilities of basic events BE-DS-PITTING-10K and BE-DS-CREVICE-10K are set to 0.0.

6.3.3.2.3 Stress Corrosion Cracking Failure of the Drip Shield

This is a time-dependent drip shield failure mechanism. As discussed in Section 6.3.3.2.5, drip shield fabrication errors can result in the formation of stress corrosion cracks. *Stress Corrosion Cracking of the Drip Shield, the Waste Package Outer Barrier, and the Stainless Steel Structural Material* (BSC 2003 [DIRS 161234], Section 6.3.7) states that stress corrosion cracks are expected to fill with corrosion products or be plugged with precipitates such as carbonate. Stress corrosion cracks are expected to be sealed within a few hundred years if water flows through the cracks at the expected very low film flow rate. If the cracks are bridged by water, the sealing process may take several thousand years, but no flow occurs. Because of the high density of the crack plugging materials and the lack of a pressure gradient to drive water through the crack, the probability of flow through the plugged crack approaches zero.

Given the very low flow rates through a stress corrosion crack in the drip shield for at most a few hundred years, it is concluded that stress corrosion cracking does not prevent the drip shield from fulfilling its primary role to keep water from contacting the waste packages. The probability of basic event BE-DS-SCC-10K is set to 0.0.

6.3.3.2.4 Emplacement Error Failure of the Drip Shield

This is a time-independent drip shield failure mechanism. The probability of a drip shield emplacement error is calculated in *Analysis of Mechanisms for Early Waste Package/Drip Shield Failure*, (BSC 2003 [DIRS 164475], Section 6.3.7) as having a median value of 6.0×10^{-6} per drip shield with an error factor of 4.7. The 5th percentile, the 95th percentile, and the mean values are calculated to be 1.3×10^{-6} , 2.8×10^{-5} , and 9.3×10^{-6} , respectively.

However, *Analysis of Mechanisms for Early Waste Package/Drip Shield Failure* (BSC 2003 [DIRS 164475], Section 6.4.7) goes on to state that there are no credible consequences of a drip shield emplacement error. Because the gap between two adjacent drip shields improperly

interlocked is expected to be small, water from the drift is not expected to fall directly onto an underlying waste package. Because of the drip shield interlock geometry, water will most likely first hit the lower drip shield's connecting plate and be diverted from the waste package surface. Therefore, although a drip shield emplacement error is probable, the drip shield failure area due to such an emplacement error is zero. Because the primary function of the drip shield (to prevent advective flow onto the waste package) is not compromised, the value of basic event BE-DS-EMPLACEMENT is set to 0.0.

6.3.3.2.5 Fabrication Error Failure of the Drip Shield

This is a time-independent drip shield failure mechanism. Four drip shield fabrication errors are identified in *Analysis of Mechanisms for Early Waste Package/Drip Shield Failure*, (BSC 2003 [DIRS 164475], Table 20) as having the potential to increase the susceptibility of the drip shield to stress corrosion cracking or localized corrosion. These fabrication errors are weld flaws, base metal flaws, improper heat treatment, and damage by mishandling.

However, *General Corrosion and Localized Corrosion of the Drip Shield* (BSC 2003 [DIRS 161236], Section 6.4.3) states that "Localized corrosion of Titanium Grade 7 would not initiate in a repository-relevant environment..." In addition, *Stress Corrosion Cracking of the Drip Shield, the Waste Package Outer Barrier, and the Stainless Steel Structural Material* (BSC 2003 [DIRS 161234], Section 6.3.7) states that stress corrosion cracks are expected to fill with corrosion products or be plugged with precipitates such as carbonate. Stress corrosion cracks are expected to be sealed within a few hundred years if water flows through the cracks at the expected very low film flow rate. If the cracks are bridged by water, the sealing process may take several thousand years, but no flow occurs. Because of the high density of the crack plugging materials and the lack of a pressure gradient to drive water through the crack, the probability of flow through the plugged crack approaches zero.

Since neither localized corrosion or stress corrosion cracking will result in an advective flow area through the drip shield, the drip shield failure area associated with drip shield fabrication errors is zero. Therefore, because the primary function of the drip shield is not compromised the value of basic event BE-SE-FABRICATION is set to 0.0.

6.3.3.2.6 Thermal Expansion Failure of the Drip Shield

This is a time-independent drip shield failure mechanism. As stated in *EBS Radionuclide Transport Abstraction* (BSC 2003 [DIRS 166466], Section 6.3.1.3), "Thermal expansion will produce minor structural response in relation to the potential slippage or overlap between adjacent drip shields for the as-emplaced drip shield configuration. This mechanism has therefore been screened out from the TSPA-LA..." Therefore, the probability of basic event BE-DS-THERM-EXPAN is set to 0.0.

6.3.3.2.7 Seismic Failure of the Drip Shield

This is a time-independent drip shield failure mechanism. Seismic failures of the drip shield are not considered during the base case criticality FEPs analysis. This failure mechanism is only

considered during the evaluation of the seismic disruptive event criticality FEPs analysis (Section 6.4). Therefore, the probability of basic event BE-DS-SEISMIC is set to 0.0.

6.3.3.2.8 Rockfall Failure of the Drip Shield

This is a time-independent drip shield failure mechanism. Rockfall failures of the drip shield are not considered during the base case criticality FEPs analysis. This failure mechanism is only considered during the evaluation of the rockfall disruptive event criticality FEPs (Section 6.5). Therefore, the probability of basic event BE-DS-ROCK-FALL is set to 0.0.

It should be noted that rockfall damage to the drip shield due to a seismic event is accounted for in the BE-DS-SEISMIC1 basic event during the seismic initiating event evaluation presented in Section 6.4.

6.3.3.3 Top Event MS-IC-3

The ability for water to enter a failed waste package is an important factor in waste package degradation and criticality and is associated with top event MS-IC-3 of the criticality FEP analysis event tree (Figure II-4) and its associated fault tree (Figures II-7). Water pathways into the waste package can be created by corrosion and/or failures caused by the waste package response to events such as seismic activity and fabrication errors. Waste package failures can be categorized as being caused by either time-dependent or time-independent mechanisms. Corrosion failure mechanisms are time-dependent and may be active or inactive during the performance evaluation period.

Time-independent waste package failure mechanisms are defined as those failure mechanisms that can occur randomly from the time of initial emplacement. A seismic event is a type of time-independent failure mechanism that can potentially result in immediate creation of an advective pathway into the waste package. In certain cases, such as fabrication errors, the failure mechanism is an initiator that exacerbates corrosion (a time-dependent mechanism).

The waste package failure mechanisms identified in *Configuration Generator Model for In-Package Criticality* (BSC 2003 [DIRS 165629], Figure II-4) are discussed in the remainder of this section. The intent of these discussions is to justify the basic event probability values used in the evaluation of the base case criticality FEPs. Waste package failure is defined as those waste package damage mechanisms that can result in an advective flow path into the waste package. Waste package failure could be the result of a crack in the waste package surface or from the catastrophic failure of the complete waste package. As will be discussed, not all waste package damage results in the failure of the waste package's primary function. The basic event probability values for waste package failure are presented in Table 6.3-5.

Table 6.3-5. SAPHIRE Basic Event Assignment for Fault Tree MS-IC-3

Input Data Description	Input Data Probability (per waste package for all waste package types)	Justification
Waste package degrades due to general corrosion within 10,000 years. BE-WP-GENCOR-10K	0.0	Section 6.3.3.3.1

Input Data Description	Input Data Probability (per waste package for all waste package types)	Justification
Waste package degrades due to crevice corrosion within 10,000 years (form of localized corrosion). BE-WP-CREVICE-10K	0.0	Section 6.3.3.3.2
Waste package degrades due to pitting corrosion within 10,000 years (form of localized corrosion). BE-WP-PITTING-10K	0.0	Section 6.3.3.3.2
Waste package degrades due to stress corrosion cracking within 10,000 years. BE-WP-SCC-10K	0.0	Section 6.3.3.3.3
Early failure of waste package. BE-WP-EARLY-F	2.8×10^{-5}	Section 6.3.3.3.4
Waste package failure due to seismic event. BE-WP-SEISMIC	0.0	Section 6.3.3.3.5

6.3.3.3.1 General Corrosion Failure of the Waste Package

This is a time-dependent waste package failure mechanism. As stated in *WAPDEG Analysis of Waste Package and Drip Shield Degradation* (BSC 2003 [DIRS 161317], Section 6.6.2 and Figure 36), the earliest patch failure of the waste package due to general corrosion does not occur until after 10,000 years (approximately 120,000 years). However, this information cannot be referenced as it requires confirmation by TSPA-LA (BSC 2003 [DIRS 161317], Section 1).

It is assumed that TSPA-LA will show that there are no general corrosion failures of the waste package before 10,000 years (Assumption 5.1.1) and, therefore, the probability of waste package failure due to general corrosion during the performance period is zero. The probability of basic event BE-WP-GENCOR-10K is, therefore, set to 0.0.

6.3.3.3.2 Localized Corrosion Failure of the Waste Package

This is a time-dependent waste package failure mechanism. As stated in *WAPDEG Analysis of Waste Package and Drip Shield Degradation* (CRWMS M&O 2000 [DIRS 151566], Section 6.5.1), localized corrosion does not initiate for the waste package because the exposure conditions on the waste package surface are not severe enough. However, because this information was initially developed for TSPA-SR, it cannot be referenced as it requires confirmation by TSPA-LA.

TSPA-LA results will show that there are no localized corrosion failures of the waste package before 10,000 years (Assumption 5.1.1) and, therefore, the probability of waste package failure due to localized corrosion during the performance period is zero. The probabilities of basic events BE-WP-PITTING-10K and BE-WP-CREVICE-10K are therefore set to 0.0.

6.3.3.3.3 Stress Corrosion Cracking Failure of the Waste Package

This is a time-dependent waste package failure mechanism. As stated in *WAPDEG Analysis of Waste Package and Drip Shield Degradation* (BSC 2003 [DIRS 161317], Section 6.6.2 and Figure 38), the earliest crack failure of the waste package due to stress corrosion cracking does not occur until after 10,000 years (approximately 120,000 years). However, this information

cannot be referenced as it requires confirmation by TSPA-LA (BSC 2003 [DIRS 161317], Section 1).

It is assumed that TSPA-LA will show that there are no stress corrosion cracking failures of the waste package before 10,000 years (Assumption 5.1.1) and, therefore, the probability of waste package failure due to stress corrosion cracking during the performance period is zero. The probability of basic event BE-WP-SCC-10K is, therefore, set to 0.0.

6.3.3.3.4 Early Failure of the Waste Package

This is a time-independent waste package failure mechanism. Four waste package fabrication errors are identified in *Analysis of Mechanisms for Early Waste Package/Drip Shield Failure*, (BSC 2003 [DIRS 164475], Table 20) as having the potential to increase the susceptibility of the waste package to stress corrosion cracking or localized corrosion. These fabrication errors are weld flaws, improper heat treatment, improper laser peening, and damage by mishandling.

After ultrasonic testing inspection, the mean probability of the occurrence of one or more weld flaws in the upper and middle closure lids is 0.18 and 0.20, respectively (BSC 2003 [DIRS 164475], Table 13). For the waste package seam weld, the mean probability increases to 0.46 (BSC 2003 [DIRS 164475], Table 13). The residual stresses/stress intensity factors resulting from weld flaws may induce stress corrosion cracking. However, as noted in Section 6.3.3.3.3, the earliest crack failure of the waste package due to stress corrosion cracking is not predicted to occur until after 10,000 years (approximately 120,000 years) (BSC 2003 [DIRS 161317], Figure 38). As noted in Section 6.3.3.3.3, it is assumed that TSPA-LA will confirm the results of evaluations of waste package failures due to stress corrosion cracking as required by *WAPDEG Analysis of Waste Package and Drip Shield Degradation* (BSC 2003 [DIRS 161317], Section 1) (Assumption 5.1.1).

The probability of improper heat treatment has been combined with the probabilities of improper laser peening and damage by mishandling. From the information presented in Table 4.1-5, this event has been calculated to have a median value of 7.2×10^{-6} per waste package with an error factor of 15. The mean value has been calculated to be 2.8×10^{-5} per waste package. The probability of having at least one waste package early failure in the repository due to improper heat treatment has been calculated to be 0.17 (BSC 2003 [DIRS 161317], Table 46). An average of 1.8 waste package failures are calculated from the information provided in Table 47 of *WAPDEG Analysis of Waste Package and Drip Shield Degradation* (BSC 2003 [DIRS 161317]). Recommendations from *Analysis of Mechanisms for Early Waste Package/Drip Shield Failure* (BSC 2003 [DIRS 164475], Section 6.4.8) include that the entire waste package surface should be considered affected by a waste package early failure due to an improper heat treatment.

Based on the information above, the basic event value for waste package early failure, BE-WP-EARLY-F, is set to 2.8×10^{-5} . This is appropriate since the SAPHIRE event tree evaluations are performed on a per waste package basis.

6.3.3.3.5 Seismic Failure of the Waste Package

This is a time-independent waste package failure mechanism. Seismic failures of the waste package are not considered during the base case criticality FEPs analysis. This failure mechanism is only considered during the evaluation of the seismic disruptive event criticality FEPs (Section 6.4). Therefore, the probability of basic event BE-WP-SEISMIC is set to 0.0.

6.3.3.4 Top Event MS-IC-4

Water accumulating in a waste package is associated with top event MS-IC-4 of the criticality FEPs analysis event tree (Figure II-4) and its associated fault tree (Figure II-8). The parameters associated with the formation of a waste package bathtub configuration are the likelihood that the waste package failure locations will support a bathtub formation and that the waste package degradation processes will maintain this configuration for a sufficient time period to degrade the waste package internals, flush the neutron absorber materials from the waste package, and allow for the generation of a potentially critical configuration. The process for evaluating these parameters is presented in *Configuration Generator Model for In-Package Criticality* (BSC 2003 [DIRS 165629], Section 6.6.6). The basic events necessary to quantify fault tree MS-IC-4 are summarized in Table 6.3-6. The justification for their value assignment is discussed in the remainder of this section.

Table 6.3-6. SAPHIRE Basic Event Assignment for Fault Tree MS-IC-4

Input Data Description	Input Data Probability (per waste package for all waste package types)	Justification
Probability of being in a bathtub at 10,000 years for general corrosion waste package failures BE-BATHTUB-10K	0.0	Section 6.3.3.4.1
Probability of being in a bathtub at 10,000 years for nongeneral corrosion waste package failures BE-BATHTUB-10K	1.0	Section 6.3.3.4.1
Bathtub configuration formed for general corrosion BE-MS-IC-4	0.0	Section 6.3.3.4.2
Bathtub configuration formed for nongeneral corrosion waste package failures BE-MS-IC-4	1.0	Section 6.3.3.4.2

6.3.3.4.1 Duration of Bathtub Configuration

A bathtub configuration is when a breach, or failure, on the top part of the waste package occurs prior to a breach or failure on the bottom part. The duration of flooding conditions, which last as long as the bottom surface is intact, is a function of the waste package failure mechanisms, evaluated as:

- Start time for accumulating water = First failure time at top of outer barrier
- Start time for flow-through geometry = First failure time at bottom of outer barrier
- Bathtub Duration Time = Start time for flow-through geometry – Start time for accumulating water.

Possible closure of the bottom failures converting a flow-through geometry into a bathtub arrangement are considered to be very unlikely since a second patch failure is likely to occur within a relatively short period (CRWMS M&O 2000 [DIRS 151566], Figure 24).

Bathtub configuration duration starts at the time of first breach of the waste package and stops at the occurrence of a breach of the waste package bottom or at the end of the performance period, whichever comes first. For waste package failures resulting from general corrosion, the earliest failure of the waste package occurs at 120,000 years (BSC 2003 [DIRS 161317], Section 6.6.2 and Figure 36). Since the first waste package failure does not occur until substantially after the end of the performance period, the probability of maintaining a bathtub configuration during the performance period for general corrosion waste package failures is 0.0. This value is assigned to basic event BE-BATHTUB-10K. It should be noted that, as stated in Section 6.3.3.3.1, the information from *WAPDEG Analysis of Waste Package and Drip Shield Degradation* (BSC 2003 [DIRS 161317]) requires confirmation by TSPA-LA (BSC 2003 [DIRS 161317], Section 1). It is assumed (Assumption 5.1.1) that TSPA-LA will confirm general corrosion of the waste package outer barrier does not occur until well after 10,000 years.

However, no information is available for the duration of bathtub configurations resulting from any waste package failure mechanism other than general corrosion. It is conservative to assume that if a bathtub configuration is formed, it will endure for the remainder of the performance period (Assumption 5.2.1) as this will maximize the BATHTUB-CONFIG end state probability of Figure 6.2-3. Therefore, for nongeneral corrosion waste package failures, basic event BE-BATHTUB-10K is assigned a value of 1.0.

6.3.3.4.2 Probability of Bathtub Configuration Formation

The first failure location on the waste package can occur either on its top or bottom. Only waste package top failures can result in the formation of a bathtub configuration. The probability of bathtub configuration formation has been previously calculated based on the results of *WAPDEG Analysis of Waste Package and Drip Shield Degradation* (CRWMS M&O 2000 [DIRS 151566]). But this evaluation is only applicable to waste package failures due to general corrosion. However, since the currently calculated mean first failure of the waste package due to general corrosion does not occur until 120,000 years (BSC 2003 [DIRS 161317], Figure 36), the probability of forming a bathtub configuration during the performance period as a result of general corrosion is 0.0. Therefore, basic event BE-MS-IC-4 is assigned a value of 0.0 for general corrosion waste package failure mechanisms.

It should be noted that, as stated in Section 6.3.3.3.1, the information from *WAPDEG Analysis of Waste Package and Drip Shield Degradation* (BSC 2003 [DIRS 161317]) requires confirmation by TSPA-LA (BSC 2003 [DIRS 161317], Section 1). It is assumed (Assumption 5.1.1) that TSPA-LA will confirm general corrosion of the waste package outer barrier does not occur until well after 10,000 years.

No information is available for the formation of bathtub configurations resulting from any waste package failure mechanism other than general corrosion. It is conservative to assume that if an event, such as a seismic event, results in damage to the waste package, this damage occurs on the top of the waste package (Assumption 5.2.1) and a bathtub configuration is formed. This

assumption will maximize the BATHTUB-CONFIG end state probability of Figure 6.2-3. Therefore, basic event BE-MS-IC-4 is assigned a value of 1.0 for all waste package failure mechanisms other than general corrosion.

6.3.4 Base Case Criticality FEPs Analysis Results

6.3.4.1 In-Package Results

The probabilities of waste package flooding at the end of the performance period are shown in Table 6.3-7. These probability results have been generated to address in-package criticality FEPs. Because there is no mechanism to breach the drip shield for these base case criticality FEPs during the performance period, there is no probability of water entering the waste package and generating a bathtub configuration. Therefore, the probability of waste package flooding is zero and there is no probability of criticality for the in situ criticality FEPs presented in Table 6.3-1.

Table 6.3-7. Per Waste Package Flooding Probabilities for Base Case Criticality FEPs

Waste Package Type	Number of Waste Packages ^a	Per Waste Package Flooding Probability ^b
21-PWR with Absorber Plates	4,299	0.00E+00
21-PWR with Control Rods	95	0.00E+00
12-PWR Long	163	0.00E+00
44 BWR	2,831	0.00E+00
24 BWR	84	0.00E+00
DOE SNF	3,412 ^c	0.00E+00

Source: ^a Values from Table 4.1-8

^b SAPHIRE V7.18 (BSC 2002 [DIRS 160873]) analysis results (Attachment II, p. II-20)

^c Sum of 5-DHLW/DOE SNF Short, 5DHLW/DOE SNF Long and 2-MCO/2-DHLW Long values from Table 4.1-8

6.3.4.2 External Probability Results

External criticality FEPs can originate from either a bathtub or flow-through waste package configuration. However, because there is no mechanism to breach the drip shield during the performance period under base case conditions, there is no probability of water entering the waste package. Therefore, there is no probability of criticality for the external criticality FEPs presented in Table 6.3-2.

6.4 ANALYSIS OF SEISMIC DISRUPTIVE EVENT CRITICALITY FEPs

The seismic disruptive event criticality FEPs are presented in Table 6.4-1.

Table 6.4-1. Seismic Disruptive Event Criticality FEPs

FEP Number	FEP Title	FEP Description
2.1.14.18.0A	In-package criticality resulting from a seismic event (intact configuration)	The waste package internal structures and the waste form remain intact either during or after a seismic disruptive event. A breach (or breaches) in the waste package allow(s) water to either accumulate or flow-through the waste package. Criticality then occurs in situ.
2.1.14.19.0A	In-package criticality resulting from a seismic event (degraded configurations)	Either during, or as a result of, a seismic disruptive event, the waste package internal structures and the waste form degrade. A critical configuration develops and criticality occurs in situ. Potential in situ critical configurations are defined in Figures 3.2a and 3.2b of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]).
2.1.14.20.0A	Near-field criticality resulting from a seismic event	Either during, or as a result of, a seismic disruptive event, near-field criticality occurs when fissile material-bearing solution from the waste package is transported into the drift and the fissile material is precipitated into a critical configuration. Potential near-field critical configurations are defined in Figure 3.3a of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]).
2.2.14.10.0A	Far-field criticality resulting from a seismic event	Either during, or as a result of, a seismic disruptive event, far-field criticality occurs when fissile material-bearing solution from the waste package is transported beyond the drift and the fissile material is precipitated into a critical configuration. Potential far-field critical configurations are defined in Figure 3.3b of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]).

Source: Table 6.1-4

Vibratory ground motion and rockfall induced by a seismic event can cause damage to the drip shield and waste package allowing the influx of seepage into the waste package, which has the potential to cause a criticality. A seismic event can also induce fault displacement, which can lead to damage of the drip shield and waste package that can also allow advective flow into the waste package and lead to a potential criticality. Additionally, new fractures that intersect the drift segments and the collapsing of the drift as a result of a seismic event would have an affect on the seepage water. This change in seepage water onto damaged waste packages may increase their potential for criticality. Table 6.4-1 presents the seismic disruptive event criticality FEPs 2.1.14.18.0A, 2.1.14.19.0A, 2.1.14.20.0A, and 2.2.14.10.0A, which may initiate a sequence of events that can lead to a potential critical event. The direct and indirect effects of seismic activities on in-package criticality, near field criticality, and far field criticality are analyzed in this section.

Because uncertainty is an important part of any analysis, it is included in the seismic evaluation of potential in-package criticality. Uncertainty is included throughout the evaluation by the development of probability distributions sampled via a Latin Hypercube Sampling method. The principle of Latin Hypercube Sampling is provided by Modarres (1993 [DIRS 104667], p. 244). The developed probability distributions represent the epistemic uncertainty for the parameters of interest. An example is the damaged area of a drip shield depending upon the PGV of the seismic event. The analysis will develop a probability distribution representing the epistemic uncertainty about the damaged area of the drip shield and then sample this distribution to obtain the damaged area based on the seismic event.

The developed Latin Hypercube Sampling method evaluates the epistemic uncertainty of all input parameters either developed within the evaluation (e.g., probability distribution for

damaged area of drip shield based on PGV of seismic event) or based on other reports. An example of an external parameter with its epistemic uncertainty accounted for in the Latin Hypercube Sampling method would be the seepage rate. By using the Latin Hypercube Sampling method, uncertainty is handled in the seismic evaluation of in-package criticality.

It should be noted, in addition to the assumption referenced directly by this section, several assumptions from the supporting documents used in the development of the seismic disruptive event criticality FEPs analysis are listed in Section 5.2.3. Although not referenced directly by this analysis, these assumptions may influence the reported results.

6.4.1 Seismic Ground Motion Effects on In-Package Criticality Evaluations

A seismic event has the potential to lead to a critical event by causing damage to the drip shield and waste package, which can allow advective flow to penetrate the damaged waste package. Water moderation is an important factor that is required for criticality. This section will use the information from *Seismic Consequence Abstraction* (BSC 2003 [DIRS 161812]), *Boron Loss from CSNF Waste Packages* (BSC 2003 [DIRS 165890]) and *Abstraction of Drift Seepage* (BSC 2003 [DIRS 165564]) to evaluate the probability of sufficient seepage penetrating a damaged waste package, which can lead a criticality.

6.4.1.1 Base Case Seismic Evaluation

The following sections are based on the nominal design of the commercial SNF waste packages. This part of the analysis is deemed base case.

6.4.1.1.1 Seismic Effects in the Lithophysal Zone

A seismic event can affect the drip shield, waste package, and cladding from vibratory ground motion and induced rockfall. A seismic event can also affect the seepage of water into the drift from new fractures or the collapsing of the drift. Seepage is an important factor that can lead to a waste package criticality. Seepage is required to degrade and flush out the neutron absorbing material and provide moderation. In order for seepage to penetrate the waste package and potentially lead to a criticality, multiple barriers must be breached. A seismic event can breach these barriers, which are the drip shield and the waste package outer barrier. Breaching (i.e., percent damaged area) of a drip shield and waste package due to vibratory ground motion will be analyzed below. In addition, the development and use of seepage rate distributions along with the evaluation of the degradation and flushing of the neutron absorbing material from a damaged waste package.

The drip shield failure for this analysis is divided into two separate repository geological zones—nonlithophysal and lithophysal—require a separate evaluation because of the different effects induced by a seismic event on a drip shield. In addition, seepage water is affected within each of these zones because of drift fracturing or collapse. The lithophysal zone represents approximately 85 percent of the total repository drift area (refer to Section 6.2).

The damage to a waste package is the same for both repository drift zones because rockfall cannot impact the waste package, since the drip shield protects it. Therefore, waste package damage is independent of location within the repository.

Drip Shield and Waste Package Damage

Drifts in the lithophysal zone are expected to collapse during a seismic event and the void area between the drip shield and the drift area to become filled. The collapse of the drift in this area does not damage the drip shield because the rock type is very low in compressive strength and is permeated with void spaces (BSC 2003 [DIRS 161812], Section 6.6.2). This weak rock is expected to collapse into small fragments under the load imposed by the vibratory ground motion. Any damage to the drip shield in this zone is expected to occur only from the vibratory ground motion.

To account for the damage to the drip shield, *Seismic Consequence Abstraction* (BSC 2003 [DIRS 161812], Section 6.6.3) developed an abstraction used to calculate the percent damaged area of the drip shield. A Mathcad spreadsheet is developed (Attachment III) to use the seismic inputs from Section 4.1.2 and account for the uncertainty in the percent damaged area of the drip shield by performing a Latin Hypercube Sampling process.

The process to calculate the percent damaged area on the drip shield is outlined in *Seismic Consequence Abstraction* (DTN: MO0308SPACALSS.002 [DIRS 164822]). The process discusses sampling the mean annual exceedance frequency for a seismic event to obtain a PGV value. The mean annual seismic exceedance frequency follows a uniform distribution between 1.0×10^{-8} to 1.0×10^{-4} . The sampled mean annual seismic exceedance frequency is used to obtain the corresponding PGV value from log-linear interpolation of the lookup table (refer to Table 4.1-2). The interpolated PGV value is used to determine the upper and lower bounds of the uniform distribution representing the percent damaged area of the drip shield.

The upper-bound percent damaged area is interpolated from Table 4.1-4 based on the sampled PGV value. This interpolated upper-bound value is input into a uniform distribution for the percent damaged area of the drip shield. The lower bound of the uniform distribution is also determined by interpolation. The lower-bound percent damaged area uses the lookup table shown in Table 4.1-3. The lower-bound percent damaged area is based on the same sampled PGV value. Once the lower and upper bounds of the uniform distribution are obtained, this distribution is then sampled to calculate the percent damaged area of the drip shield for that particular seismic event. This percent damaged area value is stored within the Mathcad spreadsheet.

The process then repeats with a newly sampled mean seismic exceedance frequency. This newly sampled mean seismic exceedance frequency leads to a new percent damaged area of the drip shield based on that seismic event. This process is continued for 20,000 realizations. From these (refer to Attachment III, p. III-7), the mean fraction of damaged area on the drip shield (i.e., percent damage divided by 100) from sampled vibratory ground motions is 2.23×10^{-3} and the 5th and 95th are 0.0 and 6.49×10^{-3} , respectively.

The waste package is also damaged due to vibratory ground motion in the lithophysal zone. The damage to the waste package is calculated in the same manner as that done for the drip shield. The only difference between these two calculations is how the upper-bound value for the uniform distribution representing the percent damaged area of the waste package is calculated. The upper-bound value for the uniform distribution is calculated using Equation 6.4-1.

$$WP_{upperbound} = 0.436 \cdot PGV - 0.305 \quad (\text{Eq. 6.4-1})$$

The upper-bound value is calculated by inputting the sampled PGV value, which is obtained from log-linear interpolation of the lookup table (Table 4.1-2) based on the sampled mean annual seismic exceedance frequency. The lower-bound value for the uniform distribution is set to zero. This uniform distribution is then sampled to obtain the percent damaged area of the waste package due to that seismic event. As discussed for the drip shield, the process starts all over again by sampling a new mean annual seismic exceedance frequency, which is used to calculate a PGV value. This newly calculated PGV value is used to calculate the upper-bound value for the uniform distribution that represents the percent damaged area of the waste package. This newly created uniform distribution is then sampled to obtain the new percent damaged area of the waste package for that seismic event. This process continues for 20,000 realizations. From these, the mean fraction of damaged area on the waste package outer barrier (i.e., percent damage divided by 100) is 2.58×10^{-4} and the 5th and 95th percentiles are 0 and 1.47×10^{-3} , respectively (Attachment III, p. III-9).

The fraction of damaged area (i.e., percent damage divided by 100) calculated above occurs on all of the drip shields and waste packages in the lithophysal zone of the repository; therefore, the probability that a drip shield or waste package is damaged due to a seismic event is 1.0. It is assumed that this damaged area occurs on the top of the drip shield and waste package allowing advective flow through the drip shield and into the waste package, forming a bathtub configuration (Assumption 5.2.1). This probability is input into basic events BE-DS-SEISMIC1 and BE-WP-SEISMIC1, which are substituted for basic events BE-DS-SEISMIC and BE-WP-SEISMIC of fault trees MS-IC-2 and MS-IC-3, respectively. These fault trees are used in the SAPHIRE evaluation of the seismic disruptive event criticality FEPs.

Although it is possible to have seismic induced damage on a waste package already damaged due to an early failure event, the probability of damage due to a seismic event is greater than that of an early failure. Therefore, the probability of damage from a seismic event (i.e., probability of 1.0) overwhelms the probability (i.e., probability of 2.8×10^{-5}) of damage occurring from an early failure. The damaged area on a waste package from a seismic event is smaller (BSC 2003 [DIRS 161812], Section 6.6.3) than that recommended to be modeled for an early failure (BSC 2003 [DIRS 164475], Section 6.4.8), however, by including the probability of each event, damage to the waste package from early failure becomes negligible. For these reasons, basic event BE-WP-EARLY-F is replaced by basic event BE-WP-EARLY-F1 during the seismic initiating event evaluations. The probability of BE-WP-EARLY-F1 is set to 0.0.

Seepage Rate Probability Distribution for Lithophysal

The process used to determine the seepage rate distribution, which is used to calculate the seepage probability, follows process steps discussed in *Abstraction of Drift Seepage* (BSC 2003 [DIRS 165564], Section 6.7.1). The determination of the seepage rate distribution is discussed below and presented in Attachment IV.

In order to determine seepage rate distribution, a Latin Hypercube Sampling method was developed to handle spatial variability and uncertainty. The routine sampled each input for

20,000 realizations to ensure sufficient coverage of the parameter range. Three key parameters are sampled to determine the seepage rate distribution.

The first parameter, capillary strength (l/α), is determined to have a spatial variability that is uniformly distributed with a range between 402 Pa to 780 Pa, and a mean of 591 Pa. The uncertainty about the capillary strength, $\Delta l/\alpha$, follows a triangular distribution with a lower bound of -105 Pa, upper bound of $+105$ Pa, and a mean of 0.0. These distributions are identical for all geological zones. The Latin Hypercube Sampling method samples a capillary strength value from the spatial variability and adds it to the sampled capillary strength value from the uncertainty distribution. This calculated capillary strength is used in the interpolation process along with the other sampled key parameters to determine the seepage rate. This sampling process is performed for 20,000 realizations.

The next key parameter for the lithophysal zone, permeability (k), is determined to have a spatial variability distribution that is lognormal with a mean of -11.5 (in log 10) and a standard deviation of 0.47 (in log 10). The mean and standard deviation of permeability was determined from statistical analysis on the log-transformed data (BSC 2003 [DIRS 165564], Section 6.6.2.1). The permeability uncertainty (Δk) follows a triangular distribution with a lower bound of -0.92 , upper bound $+0.92$, and a mean of 0.0. These distributions are for the lithophysal zone only. The Latin Hypercube Sampling method samples a permeability value from the spatial variability and adds it to the sampled permeability value from the uncertainty distribution. This calculated permeability is used in the interpolation process along with the other sampled key parameters to determine the seepage rate. This sampling process is performed for 20,000 realizations.

Percolation flux is sampled from the percolation flux information that represents the repository area (BSC 2003 [DIRS 165564], Figure 6.6-10). The sampling process uses glacial transition climate percolation flux information, which occurs 2,000 years after repository closure and lasts through the regulatory period of 10,000 years (USGS 2001 [DIRS 158378], Section 6.6.1). The percolation flux uncertainty is expressed by three different scenarios (lower-bound, mean, and upper-bound). Since there are three different scenarios that are used to represent the uncertainty, three different final seepage rate distributions are obtained (one for each scenario).

The percolation flux is adjusted for intermediate-scale heterogeneity by using flow focusing factors (Equation 6.4-2) (DTN: LB0104AMRU0185.012 [DIRS 163906]), which is sampled and multiplied by the sampled percolation flux. Equation 6.4-2 is the cumulative distribution function for the flow focusing factors where the variable x represents the flow focusing factor.

$$ff = -0.3137x^4 + 5.4998x^3 - 35.66x^2 + 102.3x - 11.434 \quad (\text{Eq. 6.4-2})$$

The seepage rate for each of the uncertainty scenarios (i.e., lower-bound, mean, and upper-bound) is determined using a sampling routine (refer to Attachment IV). The sampled value from the three key parameters (i.e., capillary strength, permeability, adjusted percolation flux) is used to interpolate the mean seepage rate and seepage rate standard deviation from the lookup table for the degraded drift (DTN: LB0307SEEPDRCL.002 [DIRS 164337]). The standard deviation is adjusted to account for uncertainty by creating a uniform distribution with a lower bound of -1.7321 times the sampled standard deviation and an upper bound of 1.7321 times the sampled standard deviation. The uniform distribution to account for uncertainty is sampled and

added to the interpolated mean seepage rate. This process is performed for 20,000 realizations (refer to Attachment IV).

The resulting seepage rate values are adjusted prior to being used to determine the seepage flux probability by (1) setting seepage rates less than 0.1 kg/yr per waste package to zero (since these small values are the result of interpolation (BSC 2003 [DIRS 165564], p. 173)), and (2) setting calculated seepage rates greater than 100 percent to 100.

Seepage rates are then filtered in order to develop a distribution that represents the seepage rate values by discarding all seepage rates with a zero value. The remaining nonzero seepage rates are then used to develop a Weibull distribution for each of the scenarios (i.e., lower-bound, mean, and upper-bound) to represent the seepage rate at the drift (refer to Attachment IV). These Weibull distributions are used to calculate the probability of having sufficient seepage in order to degrade and flush out the Neutronit from a seismically damaged waste package. In addition, to calculate the fraction of waste package locations with seepage, the number of nonzero seepage rates is divided by the total number of realizations (seepage fraction). The Weibull parameters, scale and shape (α and β , respectively), and seepage fraction for each scenario are listed in Table 6.4-2.

Table 6.4-2. Weibull Parameters and Seepage Fraction (Lithophysal Zone)

Weibull Parameters	Value	Seepage Fraction
Lower Bound (Drift Collapse)		
α (scale)	8.87E-03 ^a (m ³ /yr)	1.94E-01 ^b
β (shape)	5.20E-01 ^a	
Mean (Drift Collapse)		
α (scale)	1.46E-01 ^c (m ³ /yr)	5.14E-01 ^d
β (shape)	4.68E-01 ^c	
Upper Bound (Drift Collapse)		
α (scale)	3.83E-01 ^e (m ³ /yr)	6.37E-01 ^f
β (shape)	4.94E-01 ^e	

Source: ^a Attachment IV, p. IV-15

^b Attachment IV, p. IV-14

^c Attachment IV, p. IV-28

^d Attachment IV, p. IV-27

^e Attachment IV, p. IV-41

^f Attachment IV, p. IV-40

Boron Loss from Commercial SNF Waste Packages

The loss of Neutronit from a commercial SNF waste package depends on the specific commercial SNF parameters (Assumption 5.1.2) and the time a seismic event occurs. The specific commercial SNF waste package parameters are input into the boron loss equation (i.e., loss of Neutronit), which is used to calculate the required drip rate (i.e., seepage rate m³/yr). The calculated required drip rate is based on the time available for Neutronit degradation and flushing. Since the time when a seismic event occurs is random, the boron loss equation is solved for each of the 20,000 realizations. Therefore, some of the commercial SNF inputs are not constant and vary based on the randomness of the seismic event. In addition, the time required to degrade and flush out the Neutronit is limited based on when water can first penetrate

a damaged waste package, assumed to be 700 years after repository closure (Assumption 5.2.2). The boron loss equation used in this analysis to calculate the required drip rate is:

$$N_B(t > t_f) = \frac{V_R \cdot D}{v} \cdot \exp \frac{v(t-t_f)}{V_R} \cdot \left(1 - \exp \frac{t_f \cdot v}{V_R} \right) \quad (\text{Eq. 6.4-3})$$

where:

- N_B = boron in waste package (moles)
- t = time (years) (maximum time is the regulatory period of 10,000 years)
- t_f = time when the Neutronit has fully degraded (years)
- V_R = waste package void volume (liters)
- D = boron released from Neutronit (moles/year)
- v = volumetric flow rate (m^3/year)

Equation 6.4-3 is solved for v , which is the minimum drip rate (i.e., seepage rate m^3/yr) required to degrade and flush out the Neutronit from a commercial SNF waste package. The input parameters used in calculating the minimum drip rate (i.e., seepage rate m^3/yr) depends on which commercial SNF waste package is analyzed. The commercial SNF waste package input parameters are discussed below.

The input parameters (constant or random) for the 21-PWR with Absorber Plates Waste Package are listed in Table 6.4-3. Random parameters are based on the time when a seismic event occurs and the corrosion rate distribution.

Table 6.4-3. 21-PWR with Absorber Plates Waste Package Neutronit Degradation Parameters

Variable	Description	Value	Source
t	Neutronit plate thickness	7 mm	BSC 2003 [DIRS 163855], Table 2
n	Neutronit initially in waste package	2.06E+06 grams	From Table 5.1-1 (Assumption 5.1.2) [(g per A-plate × A plates per waste package) + (g per B-plate × B plates per waste package) + (g per C-plate × C plates per waste package)]
b	Boron content in Neutronit	1.245E-02 weight fraction	Average of lowest boron content (0.75 wt%) and highest content (1.74 wt%) from Table 4.1-11, divided by 100
B_i	Initial boron in waste package	2.38E+03 moles	$B_i = (n \times b)/AW$ (AW in Table 4.1-11)
V_R	Void volume of waste package	4.685E+03	From Table 5.1-1 (Assumption 5.1-2)
k	Degradation rate	Varies (g/cm ² × yr)	$k = cr_n \times \rho \times conv$ (where: cr_n = corrosion rate of Neutronit (follows a Weibull distribution (see Assumption 5.1.4) ρ = density of Stainless Steel Type 316 (Table 4.1-11) $conv$ = conversion factor 1.0E-04 cm/μm)
t_{deg}	Time required to degrade all of the Neutronit	varies (years)	$t_{deg} = (n/k \times SA) + Ts$ (where: SA = surface area (Table 5.1-1 [Assumption 5.1.2]) Ts = time to seismic event greater than 700 years [700 years based on Assumption 5.2.2])
D	Moles of boron released from Neutronit	varies (moles/year)	$D = B_i/t_{deg}$

The input parameters (constant or random) for the 12-PWR Long Waste Package are listed in Table 6.4-4. Random parameters are based on the time when a seismic event occurs and the corrosion rate distribution.

Table 6.4-4. 12-PWR Long Waste Package Neutronit Degradation Parameters

Variable	Description	Value	Source
t	Neutronit plate thickness	7 mm	BSC 2003 [DIRS 163855], Table 8
n	Neutronit initially in waste package	1.15E+06 grams	From Table 5.1-1 (Assumption 5.1.2) [(g per A-plate × A plates per waste package) + (g per B-plate × B plates per waste package) + (g per C-plate × C plates per waste package)]
b	Boron content in Neutronit	1.245E−02 weight fraction	Average of lowest boron content (0.75 wt%) and highest content (1.74 wt%) from Table 4.1-11, divided by 100
B_i	Initial boron in waste package	1.33E+03 moles	$B_i = (n \times b)/AW$ (AW in Table 4.1-11)
V_R	Void volume of waste package	3.28E+03	From Table 5.1-1 (Assumption 5.1.2)
k	Degradation rate	varies (g/cm ² × yr)	$k = cr_n \times \rho \times conv$ (where: cr_n = corrosion rate of Neutronit (follows a Weibull distribution (see Assumption 5.1.4) ρ = density of Stainless Steel Type 316 (Table 4.1-11) $conv$ = conversion factor 1.0E-04 cm/μm)
$tdeg$	Time required to degrade all of the Neutronit	varies (years)	$tdeg = (n/k \times SA) + Ts$ (where: SA = surface area (Table 5.1-1, Assumption 5.1.2) Ts = time to seismic event greater than 700 years [700 years based on Assumption 5.2.2])
D	Moles of boron released from Neutronit	varies (moles/year)	$D = B_i/tdeg$

The input parameters (constant or random) for the 44-BWR Waste Package are listed in Table 6.4-5. Random parameters are based on the time when a seismic event occurs and the corrosion rate distribution.

Table 6.4-5. 44-BWR Waste Package Neutronit Degradation Parameters

Variable	Description	Value	Source
t	Neutronit plate thickness	5 mm	BSC 2003 [DIRS 163855], Table 3
n	Neutronit initially in waste package	2.15E+06 grams	From Table 5.1-1 (Assumption 5.1.2) [(g per A-plate × A plates per waste package) + (g per B-plate × B plates per waste package) + (g per C-plate × C plates per waste package) (g per D-plate × D plates per waste package) (g per E-plate × E plates per waste package)]
b	Boron content in Neutronit	1.245E−02 weight fraction	Average of lowest boron content (0.75 wt%) and highest content (1.74 wt%) from Table 4.1-11, divided by 100
B_i	Initial boron in waste package	2.48E+03 moles	$B_i = (n \times b)/AW$ (AW in Table 4.1-11)
V_R	Void volume of waste package	4.85E+03	From Table 5.1-1 (Assumption 5.1.2)
k	Degradation rate	varies (g/cm ² × yr)	$k = cr_n \times \rho \times conv$ (where: cr_n = corrosion rate of Neutronit (follows a Weibull distribution (see Assumption 5.1.4) ρ = density of Stainless Steel Type 316 (Table 4.1-11) $conv$ = conversion factor 1.0E−04 cm/μm)
$tdeg$	Time required to degrade all of the Neutronit	varies (years)	$tdeg = (n/k \times SA) + Ts$ (where: SA = surface area (Table 5.1-1, Assumption 5.1.2) Ts = time to seismic event greater than 700 years [700 years based on Assumption 5.2.2])
D	Moles of boron released from Neutronit	varies (moles/year)	$D = B_i/tdeg$

The input parameters for the 24-BWR Waste Package are listed in Table 6.4-6. The parameters are either constant or random. The random parameters are based on the time when a seismic event occurs and the corrosion rate distribution.

Table 6.4-6. 24-BWR Waste Package Neutronit Degradation Parameters

Variable	Description	Value	Source
t	Neutronit plate thickness	10 mm	BSC 2003 [DIRS 163855], Table 9
n	Neutronit initially in waste package	2.63E+06 grams	From Table 5.1-1 (Assumption 5.1.2) [(g per A-plate * A plates per waste package) + (g per B-plate * B plates per waste package) + (g per C-plate * C plates per waste package) + (g per D-plate * D plates per waste package) + (g per E-plate * E plates per waste package)]
b	Boron content in Neutronit	1.245E-02 weight fraction	Average of lowest boron content (0.75 wt%) and highest content (1.74 wt%) from Table 4.1-11, divided by 100
B_i	Initial boron in waste package	3.03E+03 moles	$B_i = (n * b)/AW$ (AW in Table 4.1-11)
V_R	Void volume of waste package	2.70E+03	From Table 5.1-1 (Assumption 5.1.2)
k	Degradation rate	varies (g/cm ² ·yr)	$k = cr_n * \rho * conv$ (where: cr_n = corrosion rate of Neutronit (follows a Weibull distribution (see Assumption 5.1.4) ρ = density of Stainless Steel Type 316 (Table 4.1-11) $conv$ = conversion factor 1.0E-04 cm/ μ m)
$tdeg$	Time required to degrade all of the Neutronit	varies (years)	$tdeg = (n/k * SA) + Ts$ (where: SA = surface area (Table 5.1-1, Assumption 5.1.2) Ts = time to seismic event greater than 700 years [700 years based on Assumption 5.2.2])
D	Moles of boron released from Neutronit	varies (moles/year)	$D = B_i/tdeg$

Using the input parameters, the boron loss equation is solved to determine the minimum drip rate (i.e., seepage rate m³/yr) required to degrade and flush out the Neutronit. The minimum drip rate is based on the sampled corrosion rate of Neutronit and time when the seismic event occurred after closure. The boron loss equation is solved for the drip rate (i.e., seepage rate m³/yr) when 90 percent of the boron has been flushed from a damaged PWR commercial SNF waste package. For the damaged BWR commercial SNF waste package, the boron loss equation is solved for the drip rate (i.e., seepage rate m³/yr) when 50 percent of the boron has been flushed out. The amount of boron flushed from the commercial SNF waste packages is based on Assumption 5.1.5. The minimum required drip rate (i.e., seepage rate m³/yr), as calculated by the boron loss equation, is fed into the equations to determine the required seepage rate at the drift, as discussed in the next section.

Minimum Seepage Rate Probability

The seepage rate required to reach the drift is calculated using the parameters that were in the previous sections. The seepage rate required to reach the drift is calculated by using the

calculated required drip rate and the damaged area to the drip shield and waste package from a seismic event. The required seepage rate at the drift is calculated as:

$$Q_{seepage} = Q_{req} \cdot \left[\frac{1}{DS_{fr} \cdot WP_{fr}} \right] - Q_{cond} \quad (\text{Eq. 6.4-4})$$

where:

- $Q_{seepage}$ = seepage rate required to reach the drift (m³/yr)
- Q_{req} = minimum required drip rate to degrade and flush the Neutronit based on the solution of the boron loss equation (m³/yr) (Section 6.4.1.1.3)
- DS_{fr} = fraction of damaged drip shield area due to a seismic event
- WP_{fr} = fraction of damaged waste package area due to a seismic event
- Q_{cond} = amount of condensation rate that can enter the waste package (m³/yr).
- Q_{cond} = 0.0 as long as the temperature of the drip shield is greater than the temperature of the drift invert. Otherwise, Q_{cond} is equal to the evaporation rate in the drift.

Equation 6.4-4, based on *EBS Radionuclide Transport Abstraction* (BSC 2003 [DIRS 166466], Section 6.3.1.1), back calculates the seepage rate required to reach the drift by starting with the drip rate required to penetrate the damaged waste package in order to degrade and flush out Neutronit. The required drip rate to penetrate a damaged waste package is divided by the fraction of damaged area of the waste package and drip shield to account for the fraction of seepage rate that can reach the damaged waste package. The remaining seepage rate will flow around the drip shield and waste package damaged areas and into the invert. Therefore, the calculated seepage rate that is required to reach the drift accounts for the amounts of seepage rate that will penetrate the damaged waste package and that will flow into the invert.

The minimum required seepage rate at the drift, as determined from Equation 6.4-4, is fed into Equation 6.4-5 (Walpole et al. 1998 [DIRS 152180], Section 3.3) to calculate the probability of having at least the minimum seepage flux reaching the drift (based on solution of Equation 6.4-4).

$$P_{seep} = F(X \geq Q_{seepage}) = \int_{Q_{seepage}}^{\infty} f(x) dx \quad (\text{Eq. 6.4-5})$$

where:

- P_{seep} = probability of having the required seepage rate or greater reaching the drift
- $f(x)$ = probability distribution of the seepage rate into the drift (Attachment IV)

Seepage rate distributions (i.e., low, mean and upper scenario), $f(x)$ in Equation 6.4-5, were determined in Section 6.4.1.1.2 and discussed in Attachment IV and are based on the glacial transition climate, which is expected to last from roughly 2,000 to 10,000 years after closure (USGS 2001 [DIRS 158378], Section 6.6.1). The seepage rate distributions associated probabilities are 0.24, 0.41, and 0.35 for the low, mean, and upper scenario cases, respectively (BSC 2003 [DIRS 165991], Section 7, Table 7-1). In order to determine which scenario case is used, a random number is generated and tested against the probabilities. If the random number is

(1) less than 0.24, then the low seepage rate distribution is used to determine the minimum seepage rate probability; (2) if between 0.24 and 0.65, then the mean seepage rate distribution is used to determine the minimum seepage rate probability; or (3) greater than 0.65, then the upper seepage rate distribution is used to determine the minimum seepage rate probability.

The seepage rate probability is then fed into Equation 6.4-6 (BSC 2003 [DIRS 161812], Attachment VIII, Equation VIII-2.11) to calculate the mean probability of seepage water penetrating a damaged waste package given a seismic event. The calculated mean probability is based on the minimum seepage required to reach the drift, which is required to penetrate the damaged waste package and degrade and flush out some percentage of the boron (i.e., 90 percent from PWR waste packages and 50 percent from BWR waste packages). The minimum seepage is based on the Neutronit corrosion rate which is the second probability term in Equation 6.4-6 (i.e., minimum Neutronit corrosion rate or greater). The equation takes into account the time of seismic event.

$$P(\text{Seepage} | \text{Seismic}) = \frac{[(T_u - T_l) \cdot (IE_u - IE_l)]}{n} \sum_{i=1}^n P_{\text{seep}_{j,i}} \cdot sf_j \cdot P_{cr_i}(X \geq cr_n) \quad (\text{Eq. 6.4-6})$$

where:

$P(\text{Seepage} | \text{Seismic})$ = mean probability of seepage to penetrate a waste package given a seismic event

T_u = upper bound of time sampling, regulatory period of 10,000 years

T_l = lower bound of time sampling, time after closure of 1 year

IE_u = upper bound of seismic exceedance frequencies (1.0×10^{-4})

IE_l = lower bound of seismic exceedance frequencies (1.0×10^{-8})

n = number of realizations (20,000)

P_{seep} = probability of i th minimum seepage rate or greater depending on which scenario, j , (i.e., low, mean, upper)

sf_j = seepage fraction based on which scenario (i.e., low, mean, or upper)

$P_{cr}(X \geq cr)$ = probability of Neutronit corrosion rate or greater

The sampling routine developed (to determine the damaged area of the drip shield and waste package along with how these damaged areas are used to calculate the mean probability of sufficient seepage) is presented in Attachment III and summarized as follows:

1. Sample a mean annual seismic exceedance frequency from its uniform distribution.
2. Sample the time of the seismic event from its uniform distribution.
3. Interpolate, via log-linear interpolation, the PGV value based on the sampled mean annual exceedance frequency from the lookup table.
4. Interpolate the respective lookup table to obtain the lower- and upper-bound values of the uniform distribution representing the damaged area of the drip shield using the interpolated PGV value from Step 2.

5. Calculate the upper-bound damaged area of the waste package using the interpolated PGV value from Step 2.
6. Sample from the developed uniform distributions for the damaged area of the drip shield and waste package to obtain the respective damaged area for that specific seismic event (sampled event).
7. Sample a corrosion rate for Neutronit from its developed Weibull distribution.
8. Calculate the time required to degrade Neutronit plates within the specific commercial SNF waste package based on time of the seismic event and sampled corrosion rate for Neutronit. This time to degrade the Neutronit assumes no water can penetrate a damaged waste package prior to 700 years after repository closure (see Assumption 5.2.2).
9. Calculate the required drip rate into the specific damaged commercial SNF waste package to degrade and flush out some of the boron (i.e., 90 percent from a PWR waste package and 50 percent from a BWR waste package).
10. Input the required drip rate from step 9 along with the damaged area for the drip shield and waste package into Equation 6.4-4 to calculate the required seepage rate at the drift.
11. Input the calculated minimum seepage rate at the drift into Equation 6.4-5 to calculate the probability of having at least that minimum seepage rate.
12. A random number is tested against the probability of being in the lower, mean, or upper scenario of the glacial transition climate. The lower scenario has a probability of 0.24, the mean scenario has a probability of 0.41, and the upper has a probability of 0.35. If the random number is less than 0.24, then the probability of having that minimum seepage rate or greater is based on the lower scenario case. This probability is calculated using Equation 6.4-5 and is multiplied to its respective seepage fraction and this probability is carried forward for that particular realization. If the random number is between 0.24 and 0.65, then the probability of having that minimum seepage rate or greater is based on the mean scenario case. This probability is calculated using Equation 6.4-5 and is multiplied to its respective seepage fraction and this probability is carried forward for that particular realization. If the random number is greater than 0.65, then the probability of having that minimum seepage rate or greater is based on the upper scenario case. This probability is calculated using Equation 6.4-5 and is multiplied to its respective seepage fraction and carried forward for that realization.
13. The calculated probability times its respective seepage fraction (Step 12) is input into Equation 6.4-6, which calculates the mean probability based on the 20,000 realizations. The mean probability is then input into SAPHIRE.

The mean probability from the 20,000 realizations varied depending upon which commercial SNF waste package was evaluated. The calculated probability of sufficient seepage water

available to penetrate the damaged waste package in order to degrade and flush out the Neutronit is fed into the SAPHIRE model. The calculated probabilities for the commercial SNF waste packages are presented as 0.0 for the 21-PWR with Absorber Plates, 12-PWR Long, and 24-BWR waste package types (Attachment III, p. 21). The 44-BWR Waste Package had a calculated probability of 1.53×10^{-6} .

In the SAPHIRE evaluation of seismic events for the lithophysal zone, basic event BE-SEEPAGE-10K is substituted by basic event BE-SEEPAGE-WP1-L to represent the probability for the 21-PWR with Absorber Plates Waste Package. Similarly, BE-SEEPAGE-10K will be substituted by basic events BE-SEEPAGE-WP3-L, BE-SEEPAGE-WP4-L, and BE-SEEPAGE-WP5-L to represent waste package type 12-PWR Long, 44-BWR, and 24-BWR probabilities, respectively.

For the 21-PWR Control Rod Waste Package, the probability of attaining the minimum required seepage is always zero because zirconium cladding neutron absorber material will not degrade during the performance period (Assumption 5.1.6). For the evaluation of seismic criticality FEPs, the probability of attaining the minimum required seepage for a 21-PWR with Control Rods Waste Packages in the lithophysal zone will be defined by basic event BE-SEEPAGE-WP2-L. Basic event BE-SEEPAGE-WP2-L will be assigned a value of 0.0.

The calculated probability of attaining the minimum seepage rate for the 21-PWR with Absorber Plates Waste Package is extended to the DOE SNF waste package types assuming DOE SNF waste package neutron absorber material degradation is at least the same as that of the 21-PWR with Absorber Plates Waste Package (Assumption 5.1.6). The probability of attaining the minimum required seepage for the DOE SNF waste packages in the lithophysal zone will be defined by basic events BE-SEEPAGE-WP6-L, BE-SEEPAGE-WP7-L, and BE-SEEPAGE-WP8-L for the DOE SNF Long, DOE SNF Short, and DOE SNF MCO waste package types, respectively.

As noted earlier, since the probability of the seismic event is incorporated into these basic events, the probability of a seismic disruptive event on the “FEPS” event tree has been set to 1.0.

6.4.1.1.2 Seismic Effects in the Nonlithophysal Zone

The nonlithophysal zone is analyzed separately because the drip shield can be damaged from both rock blocks ejected from the drift and vibratory ground motion. Drip shield damage due to vibratory ground motion has already been calculated and discussed in Section 6.4.1.1.1.

Drip Shield and Waste Package Damage

The calculation to obtain the percent damaged area to the drip shield from rockfall uses two separate equations. The first equation determines if damage to the drip shield occurred due to a rockfall and the second calculates the mode percent damaged area. These equations are utilized as outlined in *Seismic Consequence Abstraction* (BSC 2003 [DIRS 161812], Section 6.6.1.4 and 6.10). Based on the process, each realization constitutes a rockfall that impacts the drip shield.

The first equation (Equation 6.4-7) is evaluated based on the sampled PGV value (to determine if the rock block can damage the drip shield) by generating and comparing a random number to the value obtained from:

$$DS_{\text{nodamage}} = 0.601 \cdot PGV^{-0.735} \quad (\text{Eq. 6.4-7})$$

If the random number is less than DS_{nodamage} , then the rock block caused no damage to the drip shield. However, if the random number is larger than or equal to DS_{nodamage} , then damage has occurred to the drip shield from the rock block. The amount of damage is then calculated using a log-triangular distribution (Equation 6.4-8) with a minimum of 0.001 and a maximum of 100 percent damage. The mode of the log-triangular distribution varies based on the sampled PGV value and is calculated as:

$$DS_{\text{mode}} = 0.00204 \cdot PGV^{3.7767} \quad (\text{Eq. 6.4-8})$$

The log-triangular distribution is then sampled each time the random number is greater than DS_{nodamage} to determine the percent damaged area to the drip shield due to rockfall. This percent damaged area is then added to the percent damaged area sampled due to vibratory ground motion. The mean percent damaged area is converted to the mean fraction of damaged area by dividing by 100. The calculated mean fraction of damaged area to the drip shield from rockfall and vibratory ground motion is 4.74×10^{-3} . The calculated 5th and 95th percentiles are 9.92×10^{-9} and 1.06×10^{-2} , respectively (Attachment III, p. III-8).

The fraction of damaged area to the waste package is the same for the nonlithophysal as that calculated for the lithophysal, since the drip shield will still be intact and will deflect rock blocks from hitting a waste package.

Seepage Rate Probability Distribution for Nonlithophysal

The process used to determine the seepage rate distribution for the nonlithophysal zone, which is used to calculate the seepage probability, follows the process steps discussed in *Abstraction of Drift Seepage* (BSC 2003 [DIRS 165564], Section 6.7.1) and Section 6.4.1.1.1. The only difference is the permeability, k , and the look-up table for seepage rate and seepage rate standard deviation.

Capillary strength (l/α) is the same for the nonlithophysal zone as it is for the lithophysal zone.

The nonlithophysal zone permeability (k) is determined to have a spatial variability distribution that is lognormal with a mean of -12.2 (in log 10) and a standard deviation of 0.34 (in log 10). The mean and standard deviation of permeability was determined from statistical analysis on the log-transformed data (BSC 2003 [DIRS 165564], Section 6.6.2.1). The permeability uncertainty (Δk) follows a triangular distribution with a lower bound of -0.68, upper bound +0.68, and a mean of 0.0. These distributions are for the nonlithophysal zone only.

The percolation flux representing the repository area (BSC 2003 [DIRS 165564], Figure 6.6-10) is same for the nonlithophysal as for the lithophysal. The percolation flux uncertainty is expressed by three different scenarios for the spatial flux distributions (lower-bound, mean, and upper-bound). Since three different scenarios are used to represent the uncertainty, three seepage rate distributions (one for each scenario) are obtained for the nonlithophysal zone.

The percolation flux is adjusted for intermediate-scale heterogeneity by using flow-focusing factors (Equation 6.4-2), which are sampled and multiplied by the sampled percolation flux. However, for the nonlithophysal zone, the interpolated seepage rate is increased by 20 percent to account for rock bolts and drift degradation (BSC 2003 [DIRS 165564], Section 6.7.1).

The seepage rate at the drift for each of the uncertainty scenarios (i.e., lower-bound, mean, and upper-bound) is determined using the same sampling process discussed in Section 6.4.1.1.1. The sampled value from the three key parameters (i.e., capillary strength, permeability, adjusted percolation flux) is used to interpolate the mean seepage rate and seepage rate standard deviation using the lookup table for the nondegraded drift (DTN: LB0304SMDCREV2.002 [DIRS 163687]). The standard deviation is adjusted to account for uncertainty by creating a uniform distribution with a lower bound of -1.7321 times the sampled standard deviation and an upper bound of 1.7321 times the sampled standard deviation. The uniform distribution to account for uncertainty is sampled and then added to the interpolated mean seepage rate. This process is performed for 20,000 realizations (refer to Attachment IV).

The resulting seepage rate values are adjusted prior to being used to determine the seepage rate probability by (1) setting seepage rates less than 0.1 kg/yr per package to zero (since these small values are the result of interpolation (BSC 2003 [DIRS 165564], Section 6.7.1)), and (2) setting calculated seepage rates greater than 100 percent to 100.

Seepage rates are then filtered in order to develop a distribution that represents the seepage rate values by discarding all seepage rates with a zero value. The remaining nonzero seepage rates are then used to develop a Weibull distribution for each of the scenarios (i.e., lower-bound, mean, and upper-bound) to represent the seepage rate at the drift (refer to Attachment IV). These Weibull distributions are used to calculate the probability of having sufficient seepage in order to degrade and flush out the Neutronit from a seismically damaged waste package. In addition, to calculate the fraction of waste package locations that can see seepage, the number of nonzero seepage rates is divided by the total number of realizations (seepage fraction). The Weibull parameters, scale and shape (α and β , respectively), and seepage fraction for each scenario are listed in Table 6.4-7.

Table 6.4-7. Weibull Parameters and Seepage Fraction (Nonlithophysal Zone)

Weibull Parameters	Values	Seepage Fraction
Lower Bound (Drift Collapse)		
α (scale)	$4.95E-03^a$ (m^3/yr)	$1.54E-01^b$
β (shape)	$5.36E-01^a$	
Mean (Drift Collapse)		
α (scale)	$8.56E-02^c$ (m^3/yr)	$5.24E-01^d$
β (shape)	$4.73E-01^c$	
Upper Bound (Drift Collapse)		
α (scale)	$2.25E-01^e$ (m^3/yr)	$6.72E-01^f$
β (shape)	$5.01E-01^e$	

Source: ^a Attachment IV, p. IV-54

^b Attachment IV, p. IV-53

^c Attachment IV, p. IV-67

^d Attachment IV, p. IV-66

^e Attachment IV, p. IV-80

^f Attachment IV, p. IV-79

Minimum Seepage Rate Probability

The same process for determining the mean seepage probability discussed for the lithophysal zone is performed for the nonlithophysal zone. Equation 6.4-6 is used to calculate the mean seepage probability for nonlithophysal zone with different values for input seepage rate distributions and damaged area of the drip shield. The seepage rate distributions are different because they use different permeability parameters for the nonlithophysal zone and a different lookup table for the seepage rate. The other difference is the fraction of damaged area to the drip shield is larger because of the additional rockfall damage. Mathcad spreadsheets in Attachment III (p. 21) list probability evaluations for waste package types with at least this seepage.

The mean probability from the 20,000 realizations varied depending upon which commercial SNF waste package was evaluated. The calculated mean probability of sufficient seepage water to penetrate the damaged waste package in order to degrade and flush out the Neutronit is fed into the SAPHIRE model. The calculated probabilities for the commercial SNF waste packages are 0.0 for the 21-PWR with Absorber Plates, 12-PWR Long, and 24-BWR waste package types. The 44-BWR Waste Package had a calculated probability of 9.74×10^{-7} .

In the SAPHIRE evaluation of seismic events for the nonlithophysal zone, basic event BE-SEEPAGE-10K is substituted by basic event BE-SEEPAGE-WP1-NL to represent the probability for the 21-PWR with Absorber Plates Waste Package. Similarly, BE-SEEPAGE-WP1-NL will be substituted by basic events BE-SEEPAGE-WP3-NL, BE-SEEPAGE-WP4-NL, and BE-SEEPAGE-WP5-NL to represent waste package type 12-PWR Long, 44-BWR, and 24-BWR probabilities, respectively.

For the 21-PWR Control Rod Waste Package, the probability of attaining the minimum required seepage is always zero because zirconium cladding neutron absorber material will not degrade during the performance period (Assumption 5.1.6). For the evaluation of seismic criticality FEPs, the probability of attaining the minimum required seepage for the 21-PWR with Control Rods Waste Package in the nonlithophysal zone will be defined by basic event BE-SEEPAGE-WP2-NL. Basic event BE-SEEPAGE-WP2-NL will be assigned a value of 0.0.

The calculated probability of attaining the minimum seepage rate for the 21-PWR with Absorber Plates Waste Package is extended to the DOE SNF waste package types assuming DOE SNF waste package neutron absorber material degradation is at least the same as that of the 21-PWR with Absorber Plates Waste Package (Assumption 5.1.6). The probability of attaining the minimum required seepage for the DOE SNF waste packages in the nonlithophysal zone will be defined by basic events BE-SEEPAGE-WP6-NL, BE-SEEPAGE-WP7-NL, and BE-SEEPAGE-WP8-NL for the DOE SNF Long, DOE SNF Short, and DOE SNF MCO waste package types, respectively.

As noted earlier, since the probability of the seismic event is incorporated into these basic events, the probability of a seismic initiating event on the FEPs event tree has been set to 1.0.

6.4.1.2 Sensitivity Case Seismic Evaluation

The following sections describe a sensitivity case based on an increase in the Neutronit plate thickness for the 44-BWR Waste Package and uses the same base case analysis process and inputs, except Neutronit plate thickness is increased from 5 mm (refer to Table 6.4-5) to 7 mm.

6.4.1.2.1 Sensitivity Case of the Seismic Effects in the Lithophysal Zone

The same process for calculating the mean seepage probability for the base case was performed for this sensitivity case. The increase in the Neutronit plate thickness changed boron loss equation input parameters (mass of Neutronit, from 2.15×10^6 grams to 3.152×10^6 grams; and surface area, from 9.55×10^5 cm² to 9.837×10^5 cm²) (Attachment III, p. III-23). By making this adjustment, the boron loss equation was solved again to determine the minimum drip rate (i.e., seepage rate m³/yr) required to degrade and flush out the Neutronit. This new drip rate was input into Equation 6.4-4 to calculate the required seepage rate at the drift. Using this newly calculated seepage rate, the mean probability from Equation 6.4-6 is calculated. The probability evaluation for having this amount of seepage or more is listed in the Mathcad spreadsheet documentation of Attachment III.

The mean probability from the 20,000 realizations showed a significant decrease in the mean probability based on the increase in Neutronit plate thickness. This decrease is understandable, since the degradation and flushing would take longer because of the thicker Neutronit plates. The calculated mean probability for this sensitivity case is 1.24×10^{-10} (Attachment III, p. III-25). This calculated mean probability is input into the SAPHIRE model for the evaluation of this sensitivity case. The probabilities for the other commercial SNF waste packages remain the same since no adjustment was made to their design.

6.4.1.2.2 Sensitivity Case of the Seismic Effects in the Nonlithophysal Zone

The same process for calculating the mean seepage probability for the base case was performed for this sensitivity case. The only difference, as noted, is the increase in thickness of the Neutronit plate for the 44-BWR Waste Package. By making this adjustment, the boron loss equation was solved again to determine the minimum drip rate (i.e., seepage rate m³/yr) required to degrade and flush out the Neutronit. This new drip rate was fed into Equation 6.4-4, using the increased drip shield damaged area due to rockfall to calculate the required seepage rate at the drift. Using this newly calculated seepage rate, the mean probability from Equation 6.4-6 is calculated. The probability evaluation for having this amount of seepage or more is listed in the Mathcad spreadsheet documentation of Attachment III.

The results from the 20,000 realizations showed a significant decrease in the mean probability was obtained by increasing the Neutronit plate thickness. The calculated mean probability for this sensitivity case in the nonlithophysal zone is 9.92×10^{-12} (Attachment III, p. 25) and is input into the SAPHIRE model. The probabilities for the other commercial SNF waste packages remain the same since no adjustment was made to their design.

6.4.2 SAPHIRE Basic Event Probability Modifications for Seismic Analysis

Based on the calculations in the above sections, the following basic events are modified from the base case criticality FEPs SAPHIRE analysis for the seismic disruptive event base case and sensitivity case evaluations.

6.4.2.1 Seismic Base Case Basic Event Probability Modifications

Based on the calculations in the above sections, the following basic events are modified from the base case SAPHIRE criticality FEPs analysis for the seismic disruptive event base case evaluation. The basic event modifications for the lithophysal and nonlithophysal zones of the drift are listed in Table 6.4-8.

Table 6.4-8. Seismic Base Case SAPHIRE Basic Event Assignment

Input Data Description	Input Data Probability		Justification
	Probability	Waste Package Type	
Sufficient water (infiltrate/condensate) reaches lithophysal drift by 10,000 years BE-SEEPAGE-WP1-L (fault tree MS-IC-1)	0.0	21-PWR with Absorber Plates	Section 6.4.1.1.1
Sufficient water (infiltrate/condensate) reaches nonlithophysal drift by 10,000 years BE-SEEPAGE-WP1-NL (fault tree MS-IC-1)	0.0	21-PWR with Absorber Plates	Section 6.4.1.1.2
Sufficient water (infiltrate/condensate) reaches lithophysal drift by 10,000 years BE-SEEPAGE-WP2-L (fault tree MS-IC-1)	0.0	21-PWR with Control Rods	Section 6.4.1.1.1
Sufficient water (infiltrate/condensate) reaches nonlithophysal drift by 10,000 years BE-SEEPAGE-WP2-NL (fault tree MS-IC-1)	0.0	21-PWR with Control Rods	Section 6.4.1.1.2
Sufficient water (infiltrate/condensate) reaches lithophysal drift by 10,000 years BE-SEEPAGE-WP3-L (fault tree MS-IC-1)	0.0	12-PWR Long	Section 6.4.1.1.1
Sufficient water (infiltrate/condensate) reaches nonlithophysal drift by 10,000 years BE-SEEPAGE-WP3-NL (fault tree MS-IC-1)	0.0	12-PWR Long	Section 6.4.1.1.2
Sufficient water (infiltrate/condensate) reaches lithophysal drift by 10,000 years BE-SEEPAGE-WP4-L (fault tree MS-IC-1)	1.53E-6	44-BWR Absorber Plate	Section 6.4.1.1.1
Sufficient water (infiltrate/condensate) reaches nonlithophysal drift by 10,000 years BE-SEEPAGE-WP4-NL (fault tree MS-IC-1)	9.74E-7	44-BWR Absorber Plate	Section 6.4.1.1.2

Table 6.4-8. Seismic Base Case SAPHIRE Basic Event Assignment

Input Data Description	Input Data Probability		Justification
	Probability	Waste Package Type	
Sufficient water (infiltrate/condensate) reaches lithophysal drift by 10,000 years BE-SEEPAGE-WP5-L (fault tree MS-IC-1)	0.0	24-BWR Absorber Plate	Section 6.4.1.1.1
Sufficient water (infiltrate/condensate) reaches nonlithophysal drift by 10,000 years BE-SEEPAGE-WP5-NL (fault tree MS-IC-1)	0.0	24-BWR Absorber Plate	Section 6.4.1.1.2
Sufficient water (infiltrate/condensate) reaches lithophysal drift by 10,000 years BE-SEEPAGE-WP6-L (fault tree MS-IC-1)	0.0	DOE SNF Long	Section 6.4.1.1.1
Sufficient water (infiltrate/condensate) reaches nonlithophysal drift by 10,000 years BE-SEEPAGE-WP6-NL (fault tree MS-IC-1)	0.0	DOE SNF Long	Section 6.4.1.1.2
Sufficient water (infiltrate/condensate) reaches lithophysal drift by 10,000 years BE-SEEPAGE-WP7-L (fault tree MS-IC-1)	0.0	DOE SNF Short	Section 6.4.1.1.1
Sufficient water (infiltrate/condensate) reaches nonlithophysal drift by 10,000 years BE-SEEPAGE-WP7-NL (fault tree MS-IC-1)	0.0	DOE SNF Short	Section 6.4.1.1.2
Sufficient water (infiltrate/condensate) reaches lithophysal drift by 10,000 years BE-SEEPAGE-WP8-L (fault tree MS-IC-1)	0.0	DOE SNF MCO	Section 6.4.1.1.1
Sufficient water (infiltrate/condensate) reaches nonlithophysal drift by 10,000 years BE-SEEPAGE-WP8-NL (fault tree MS-IC-1)	0.0	DOE SNF MCO	Section 6.4.1.1.2
Drip shield failure due to seismic event BE-DS-SEISMIC1 (fault tree MS-IC-2)	1.0	All waste package types	Section 6.4.1.1.1
Waste package failure due to seismic event BE-WP-SEISMIC1 (fault tree MS-IC-3)	1.0	All waste package types	Section 6.4.1.1.1
Waste package failure due to early failures BE-WP-EARLY-F1 (fault tree MS-IC-3)	0.0	All waste package types	Section 6.4.1.1.1

6.4.2.2 Seismic Sensitivity Case Basic Event Probability Modifications

Based on the calculations in the above sections, the following basic events in Table 6.4-9 are modified from the seismic disruptive event base case for the seismic disruptive event sensitivity case evaluation.

Table 6.4-9. Seismic Sensitivity Case SAPHIRE Basic Event Assignment

Input Data Description	Input Data Probability		Justification
	Probability	Waste Package Type	
Sufficient water (infiltrate/condensate) reaches lithophysal drift by 10,000 years BE-SEEPAGE-WP4-L (fault tree MS-IC-1)	1.24E-10	44-BWR	Section 6.4.1.2.2
Sufficient water (infiltrate/condensate) reaches nonlithophysal drift by 10,000 years BE-SEEPAGE-WP4-NL (fault tree MS-IC-1)	9.92E-12	44-BWR	Section 6.4.1.2.2

6.4.3 Seismic Criticality FEPs Analysis Results

The waste package flooding probabilities resulting from the quantification of the SAPHIRE seismic disruptive event analyses are presented below.

6.4.3.1 Seismic Base Case Criticality FEPs Analysis Results

The waste package flooding probabilities resulting from the quantification of the SAPHIRE seismic disruptive event base case are presented in Table 6.4-10. These results include the flooding probabilities for waste packages in the lithophysal and nonlithophysal zones of the drifts.

Table 6.4-10. Per Waste Package Flooding Probabilities for Seismic Base Case Criticality FEPs

Waste Package Type	Number of Waste Packages ^a	Per Waste Package Flooding Probability ^b	
		Lithophysal	Nonlithophysal
21-PWR with Absorber Plates	4,299	0.00E+00	0.00E+00
21-PWR with Control Rods	95	0.00E+00	0.00E+00
12-PWR Long	163	0.00E+00	0.00E+00
44 BWR	2,831	1.30E-06	1.46E-07
24 BWR	84	0.00E+00	0.00E+00
DOE SNF	3,412 ^c	0.00E+00	0.00E+00

Source: ^a Values from Table 4.1-8

^b SAPHIRE V7.18 (BSC 2002 [DIRS 160873]) analysis results (Attachment II, p. II-20)

^c Sum of 5-DHLW/DOE SNF Short, 5-DHLW/DOE SNF Long and 2-MCO/2-DHLW Long values from Table 4.1-8

6.4.3.2 Seismic Sensitivity Case Criticality FEPs Analysis Results

The waste package flooding probabilities resulting from the quantification of the SAPHIRE seismic disruptive event sensitivity case are presented in Table 6.4-11. These results include the flooding probabilities for waste packages in the lithophysal and nonlithophysal zones of the drifts.

Table 6.4-11. Per Waste Package Flooding Probabilities for Seismic Sensitivity Case Criticality FEPs

Waste Package Type	Number of Waste Packages ^a	Per Waste Package Flooding Probability ^b	
		Lithophysal	Nonlithophysal
21-PWR with Absorber Plates	4,299	0.00E+00	0.00E+00
21-PWR with Control Rods	95	0.00E+00	0.00E+00
12-PWR Long	163	0.00E+00	0.00E+00
44 BWR	2,831	1.05E-10	1.39E-12
24 BWR	84	0.00E+00	0.00E+00
DOE SNF	3,412 ^c	0.00E+00	0.00E+00

Source: ^aValues from Table 4.1-8

^bSAPHIRE V7.18 (BSC 2002 [DIRS 160873]) analysis results (Attachment II, p. II-20)

^cSum of 5-DHLW/DOE SNF Short, 5DHLW/DOE SNF Long and 2-MCO/2-DHLW Long values from Table 4.1-8

6.4.3.3 Total Seismic Criticality FEPs Analysis Results

Table 6.4-12 summarizes the SAPHIRE seismic disruptive event results for the seismic base case and sensitivity case evaluations. The probabilities for the lithophysal and nonlithophysal zones from Tables 6.4-10 and 6.4-11 are combined to provide the total probability for each of these cases.

Table 6.4-12. Total Per Waste Package Flooding Probabilities for Seismic Criticality FEPs

Waste Package Type	Number of Waste Packages ^a	Total Per Waste Package Flooding Probability ^b	
		Base Case	Sensitivity Case
21-PWR with Absorber Plates	4,299	0.00E+00	0.00E+00
21-PWR with Control Rods	95	0.00E+00	0.00E+00
12-PWR Long	163	0.00E+00	0.00E+00
44 BWR	2,831	1.44E-06	1.07E-10 ^d
24 BWR	84	0.00E+00	0.00E+00
DOE SNF	3,412 ^c	0.00E+00	0.00E+00

Source: ^aValues from Table 4.1-8

^bSAPHIRE V7.18 (BSC 2002 [DIRS 160873]) analysis results (Attachment II, p. II-20)

^cSum of 5-DHLW/DOE SNF Short, 5DHLW/DOE SNF Long and 2-MCO/2-DHLW Long values from Table 4.1-8

^dDue to roundoff, the sum of the lithophysal and nonlithophysal results probabilities reported in Tables 6.4-10 and 6.4-11 are different than this value.

6.4.4 Seismic Ground Motion Effects on Near-Field and Far-Field Criticality

In order for a criticality to occur in the near-field or far-field, sufficient quantity of the waste form's fissile inventory must be removed from the waste package and accumulate in void spaces within the host rock. This requires sufficient damage to the waste package to allow adequate seepage to degrade waste form and flush the fissile material from the waste package. The probability evaluation for in-package criticality due to a seismic event can be used as the starting point for the additional sequence of events required to cause near-field or far-field criticality. The remaining probability of events must be evaluated to determine the probability of an external criticality due to a seismic event include: (1) the waste form will degrade within 10,000 years; (2) fissile material will be flushed from the waste package; and (3) fissile material accumulates in a sufficient quantity and geometry to allow for criticality. Therefore, once the probabilities of these events are determined, the probability of a near-field or far-field criticality due to a seismic event will be lower than that calculated for in-package criticality.

6.5 ANALYSIS OF ROCKFALL DISRUPTIVE EVENT CRITICALITY FEPS

Rockfall disruptive event criticality FEPs are presented in Table 6.5-1.

Table 6.5-1. Rockfall Disruptive Event Criticality FEPs

FEP Number	FEP Title	FEP Description
2.1.14.21.0A	In-package criticality resulting from rockfall (intact configuration)	The waste package internal structures and the waste form remain intact either during or after a rockfall event. A breach (or breaches) in the waste package allow(s) water to either accumulate or flow-through the waste package. Criticality then occurs in situ.
2.1.14.22.0A	In-package criticality resulting from rockfall (degraded configurations)	Either during, or as a result of, a rockfall event, the waste package internal structures and the waste form degrade. A critical configuration develops and criticality occurs in situ. Potential in situ critical configurations are defined in Figures 3.2a and 3.2b of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]).
2.1.14.23.0A	Near-field criticality resulting from rockfall	Either during, or as a result of, a rockfall event, near-field criticality occurs when fissile material-bearing solution from the waste package is transported into the drift and the fissile material is precipitated into a critical configuration. Potential near-field critical configurations are defined in Figure 3.3a of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]).
2.2.14.11.0A	Far-field criticality resulting from rockfall	Either during, or as a result of, a rockfall event, far-field criticality occurs when fissile material-bearing solution from the waste package is transported beyond the drift and the fissile material is precipitated into a critical configuration. Potential far-field critical configurations are defined in Figure 3.3b of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]).

Source: Table 6.1-4

The following sections discuss quantification of SAPHIRE basic events required to be modified to perform the probabilistic evaluation of the rockfall disruptive event criticality FEPs and presents the SAPHIRE evaluation results.

6.5.1 Rockfall Drip Shield Failure Probability

Rockfall disruptive event criticality FEPs 2.1.14.21.0A, 2.1.14.22.0A, 2.1.14.23.0A, and 2.2.14.11.0A require an assessment of the probability of criticality due to rockfall. A rockfall

event can occur as result of normal drift degradation, as well as the result of a seismic event. Because the frequency of rockfall due to static drift degradation cannot be readily predicted, a probability of 1.0 is assigned to this disruptive event. A rockfall event could potentially result in drip shield damage depending on the size of the rockfall, the impact velocity and drip shield impact location. Because the drip shield covers the waste package, no waste package damage is predicted due to a rockfall event.

Although the rockfall disruptive event is considered to be a static event (i.e., the rocks drop from the drift overhead due to static drift degradation, not as a result of any external initiating event such as an seismic event), the nonstatic results of *Seismic Consequence Abstraction* (BSC 2003 [DIRS 161812]) are used in this evaluation to bound the analysis results. This approach is believed to be bounding because more blocks would be expected to fall during a seismic event and the rock-to-drip-shield impact velocity is greater than would be expected under static conditions.

The probability of drip shield damage due to rockfall is based on the information contained in *Seismic Consequence Abstraction* (BSC 2003 [DIRS 161812]). The drip shield rockfall damage results are based on the impact of 279 and 380 blocks for seismic event annual exceedance frequencies of 10^{-6} and 10^{-7} , respectively (BSC 2003 [DIRS 161812], Section 6.6.1.1). These blocks occur in the nonlithophysal zone of the drifts, which comprises only 15 percent of the total drift area (745,486 m² of drift area resides in the nonlithophysal geological unit out of a total drift area of 4,983,152 m² (BSC 2003 [DIRS 164491], Table 9)). The drip shield is not damaged by rockfall impacts in the lithophysal zone (BSC 2003 [DIRS 161812], Section 6.6.2).

The total available emplacement drift length is 63,945 m (BSC 2003 [DIRS 164490], Tables 4 through 7). If the average drip shield length is 5.805 m (BSC 2004 [DIRS 167309], Table 1), then the total number of drip shields in the repository is calculated to be 11,016 (63,945 m / 5.805 m per drip shield). Therefore, the total number of drip shields available for rockfall impact damage in the nonlithophysal zone is calculated to be 1,653 (15 percent of 11,016).

Although *Seismic Consequence Abstraction* (BSC 2003 [DIRS 161812]) calculates drip shield damage due to single block impacts as well as multiple rock impacts, the determination of basic event probability for drip shield damage conservatively calculates that each rock block is available to fall on a unique drip shield. This results in a greater number of drip shields being impacted by rockfall. This calculation will also use 380 rock blocks (the number of rock blocks from the 10^{-7} annual exceedance frequency) as this will also result in a greater number of impacted drip shields. In the seismic calculation of Attachment III, the rockfall evaluation presented on page III-9 resulted in the calculation of drip shield damage occurring 14.4 percent of the time. This is based on 20,000 realizations in which each assumes a rock block hits a drip shield.

Utilizing the above information, the probability of drip shield damage due to rockfall can be determined by multiplying the fraction of drip shields hit by rocks and the probability that the drip shield will be damaged by the impact. This calculation is presented as:

$$\text{Prob}_{\text{dsd}} = N_{\text{rf}} / N_{\text{ds}} \times \text{DS}_{\text{df}} \quad (\text{Eq. 6.5-1})$$

where:

- Prob_{dsd} = probability of drip shield damage
- N_{rf} = number rock blocks available to fall (380)
- N_{ds} = number of drips shields available for the rocks to fall upon (1,653)
- DS_{df} = fraction of drip shields damaged due to rockfall (0.144).

Inserting these values into the above equation results in a probability of drip shield damage due to rockfall (Prob_{dsd}) of 3.31×10^{-2} .

However, for the rockfall disruptive event, the probability of drip shield damage does not correlate to the probability of drip shield failure. Drip shield failure is defined as the failure of the drip shield to perform its primary function – to prevent advective flow from contacting the waste package. Drip shield failure may be the result of a stress corrosion crack or complete structural failure. Although rockfall will result in stress corrosion cracking of the drip shield, the resulting cracks are predicted to be plugged with corrosion products or precipitates (BSC 2003 [DIRS 161234], Section 6.3.7) causing the probability of advective flow through the cracks to approach zero (BSC 2003 [DIRS 161234], Section 6.3.7).

Therefore, the probability of drip shield failure resulting from a rockfall disruptive event is 0.0 and is the value assigned to default basic event BE-DS-ROCK-FALL of the drip shield fault tree MS-IC-2. This is the failure probability that will be utilized in both the lithophysal and nonlithophysal geological zone analyses of the rockfall disruptive event SAPHIRE evaluation.

6.5.2 Minimum Seepage Probability for Rockfall Disruptive Event

The probability of attaining the minimum seepage flux resulting from a rockfall disruptive event is calculated to be zero because of a zero-probability function for drip shield damage area for the rockfall disruptive event (i.e., no drip shield failures). Rockfall in the nonlithophysal geological zone does not cause a drip shield failure, but produces areas of stress in the drip shield surface that may result in stress corrosion cracking. However, rockfall induced stress corrosion cracks are predicted to be plugged by corrosion products or be sealed by precipitants that will prevent advective flow onto the waste package (BSC 2003 [DIRS 161234], Section 6.3.7).

It should be noted that, as previously stated, drip shield damage due to rockfall occurs only in the nonlithophysal geological zone. No drip shield damage due to rockfall is predicted to occur in the lithophysal geological zone; therefore, the damage probability function is zero for drip shields in the lithophysal geological zone.

Since rockfall does not impact the waste package, the only viable waste package failure mechanism during the rockfall disruptive event results from fabrication errors. As discussed in

Section 6.3.3.3.4, improper heat treatment of the waste package results in a probability of early waste package failure of 2.8×10^{-5} per waste package.

However, because there are no drip shield failures to allow advective flow onto any failed waste packages, the probability of sufficient seepage water to degrade and flush out the neutron absorbing material resulting from a rockfall disruptive event is 0.0. This value is assigned to the default basic event (BE-SEEPAGE-10K) of the seepage fault tree MS-IC-1 and utilized in the lithophysal and nonlithophysal geological zone analyses.

6.5.3 SAPHIRE Basic Event Probability Modifications for Rockfall Analysis

Based on the information presented in the sections above, no basic events must be modified from the base case SAPHIRE analysis for the rockfall disruptive event SAPHIRE analysis.

6.5.4 Rockfall Criticality FEPs Analysis Results

The quantification of the SAPHIRE rockfall disruptive event resulted in the calculation of the waste package fractional probabilities presented in Table 6.5-2. Because the probability of attaining the minimum required seepage to degrade the waste package internal components and flush out the neutron absorber material is zero, the fractional probability of flooding the waste package types is also zero. This result is applicable to all rockfall criticality FEPs regardless of analysis location (internal or external to the waste package) or waste form/waste package type.

Table 6.5-2. Per Waste Package Flooding Probabilities for Rockfall Criticality FEPs

Waste Package Type	Number of Waste Packages ^a	Per Waste Package Flooding Probability ^b
21-PWR with Absorber Plates	4299	0.00E+00
21-PWR with Control Rods	95	0.00E+00
12-PWR Long	163	0.00E+00
44 BWR	2831	0.00E+00
24 BWR	84	0.00E+00
DOE SNF	3412 ^c	0.00E+00

Source: ^a Values from Table 4.1-8

^b SAPHIRE V7.18 (BSC 2002 [DIRS 160873]) analysis results (Attachment II, p. II-20)

^c Sum of 5-DHLW/DOE SNF Short, 5DHLW/DOE SNF Long and 2-MCO/2-DHLW Long values from Table 4.1-8

6.5.5 Rockfall External Criticality Probability

External criticality FEPs can originate from either a bathtub or flow-through waste package configuration. However, because there is no mechanism to breach the drip shield during the performance period for a rockfall disruptive event, there is no probability of water entering the waste package. Therefore, there is no probability of criticality for the rockfall external criticality FEPs presented in Table 6.5-1.

6.6 ANALYSIS OF IGNEOUS DISRUPTIVE EVENT CRITICALITY FEP

The igneous disruptive event criticality FEPs are presented in Table 6.6-1.

Table 6.6-1. Igneous Disruptive Event Criticality FEPs

FEP Number	FEP Name	FEP Description
2.1.14.24.0A	In-package criticality resulting from an igneous event (intact configuration)	The waste package internal structures and the waste form remain intact either during or after an igneous disruptive event. A breach (or breaches) in the waste package allow(s) water to either accumulate or flow-through the waste package. Criticality then occurs in situ.
2.1.14.25.0A	In-package criticality resulting from an igneous event (degraded configurations)	Either during, or as a result of, an igneous disruptive event, the waste package internal structures and the waste form degrade. A critical configuration develops and criticality occurs in situ. Potential in situ critical configurations are defined in Figures 3.2a and 3.2b of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]).
2.1.14.26.0A	Near-field criticality resulting from an igneous event	Either during, or as a result of, an igneous disruptive event, near-field criticality occurs when fissile material-bearing solution from the waste package is transported into the drift and the fissile material is precipitated into a critical configuration. Potential near-field critical configurations are defined in Figure 3.3a of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]).
2.2.14.12.0A	Far-field criticality resulting from an igneous event	Either during, or as a result of, an igneous disruptive event, far-field criticality occurs when fissile material-bearing solution from the waste package is transported beyond the drift and the fissile material is precipitated into a critical configuration. Potential far-field critical configurations are defined in Figure 3.3b of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]).

Source: Table 6.1-4

Characterize Framework for Igneous Activity at Yucca Mountain, Nevada (BSC 2003 [DIRS 163769], Table 22), estimates the frequency of an igneous intrusion event to be 1.7×10^{-8} per year, which is the frequency of a basaltic dike intersecting the subsurface area of the repository (intrusive scenario). If a dike intersects the repository, there is about a 78 percent chance that at least one or more eruptive centers would be located within the repository for an annual frequency of 1.3×10^{-8} per year (BSC 2003 [DIRS 163769], Table 22). An igneous disruptive event could lead to the destruction of waste packages and their waste forms. Therefore, the possibility of a waste form undergoing a criticality event must be examined.

In the event of igneous intrusion, moderating materials (primarily consisting of silicon dioxide and water) may be present. As a result of igneous intrusion into the drifts, a criticality event may be possible due to (DOE 2002 [DIRS 155943], Section 4.3.3.2.1):

1. Immediate breach of the waste package;
2. Separation of a significant fraction of the fissile material from the neutron absorber by magma transport; or
3. Accumulation of a critical mass of fissile material from, or within, the transporting magma.

6.6.1 Igneous Intrusion Impacts on Waste Packages and Waste Forms

The TSPA-LA approach to implementing the models for waste package and waste form response during igneous intrusion considers two impact regions: (1) Zone 1, which includes the emplacement drift intruded by the basalt dike; and (2) Zone 2, which includes the emplacement drift adjacent to the intruded drift (BSC 2003 [DIRS 165002], Section 1).

Zone 1

It is expected that the drip shields, invert, and waste packages in Zone 1 will be compressed and damaged, allowing magma to occupy the entire emplacement drift. The igneous intrusion temperature may be as high as 1,169°C (BSC 2003 [DIRS 166407], Table 38). The melting points of waste packages made of Alloy C-22 and Stainless Steel Type 316NG are approximately 1,357°C and 1,375°C, respectively (CRWMS M&O 1999 [DIRS 121300], Section 5.1). Although the intrusive igneous temperature is lower than the melting points of steel and alloy, these engineered materials could be severely damaged at the intrusive temperature (e.g., through softening, creeping and breaking down) combined with the shear forces of the viscous magma moving at the assumed velocity.

When the waste packages are damaged, the waste forms will be exposed to and are likely to be enveloped and fused by the flowing magma. The fuel assemblies will be crushed and fragmented, introducing different size fragments and granules of UO₂ pellets/cladding, neutron absorber, and control rods. The crushed material may form radionuclide-bearing minerals by incorporating crystallizing silicate minerals.

The igneous intrusion scenario shows a range of consequences, extending from virtually no impact up to an impact upon all waste packages in the repository. The 50th percentile value indicates approximately 3,160 waste packages impacted, out of over 11,000 (BSC 2003 [DIRS 161851], Section 7.2).

Zone 2

Analyses of possible impacts from thermal and volatile gases are conducted on Zone 2 drip shields, waste packages, and cladding to determine the potential for elevated corrosion rates due to deleterious environment, marked by the conducting heat and diffusing volatile gases evolving from the basalt magma intruded into Zone 1 emplacement drifts (BSC 2003 [DIRS 165002], Section 6.5.2). From the spatial and temporal heat conduction simulations and analysis, the high temperatures after a magma event attenuate rapidly with distance. The maximum temperature rise in an adjacent drift is small (less than 10°C), and the rock provides effective thermal insulation to the impacts of high temperature. From the gas transport simulations, the maximum gas concentrations entering the Zone 2 emplacement drifts are extremely low. It is concluded that there are no impacts from thermal or volatile gases on waste packages and waste forms in Zone 2 (BSC 2003 [DIRS 165002], Section 6.7.2).

6.6.2 Configurations Resulting from Complete Waste Package Destruction

The drip shields, waste packages, and fuel cladding in Zone 2 remain intact with no impacts resulting from the heat or volatile gases released during an igneous intrusion. Therefore, criticality evaluation of the waste packages and waste forms in Zone 2 are not required as these would be enveloped by the base case analysis of Section 6.3.

However, in Zone 1, after a postulated waste package destruction, turbulent magma could move the waste form away from the neutron absorber materials that are placed into the waste packages to inhibit criticality.

A conservative evaluation of the possibility of criticality after an igneous intrusion, is based on the following elements:

1. Fissile material (commercial SNF pellet) is surrounded by a cubic lattice of magma which serves as the moderator (Assumption 5.4.1),
2. Fissile material becomes separated from the neutron absorber material (Assumption 5.4.2), and
3. Magma water content is 0.5 weight percent (Assumption 5.4.6).

The post-Miocene data on water contents of basaltic magma in the Yucca Mountain region is sparse, making it difficult to define rigorously a probability distribution function for water content for use in the Performance Assessment. As such, it is recommended to use between 3 and 4 weight percent dissolved water. The probability decreases linearly so that it is zero at 4 weight percent, representing the expectation that at about 4 weight percent, basaltic magma will crystallize underground rather than erupt (BSC 2003 [DIRS 166407], Section 6.3.2.2). For intrusive dike impacts, the upper bound of 4 weight percent initial dissolved water content in the magma is considered. As the magma ascends, it decompresses at low pressures to cause magma crystallization and water vapor exsolving, and as a result, the initial dissolved mass of water in the magma will reduce. At the repository level and the corresponding pressure, the dissolved water in the magma is expected to reduce to roughly 0.5 weight percent at a temperature of 1,150°C (Assumption 5.4.6).

6.6.3 Complete Waste Package Destruction: Internal or Near-Field Criticality

In the event of igneous intrusion, the enrichment and burnup of the fissile materials will not change due to the crush of waste packages and the mixing of waste forms and basalt/magma. The criticality concerns would be the possibilities of separation of neutron absorber from the fuel assemblies, the presence of water and silica as potential neutron moderators, and the convergence of fuel assemblies into a critical mass.

As mentioned earlier in Section 6.6, criticality during an igneous intrusion depends on critical mass and critical configuration, which includes separation of the neutron absorber (control rods and boron plates) from the fissile material, and the presence of sufficient amounts of a neutron moderator. Although silica is abundant in the basalt/magma, its neutron moderation is much less than that of water. The initial water content in magma at the repository level is assumed to be 0.5 weight percent (Assumption 5.4.6). Considering igneous intrusion high temperature (up to 1,169°C) (BSC 2003 [DIRS 166407], Table 38), and high pressure (approximately 7.5 MPa) (CRWMS M&O 2000 [DIRS 151552], Section 6.3.2) conditions, the remaining water is expected to vaporize rapidly since the saturation temperature of water at 7.5 MPa is only 290°C (Wark 1983 [DIRS 157283], Table A-12), well below the magma temperature.

Criticality calculations of disassembled waste packages were performed previously for igneous scenarios in *Probability of Criticality Before 10,000 Years* (CRWMS M&O 2000 [DIRS 149939], Section 6.2.2) using MCNP (Monte Carlo N-Particle Transport Code System). MCNP is widely accepted software used to perform criticality analysis of waste packages and waste

forms configuration. A PWR commercial SNF waste package with 3.5 weight percent enrichment, 10.0 GWd/MTU burnup, and 5 years decay was used in that report. The lattice spacing of the commercial SNF pellets (or total volume surrounding the pellets) was varied in order to determine the optimum volume favorable to criticality. However, in real operation, there would be no pattern of loading the same PWR waste packages together. For the sake of conservatism and simplicity, that report (CRWMS M&O 2000 [DIRS 149939]) modeled fuel pellets from seven commercial SNF waste packages, spread out in a cubic lattice that was filled with magma and reflected by tuff in a spherical geometry. The maximum estimated water content of 5.0 weight percent was used in the magma composition. The maximum calculated value of k_{eff} from these analyses was 0.769.

It should be noted that although an igneous event may result in crushing and fragmenting the waste package and its contents, previous and current criticality evaluations assume the fuel pellet remains intact within the magma system. This treatment is appropriate because for low-enriched uranium systems, such as commercial SNF, a heterogeneous lattice configuration (e.g., intact fuel pellets aligned in a set order) is more reactive (yields a higher k_{eff}) than a homogeneous configuration with granulated fuel (Duderstadt and Hamilton 1976 [DIRS 106070], pp. 403 to 405).

New evaluations were performed using the estimated 0.5 weight percent water content in magma at the repository level (Assumption 5.4.6). The elemental composition and atom densities of magma based on this water content level are listed in Tables 4.1-10 and 4.1-12. A cylindrical PWR fuel pellet (0.47 cm round and 1.1 cm long) is imbedded in the magma cube (DOE 1987 [DIRS 132333], pp. 2A to 34). The elemental composition and mass densities of UO_2 with 5.0 weight percent enrichment (fresh fuel) can be found in Table 4.1-13. The atom densities input into the MCNP analyses are presented in Table 6.6-2. The element atom densities are calculated in the Microsoft EXCEL file *FepIgn1.xls* of Attachment VII (based on the information presented in Tables 4.1-10, 4.1-12, and 4.1-13).

Table 6.6-2. Atom Densities of Magma with 0.5 Weight Percent Water

Element	Atom Density (atoms/b-cm) ^c
H	9.53E-04
O	4.74E-02
Si	1.39E-02
Al	5.64E-03
Fe	2.50E-03
Mg	2.48E-03
Ca	2.63E-03
Na	1.96E-03
K	6.71E-04
Ti	4.15E-04
P	2.95E-04
Mn	4.11E-05
Total	7.88E-02

Source: Microsoft Excel spreadsheet
"FepIgn1.xls" results (Attachment VII)

The magma cube surfaces are designated to be reflective to simulate an infinite system. The size of the magma cube is varied to search for the bounding configuration - that which results in the maximum k_{eff} value. These data and geometric configurations are applied in running the MCNP code to calculate k_{eff} . The results of this evaluation are presented in Table 6.6-3.

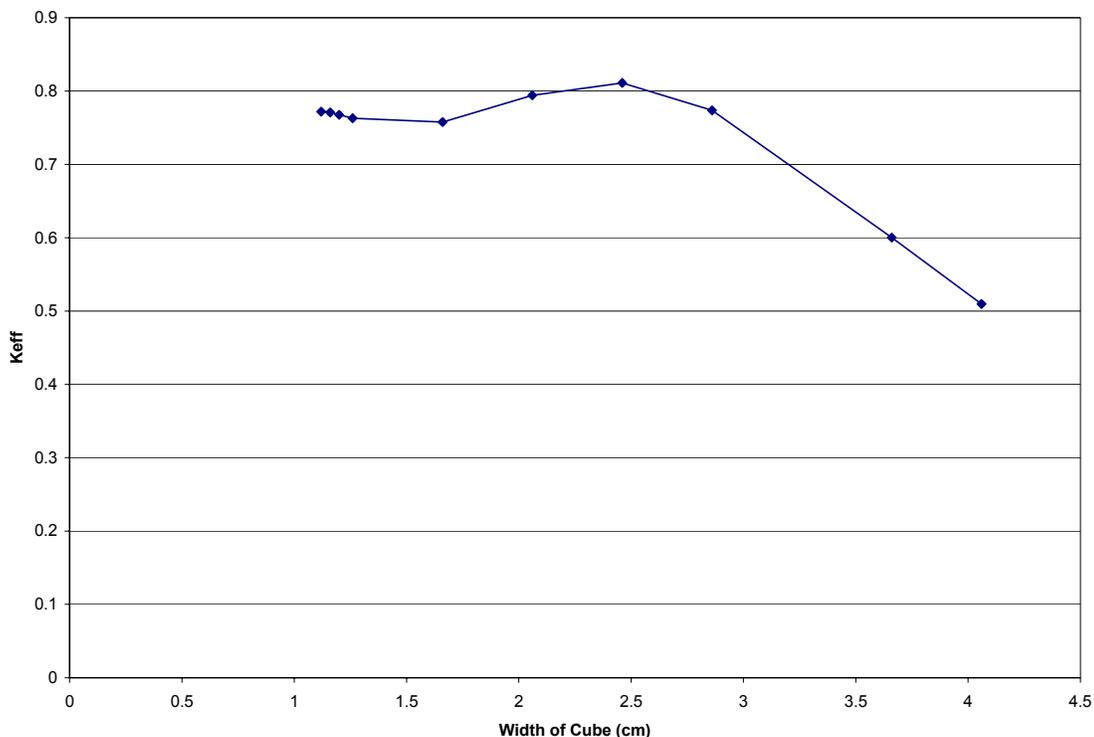
Table 6.6-3 contains values for k_{eff} and width of the magma cube. These values are plotted in Figure 6.6-1. The associated calculated uncertainty values, sigma (σ), are also presented in Table 6.6-3 for each k_{eff} value. The 95th percentile k_{eff} is calculated by adding two times the sigma value to the k_{eff} value. This result is accounted for in the last column of the table. From Table 6.6-3 it is seen that the $k_{\text{eff}}+2\sigma$ value peaks at 0.813 for a magma cube width of 2.46 cm. Since the evaluated configurations are infinite systems, these results indicated that no matter how many waste packages are disassembled by an igneous event, the systems would remain subcritical. Therefore, no probability evaluations of these configurations are required.

The value of $k_{\text{eff}}+2\sigma$ is expected to be lower than the calculated critical limit for external systems moderated by silica (tuff or magma) (Assumption 5.4.4). Although the above evaluation was performed for PWR commercial SNF fuel pellet, there are no appreciable differences between PWR and BWR fuel pellets and the results are, therefore, applicable to both. However, given the differences between commercial SNF and some highly enriched DOE SNF, results from the commercial SNF igneous evaluation cannot be directly abstracted to DOE SNF. Therefore, pending further evaluation, it is assumed that configurations resulting from an igneous event involving DOE SNF will not result in a critical system (Assumption 5.4.3). Therefore, the probability of criticality due to an igneous disruptive event is set to zero.

Table 6.6-3. Summary of Criticality Calculations with Infinite System

Case Name	Width of Cube (cm)	Volume of Cube (cm ³)	K_{eff}	Sigma (σ)	$k_{\text{eff}} + 2 \sigma$
cpinf08	1.12	1.40	0.772	5.0×10^{-4}	0.773
cpinf09	1.16	1.56	0.771	6.0×10^{-4}	0.772
cpinf10	1.2	1.73	0.767	6.1×10^{-4}	0.769
cpinf06	1.26	2.00	0.763	6.1×10^{-4}	0.764
cpinf01	1.66	4.57	0.758	6.7×10^{-4}	0.759
cpinf07	2.06	8.74	0.794	7.3×10^{-4}	0.796
cpinf02	2.46	14.9	0.811	6.6×10^{-4}	0.813
cpinf03	2.86	23.4	0.774	8.6×10^{-4}	0.775
cpinf04	3.66	49.0	0.600	6.5×10^{-4}	0.602
cpinf05	4.06	66.9	0.510	5.7×10^{-4}	0.511

Source: CRWMS M&O 1998 [DIRS 154060] analysis results (Attachment VII)



Source: Table 6.6-3

Figure 6.6-1. Criticality Calculations with Infinite System

6.7 CRITICALITY FEPS RESULTS

Evaluation of SAPHIRE event trees for the base case events, seismic disruptive event, and rockfall disruptive event resulted in the per waste package probabilities presented in Table 6.7-1. Table 6.7-1 summarizes the SAPHIRE analysis results presented in Tables 6.3-8, 6.4-12 (both seismic base case [as-designed 44-BWR Waste Package absorber plate thickness as designed of 5 mm] and sensitivity case [44-BWR Waste Package absorber plate thickness modified to 7 mm] results) and 6.5-2. Additionally, the results of the igneous disruptive event criticality FEPS evaluation of Section 6.6 have been added to this table. The total per waste package flooding probability results of Table 6.7-1 is the sum of the initiating event per waste package flooding probabilities for each waste package type (i.e., Total = Base Case + Seismic + Rockfall + Igneous).

Table 6.7-1. Per Waste Package Flooding Probability per Waste Package Type

Waste Package Type	Number of Waste Packages	Per Waste Package Flooding Probability				
		Base Case	Seismic	Rockfall	Igneous	Total
21-PWR with Absorber Plates	4,299	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
21-PWR with Control Rods	95	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
12-PWR Long	169	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
44-BWR (Seismic Base Case ^a)	2,831	0.00E+00	1.44E-6	0.00E+00	0.00E+00	1.44E-6
44-BWR (Seismic Sensitivity Case ^b)	2,831	0.00E+00	1.07E-10	0.00E+00	0.00E+00	1.07E-10
24-BWR	84	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
DOE SNF	3,412	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Source: SAPHIRE V7.18 (BSC 2002 [DIRS 160873]) analysis results (Attachment II, p. II-20)

Notes: ^a 44-BWR Waste Package Absorber Plate thickness is as designed at 5 mm.

^b 44-BWR Waste Package absorber plate thickness is modified to 7 mm.

Using the binomial distribution equation (Equation 6.7-1) (Walpole et al. 1998 [DIRS 152180], Section 5.3), the total probability of waste package flooding for each waste package type can be calculated as:

$$b(x, n, p) = \binom{n}{x} p^x (1-p)^{n-x} \quad (\text{Eq. 6.7-1})$$

where:

x = number of waste packages flooded (varied between 0 and 3)

n = number of the waste package type being evaluated (Table 6.7-1, Column 2)

p = per waste package flooding probability of the waste package type being evaluated (Table 6.7-1, Column 7)

The total probability of flooding between one and four waste packages is presented in Table 6.7-2 for each of the waste package types presented in Table 6.7-1. As presented in this table, for the 21-PWR with Absorber Plates Waste Package, the analyses show that the waste package flooding probability is always below the regulatory probability criterion of less than one chance in 10,000 of occurring over 10,000 years (10 CFR 63.114(d) [DIRS 156605]). However, the binomial distribution analysis of all waste package types using the seismic base case results (as-designed 44-BWR Waste Package absorber plate thickness of 5 mm) indicates that the individual and total probability of flooding at least one waste package is greater than the regulatory probability criterion. These table cells have been highlighted. The individual and total waste package flooding probabilities drop below the regulatory probability criterion for two or more flooded waste packages.

If the seismic sensitivity case results are considered (44-BWR Waste Package absorber plate thickness modified to 7 mm), the binomial distribution results for all waste package types indicate the individual and total waste package flooding probabilities are always below the regulatory probability criterion. Based on these results, it is expected that the absorber plate thickness of the 44-BWR Waste Package will be modified to increase its thickness to 7 mm. The criticality FEPs screening decisions of Section 6.8 will be based on the results from the 44-BWR Waste Package evaluation with the 7-mm absorber plate thickness.

Table 6.7-2. Binomial Distribution Waste Package Flooding Probability

Waste Package Type	Number of Waste Packages	Waste Package Flooding Probability Number of Flooded Waste Packages			
		1	2	3	4
21-PWR with Absorber Plates	4,299	0.00E+00	0.00E+00	0.00E+00	0.00E+00
21-PWR with Control Rods	95	0.00E+00	0.00E+00	0.00E+00	0.00E+00
12-PWR Long	169	0.00E+00	0.00E+00	0.00E+00	0.00E+00
44-BWR (Seismic Base Case ^a)	2,831	4.06E-03	8.27E-06	1.12E-08	1.14E-11
44-BWR (Seismic Sensitivity Case ^b)	2,831	3.03E-07	4.59E-14	4.63E-21	3.50E-28
24-BWR	84	0.00E+00	0.00E+00	0.00E+00	0.00E+00
DOE SNF	3,412	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total (21-PWR with Absorber Plates)	4,299	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total (all waste package types, 44-BWR Seismic Base Case ^a)	10,890	4.06E-03	8.27E-06	1.12E-08	1.14E-11
Total (all waste package types, 44-BWR Seismic Sensitivity Case ^b)	10,890	3.03E-07	4.59E-14	4.63E-21	3.50E-28

Source: Microsoft Excel spreadsheet "Binom Dist.xls" results (Attachment VII)

Notes: ^a 44-BWR Waste Package Absorber Plate thickness is as designed at 5 mm.

^b 44-BWR Waste Package absorber plate thickness is modified to 7 mm.

6.8 CRITICALITY FEPS SCREENING DECISIONS

A discussion of the screening decisions for each of the sixteen criticality FEPS follows.

6.8.1 FEP 2.1.14.15.0A Screening Discussion

Name: In-package criticality (intact configuration)

Number: 2.1.14.15.0A

Description: The waste package internal structures and the waste form remain intact. A breach (or breaches) in the waste package allow(s) water to either accumulate or flow-through the waste package. Criticality then occurs in situ. In-package criticality resulting from disruptive events is addressed in separate FEPS.

Descriptor Phrases: Criticality (in waste package)

Screening Decision: Excluded based on low probability.

Screening Argument: For a criticality event to occur, the proper combination of materials (neutron moderators, neutron absorbers, fissile) and geometric configuration must exist. A critical system for the geological repository is defined as one having an effective neutron multiplication factor (k_{eff}), larger than the critical limit. The critical limit is the value of k_{eff} at which a system (configuration of fissile material) is considered critical as characterized by statistical tolerance limits (BSC 2003 [DIRS 165733], Section 6.2.1).

Waste form criticality analyses demonstrate that an intact, fully flooded with water (a neutron moderator), waste package configuration cannot achieve criticality (CRWMS M&O 1999 [DIRS 125206], CRWMS M&O 2000 [DIRS 147650], CRWMS M&O 2000 [DIRS 147651], BSC 2003 [DIRS 166610], CRWMS M&O 2000 [DIRS 151742], CRWMS M&O 2000 [DIRS 151743], CRWMS M&O 2001 [DIRS 154194], BSC 2001 [DIRS 157733], BSC 2001 [DIRS 157734], BSC 2001 [DIRS 161125]). Additionally, intact, fully loaded, fully flooded waste packages are precluded from achieving criticality by design to satisfy a preclosure operations requirement that the MGR provide means to ensure criticality control during SNF/HLW handling operations, including waste package loading (Siddoway 2003 [DIRS 163904], Requirement 1.1.6-4).

Therefore, the probability of criticality for a nominal waste package configuration is zero (refer to Section 6.2 of this report). This result is applicable for all waste form / waste package types

TSPA Disposition: Not Applicable

Supporting Reports:

- *21 PWR Waste Package with Absorber Plates Loading Curve Evaluation* (BSC 2003 [DIRS 166610])
- *44-BWR Waste Package Loading Curve Evaluation* (BSC 2001 [DIRS 161125])
- *Evaluation of Codisposal Viability for MOX (FFTF) DOE-Owned Fuel* (CRWMS M&O 1999 [DIRS 125206])
- *Evaluation of Codisposal Viability for U₂38 (TRIGA) DOE-Owned Fuel* (CRWMS M&O 2000 [DIRS 147650])
- *Evaluation of Codisposal Viability for HEU Oxide (Shippingport PWR) DOE-Owned Fuel* (CRWMS M&O 2000 [DIRS 147651])
- *Evaluation of Codisposal Viability for U-Zr/U-Mo (Enrico Fermi) DOE-Owned Fuel* (CRWMS M&O 2000 [DIRS 151742])
- *Evaluation of Codisposal Viability for Th/U Oxide (Shippingport LWBR) DOE-Owned Fuel* (CRWMS M&O 2000 [DIRS 151743])
- *Evaluation of Codisposal Viability for U-Metal (N Reactor) DOE-Owned Fuel* (CRWMS M&O 2001 [DIRS 154194])
- *Evaluation of Codisposal Viability for Melt and Dilute DOE-Owned Fuel* (BSC 2001 [DIRS 157733])
- *Evaluation of Codisposal Viability for Th/U Carbide (Fort Saint Vrain HTGR) DOE-Owned Fuel* (BSC 2001 [DIRS 157734])
- *Criticality Model Report* (BSC 2003 [DIRS 165733])
- *Project Functional and Operational Requirements* (Siddoway 2003 [DIRS 163904])
- *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505])

6.8.2 FEP 2.1.14.16.0A Screening Discussion

<i>Name:</i>	In-package criticality (degraded configuration)
<i>Number:</i>	2.1.14.16.0A
<i>Description:</i>	<p>The waste package internal structures and the waste form degrade. A critical configuration (sufficient fissile material and neutron moderator, lack of neutron absorbers) develops and criticality occurs in situ. Potential in situ critical configurations are defined in Figures 3.2a and 3.2b of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]). In-package criticality resulting from disruptive events is addressed in separate FEPs.</p>
<i>Descriptor Phrases:</i>	Criticality (in waste package)
<i>Screening Decision:</i>	Excluded based on low probability.
<i>Screening Argument:</i>	<p>For a criticality event to occur, the proper combination of materials (neutron moderators, neutron absorbers, fissile) and geometric configuration must exist. A critical system for the geological repository is defined as one having an effective neutron multiplication factor (k_{eff}), larger than the critical limit. The critical limit is the value of k_{eff} at which a system (configuration of fissile material) is considered critical as characterized by statistical tolerance limits (BSC 2003 [DIRS 165733], Section 6.2.1).</p> <p>All base case (i.e., nominal scenario class, no disruptive events) postclosure criticality FEPs, internal and external, require water infiltration to degrade the waste package internals and waste form. Neutron absorber material loss and a flooded waste package condition for neutron moderation is the most likely scenario that could result in a potentially critical configuration in any of the in situ criticality FEPs. External criticality FEPs (near-field and far-field) also require the separation of neutron absorber materials from the waste form, transport of fissile material from the waste package, and accumulation of the fissile material within the drift invert or beyond.</p> <p>Water, silica, and carbon are the only potential moderating materials for both internal and external configurations. Water is the most effective neutron-moderating material, which can enter the waste package as percolation flow or be present in the pores of the rock. Silica is present in appreciable quantities in the high-level radioactive waste glass canisters and in the rock. Silica can also be introduced into the waste package through precipitation from the percolation flow. Carbon is present in only limited amounts in select DOE SNF types and, therefore, has a limited impact on the potential for criticality. The loading of the DOE-standardized SNF canisters, the design of the basket structure</p>

inside the canisters, and the addition of neutron absorbers take into account the presence and effect of glass in DOE SNF codisposal waste packages. Silica from the high-level radioactive waste glass canisters has no impact on the potential for criticality in DOE SNF codisposal waste packages. Silica is a much less effective moderator than water and its introduction into commercial SNF waste packages will displace water and effectively reduce the reactivity of the system, thus reducing the potential for criticality.

In addition, criticality without water infiltration is unlikely for the geologic repository because the waste package is designed so a criticality event in an intact waste package configuration is not possible. This satisfies a preclosure operations requirement that the MGR provide means to ensure criticality control during SNF/HLW handling operations, including waste package loading (Siddoway 2003 [DIRS 163904], Requirement 1.1.6-4).

Some of the DOE SNF waste forms have highly enriched fuel or a waste form that could potentially support unmoderated (fast) criticality if (1) the (fissile) material is concentrated beyond its design concentration in the waste form, and (2) the neutron absorber materials are removed. Concentration of the fissile material beyond its design concentration could result from either the degradation of the waste form resulting from water infiltration or a disruptive event. However, removal of the neutron absorber materials from a DOE SNF waste package would require a breach of the waste package and a removal mechanism. The most likely neutron absorber material removal mechanism is through water infiltration resulting in degradation of the waste package internal components, dissolving of the neutron absorber material in the water, and flushing of the material from the waste package. Since water infiltration does not occur, fast criticality can be excluded based on low probability.

The probability of criticality estimate accounts for factors such as early failures, manufacturing defects, fuel assembly misloads, etc. However, it may not be necessary to directly account for these factors if the total probability of criticality is calculated to be sufficiently below the regulatory probability criterion without utilizing them. For example, if the waste package flooding calculated probability is below the regulatory probability criterion, incorporation of the probability of a waste package misload would only result in a lower probability than has already been calculated.

Fuel assembly misloads (enrichment and/or burnup) could result in more (or less) fissile material being loaded into the waste package than permitted by the design loading curves. Additional fissile material in the waste package results in a higher criticality potential of the in-

package degraded configurations. However, because no water (i.e., neutron moderator) enters the waste package for base case criticality FEP conditions, the additional fissile material that could result from a fuel assembly misload cannot result in the formation of a critical configuration.

Because the probability function for drip shield damage area is zero for the base case (i.e., no drip shield failures [refer to Section 6.3.4.1]), there is no advective flow path into the waste package. Waste package failures result only from early waste package failure mechanisms (refer to Section 6.3.3.3 of this report). Therefore, the probability of waste package flooding is zero and the probability of criticality for this base case FEP is zero (refer to Table 6.7-2 of this report). Based on assumptions requiring confirmation, this result is applicable for all waste form / waste package types.

TSPA Disposition: Not Applicable

Supporting Reports:

- *Configuration Generator Model for In-Package Criticality* (BSC 2003 [DIRS 165629])
- *Stress Corrosion Cracking of the Drip Shield, the Waste Package Outer Barrier, and the Stainless Steel Structural Material* (BSC 2003 [DIRS 161234])
- *General Corrosion and Localized Corrosion of the Drip Shield* (BSC 2003 [DIRS 161236])
- *Analysis of Mechanisms for Early Waste Package/Drip Shield Failure* (BSC 2003 [DIRS 164475])
- *WAPDEG Analysis of Waste Package and Drip Shield Degradation* (BSC 2003 [DIRS 161317])
- *EBS Radionuclide Transport Abstraction* (BSC 2003 [DIRS 166466])
- *Criticality Model Report* (BSC 2003 [DIRS 165733])
- *Project Functional and Operational Requirements* (Siddoway 2003 [DIRS 163904])
- *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505])

6.8.3 FEP 2.1.14.17.0A Screening Discussion

Name: Near-field criticality

Number: 2.1.14.17.0A

Description: Near-field criticality occurs when fissile material-bearing solution from the waste package is transported into the drift and the fissile material is precipitated into a critical configuration. Potential near-field critical

configurations are defined in Figure 3.3a of *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505]). In-package criticality resulting from disruptive events is addressed in separate FEPs.

Descriptor Phrases: Criticality (in drift)

Screening Decision: Excluded based on low probability.

Screening Argument: For a criticality event to occur, the proper combination of materials (neutron moderators, neutron absorbers, fissile) and geometric configuration must exist. A critical system for the geological repository is defined as one having an effective neutron multiplication factor (k_{eff}), larger than the critical limit. The critical limit is the value of k_{eff} at which a system (configuration of fissile material) is considered critical as characterized by statistical tolerance limits (BSC 2003 [DIRS 165733], Section 6.2.1).

All base case (i.e., nominal scenario class, no disruptive events) postclosure criticality FEPs, internal and external, require water infiltration to degrade the waste package internals and waste form. Neutron absorber material loss and a flooded waste package condition for neutron moderation is the most likely scenario that could result in a potentially critical configuration in any of the in situ criticality FEPs. External criticality FEPs (near-field and far-field) also require the separation of neutron absorber materials from the waste form, transport of fissile material from the waste package, and accumulation of the fissile material within the drift invert or beyond.

Water, silica, and carbon are the only potential moderating materials for both internal and external configurations. Water is the most effective neutron-moderating material, which can enter the waste package as percolation flow or be present in the pores of the rock. Silica is present in appreciable quantities in the high-level radioactive waste glass canisters and in the rock. Silica can also be introduced into the waste package through precipitation from the percolation flow. Carbon is present in only limited amounts in select DOE SNF types and, therefore, has a limited impact on the potential for criticality. The loading of the DOE-standardized SNF canisters, the design of the basket structure inside the canisters, and the addition of neutron absorbers take into account the presence and effect of glass in DOE SNF codisposal waste packages. Silica from the high-level radioactive waste glass canisters has no impact on the potential for criticality in DOE SNF codisposal waste packages. Silica is a much less effective moderator than water and its introduction into commercial SNF waste packages will displace water and effectively reduce the reactivity of the system, thus reducing the potential for criticality.

In addition, criticality without water infiltration is unlikely for the geologic repository because the waste package is designed such that a criticality event in an intact waste package configuration is not possible. This satisfies a preclosure operations requirement that the MGR provide means to ensure criticality control during SNF/HLW handling operations, including waste package loading (Siddoway 2003 [DIRS 163904], Requirement 1.1.6-4).

Some of the DOE SNF waste forms have highly enriched fuel or waste form that could potentially support unmoderated (fast) criticality if (1) the (fissile) material is concentrated beyond its design concentration in the waste form and (2) the neutron absorber materials are removed. Concentration of the fissile material beyond its design concentration could result from either the degradation of the waste form resulting from water infiltration or a disruptive event. However, removal of the neutron absorber materials from a DOE SNF waste package would require a breach of the waste package and a removal mechanism. The most likely neutron absorber material removal mechanism is through water infiltration resulting in degradation of the waste package internal components, dissolving of the neutron absorber material in the water, and flushing of the material from the waste package. Since water infiltration does not occur, fast criticality can be excluded based on low probability.

The probability of criticality estimate accounts for factors such as early failures, manufacturing defects, fuel assembly misloads, etc. However, it may not be necessary to directly account for these factors if the total probability of criticality is calculated to be sufficiently below the regulatory probability criterion without utilizing them. For example, if the calculated probability of waste package flooding is below the regulatory probability criterion, incorporation of the probability of a waste package misload would only result in a lower probability than has already been calculated.

Fuel assembly misloads (enrichment and/or burnup) could result in more (or less) fissile material being loaded into the waste package than permitted by the design loading curves. Additional fissile material in the waste package results in a higher criticality potential of the in-package degraded configurations. However, because no water (i.e., neutron moderator) enters the waste package for the base case criticality FEPs' conditions, the additional fissile material that could result from a fuel assembly misload cannot result in the formation of a critical configuration.

It then follows that the probability of external criticality must be less than the probability of waste package flooding. This is because, in addition to the events evaluated to calculate the probability of water

entering a failed waste package, the probability of the following events must also be considered for external criticality:

- Waste form degradation over the performance period;
- Separating the fissile materials from the degraded waste form;
- Removing the fissile materials from the waste package;
- Accumulating sufficient fissile material into a potentially critical configuration in the near-field or far-field environments; and
- Having sufficient neutron moderator available.

Because the probability function for drip shield damage area is zero for the base case (i.e., no drip shield failures [refer to Section 6.3.4.1 of this report]), thereby preventing an advective flow path into the waste package, the probability of waste package flooding is zero. Since no water can enter the waste package to degrade the waste package internals or waste form, no fissile material can be transported from the waste package and into the near-field environment. Therefore, the probability of criticality for this base case FEP is zero (refer to Section 6.3.4.2 of this report). Based on assumptions requiring confirmation, this result is applicable for all waste form / waste package types.

TSPA Disposition: Not Applicable

Supporting Reports:

- *Geochemistry Model Abstraction and Sensitivity Studies for the 21 PWR CSNF Waste Packages* (BSC 2002 [DIRS 160638])
- *External Accumulation of Fissile Material from DOE Co-Disposal Waste Packages* (BSC 2002 [DIRS 159913])
- *Criticality Model Report* (BSC 2003 [DIRS 165733])
- *Project Functional and Operational Requirements* (Siddoway 2003 [DIRS 163904])
- *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505])

6.8.4 FEP 2.2.14.09.0A Screening Discussion

Name: Far-field criticality

Number: 2.2.14.09.0A

Description: Far-field criticality occurs when fissile material-bearing solution from the waste package is transported beyond the drift and the fissile material is precipitated into a critical configuration. Potential far-field critical configurations are defined in Figure 3.3b of *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505]). In-package criticality resulting from disruptive events is addressed in

separate FEPs.

Descriptor Phrases: Criticality (in the geosphere)

Screening Decision: Excluded based on low probability.

Screening Argument: For a criticality event to occur, the proper combination of materials (neutron moderators, neutron absorbers, fissile) and geometric configuration must exist. A critical system for the geological repository is defined as one having an effective neutron multiplication factor (k_{eff}), larger than the critical limit. The critical limit is the value of k_{eff} at which a system (configuration of fissile material) is considered critical as characterized by statistical tolerance limits (BSC 2003 [DIRS 165733], Section 6.2.1).

All base case (i.e., nominal scenario class, no disruptive events) postclosure criticality FEPs, internal and external, require water infiltration to degrade the waste package internals and waste form. Neutron absorber material loss and a flooded waste package condition for neutron moderation is the most likely scenario that could result in a potentially critical configuration in any of the in situ criticality FEPs. External criticality FEPs (near-field and far-field) also require the separation of neutron absorber materials from the waste form, transport of fissile material from the waste package, and accumulation of the fissile material within the drift invert or beyond.

Water, silica, and carbon are the only potential moderating materials for both internal and external configurations. Water is the most effective neutron-moderating material, which can enter the waste package as percolation flow or be present in the pores of the rock. Silica is present in appreciable quantities in the high-level radioactive waste glass canisters and in the rock. Silica can also be introduced into the waste package through precipitation from the percolation flow. Carbon is present in only limited amounts in select DOE SNF types and, therefore, has a limited impact on the potential for criticality. The loading of the DOE-standardized SNF canisters, the design of the basket structure inside the canisters, and the addition of neutron absorbers take into account the presence and effect of glass in DOE SNF codisposal waste packages. Silica from the high-level radioactive waste glass canisters has no impact on the potential for criticality in DOE SNF codisposal waste packages. Silica is a much less effective moderator than water and its introduction into commercial SNF waste packages will displace water and effectively reduce the reactivity of the system, thus reducing the potential for criticality.

In addition, criticality without water infiltration is unlikely for the geologic repository because the waste package is designed such that a

criticality event in an intact waste package configuration is not possible. This satisfies a preclosure operations requirement that the MGR provide means to ensure criticality control during SNF/HLW handling operations, including waste package loading (Siddoway 2003 [DIRS 163904], Requirement 1.1.6-4).

Some of the DOE SNF waste forms have highly enriched fuel or waste form that could potentially support unmoderated (fast) criticality if (1) the (fissile) material is concentrated beyond its design concentration in the waste form and (2) the neutron absorber materials are removed. Concentration of the fissile material beyond its design concentration could result from either the degradation of the waste form resulting from water infiltration or a disruptive event. However, removal of the neutron absorber materials from a DOE SNF waste package would require a breach of the waste package and a removal mechanism. The most likely neutron absorber material removal mechanism is through water infiltration resulting in degradation of the waste package internal components, dissolving of the neutron absorber material in the water, and flushing of the material from the waste package. Since water infiltration does not occur, fast criticality can be excluded based on low probability.

The probability of criticality estimate accounts for factors such as early failures, manufacturing defects, fuel assembly misloads, etc. However, it may not be necessary to directly account for these factors if the total probability of criticality is calculated to be sufficiently below the regulatory probability criterion without utilizing them. For example, if the calculated probability of waste package flooding is below the regulatory probability criterion, incorporation of the probability of a waste package misload would only result in a lower probability than has already been calculated.

Fuel assembly misloads (enrichment and/or burnup) could result in more (or less) fissile material being loaded into the waste package than permitted by the design loading curves. Additional fissile material in the waste package results in a higher criticality potential of the in-package degraded configurations. However, because no water (i.e., neutron moderator) enters the waste package for the base case criticality FEPs' conditions, the additional fissile material that could result from a fuel assembly misload cannot result in the formation of a critical configuration.

It then follows that the probability of external criticality must be less than the probability of waste package flooding. This is because, in addition to the events evaluated to calculate the probability of water entering a failed waste package, the probability of the following events must also be considered for external criticality:

- Waste form degradation over the performance period;
- Separating the fissile materials from the degraded waste form;
- Removing the fissile materials from the waste package;
- Accumulating sufficient fissile material into a potentially critical configuration in the near-field or far-field environments; and
- Having sufficient neutron moderator available.

Because the probability function for drip shield damage areas is zero for the base case (i.e., no drip shield failures [refer to Section 6.3.4.1 of this report]), thereby preventing an advective flow path into the waste package, the probability of waste package flooding is zero [refer to Section 6.3.4.2 of this report]. Since water cannot enter the waste package to degrade the waste package internals and waste form, fissile material cannot be transported from the waste package and into the far-field environment. Therefore, the probability of criticality for this base case FEP is zero. Based on assumptions requiring confirmation, this result is applicable for all waste form / waste package types.

TSPA Disposition: Not Applicable

Supporting Reports:

- *Geochemistry Model Abstraction and Sensitivity Studies for the 21 PWR CSNF Waste Packages* (BSC 2002 [DIRS 160638])
- *External Accumulation of Fissile Material from DOE Co-Disposal Waste Packages* (BSC 2002 [DIRS 159913])
- *Criticality Model Report* (BSC 2003 [DIRS 165733])
- *Project Functional and Operational Requirements* (Siddoway 2003 [DIRS 163904])
- *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505])

6.8.5 FEP 2.1.14.18.0A Screening Discussion

Name: In-package criticality resulting from a seismic event (intact configuration)

Number: 2.1.14.18.0A

Description: The waste package internal structures and the waste form remain intact either during or after a seismic disruptive event. A breach (or breaches) in the waste package allow(s) water to either accumulate or flow-through the waste package. Criticality then occurs in situ.

Descriptor Phrases: Criticality (in waste package), Criticality (from a seismic event)

Screening Decision: Excluded based on low probability.

Screening Argument: For a criticality event to occur, the proper combination of materials (neutron moderators, neutron absorbers, fissile) and geometric configuration must exist. A critical system for the geological repository is defined as one having an effective neutron multiplication factor (k_{eff}), larger than the critical limit. The critical limit is the value of k_{eff} at which a system (configuration of fissile material) is considered critical as characterized by statistical tolerance limits (BSC 2003 [DIRS 165733], Section 6.2.1).

Waste form criticality analyses demonstrate that an intact, fully flooded with water (a neutron moderator), waste package configuration cannot achieve criticality (CRWMS M&O 1999 [DIRS 125206], CRWMS M&O 2000 [DIRS 147650], CRWMS M&O 2000 [DIRS 147651], BSC 2003 [DIRS 166610], CRWMS M&O 2000 [DIRS 151742], CRWMS M&O 2000 [DIRS 151743], CRWMS M&O 2001 [DIRS 154194], BSC 2001 [DIRS 157733], BSC 2001 [DIRS 157734], BSC 2001 [DIRS 161125]). Additionally, intact, fully loaded, fully flooded waste packages are precluded from achieving criticality by design to satisfy a preclosure operations requirement that the MGR provide means to ensure criticality control during SNF/HLW handling operations, including waste package loading (Siddoway 2003 [DIRS 163904], Requirement 1.1.6-4).

Therefore, the probability of criticality for a nominal waste package configuration for the seismic disruptive event is zero. This result is applicable for all waste form / waste package types

TSPA Disposition: Not Applicable

Supporting Reports:

- *21 PWR Waste Package with Absorber Plates Loading Curve Evaluation* (BSC 2003 [DIRS 166610])
- *44-BWR Waste Package Loading Curve Evaluation* (BSC 2001 [DIRS 161125])
- *Evaluation of Codisposal Viability for MOX (FFTF) DOE-Owned Fuel* (CRWMS M&O 1999 [DIRS 125206])
- *Evaluation of Codisposal Viability for U₂38 (TRIGA) DOE-Owned Fuel* (CRWMS M&O 2000 [DIRS 147650])
- *Evaluation of Codisposal Viability for HEU Oxide (Shippingport PWR) DOE-Owned Fuel* (CRWMS M&O 2000 [DIRS 147651])
- *Evaluation of Codisposal Viability for U-Zr/U-Mo (Enrico Fermi) DOE-Owned Fuel* (CRWMS M&O 2000 [DIRS 151742])
- *Evaluation of Codisposal Viability for Th/U Oxide (Shippingport LWBR) DOE-Owned Fuel* (CRWMS M&O 2000 [DIRS 151743])
- *Evaluation of Codisposal Viability for U-Metal (N Reactor) DOE-Owned Fuel* (CRWMS M&O 2001 [DIRS 154194])

- *Evaluation of Codisposal Viability for Melt and Dilute DOE-Owned Fuel* (BSC 2001 [DIRS 157733])
- *Evaluation of Codisposal Viability for Th/U Carbide (Fort Saint Vrain HTGR) DOE-Owned Fuel* (BSC 2001 [DIRS 157734])
- *Criticality Model Report* (BSC 2003 [DIRS 165733])
- *Project Functional and Operational Requirements* (Siddoway 2003 [DIRS 163904])
- *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505])

6.8.6 FEP 2.1.14.19.0A Screening Discussion

Name: In-package criticality resulting from a seismic event (degraded configuration)

Number: 2.1.14.19.0A

Description: Either during, or as a result of, a seismic disruptive event, the waste package internal structures and the waste form degrade. A critical configuration develops and criticality occurs in situ. Potential in situ critical configurations are defined in Figures 3.2a and 3.2b of *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505]).

Descriptor Phrases: Criticality (in waste package), Criticality (from a seismic event)

Screening Decision: Excluded based on low probability.

Screening Argument: For a criticality event to occur, the proper combination of materials (neutron moderators, neutron absorbers, fissile) and geometric configuration must exist. A critical system for the geological repository is defined as one having an effective neutron multiplication factor (k_{eff}), larger than the critical limit. The critical limit is the value of k_{eff} at which a system (configuration of fissile material) is considered critical as characterized by statistical tolerance limits (BSC 2003 [DIRS 165733], Section 6.2.1).

All base case (i.e., nominal scenario class, no disruptive events) postclosure criticality FEPs, internal and external, require water infiltration to degrade the waste package internals and waste form. Neutron absorber material loss and a flooded waste package condition for neutron moderation is the most likely scenario that could result in a potentially critical configuration in any of the in situ criticality FEPs. External criticality FEPs (near-field and far-field) also require the separation of neutron absorber materials from the waste form, transport

of fissile material from the waste package, and accumulation of the fissile material within the drift invert or beyond.

Water, silica, and carbon are the only potential moderating materials for both internal and external configurations. Water is the most effective neutron-moderating material, which can enter the waste package as percolation flow or be present in the pores of the rock. Silica is present in appreciable quantities in the high-level radioactive waste glass canisters and in the rock. Silica can also be introduced into the waste package through precipitation from the percolation flow. Carbon is present in only limited amounts in select DOE SNF types and, therefore, has a limited impact on the potential for criticality. The loading of the DOE-standardized SNF canisters, the design of the basket structure inside the canisters, and the addition of neutron absorbers take into account the presence and effect of glass in DOE SNF codisposal waste packages. Silica from the high-level radioactive waste glass canisters has no impact on the potential for criticality in DOE SNF codisposal waste packages. Silica is a much less effective moderator than water and its introduction into commercial SNF waste packages will displace water and effectively reduce the reactivity of the system, thus reducing the potential for criticality.

In addition, criticality without water infiltration is unlikely for the geologic repository because the waste package is designed such that a criticality event in an intact waste package configuration is not possible. This satisfies a preclosure operations requirement that the MGR provide means to ensure criticality control during SNF/HLW handling operations, including waste package loading (Siddoway 2003 [DIRS 163904], Requirement 1.1.6-4).

Some of the DOE SNF waste forms have highly enriched fuel or waste form that could potentially support unmoderated (fast) criticality if (1) the (fissile) material is concentrated beyond its design concentration in the waste form and (2) the neutron absorber materials are removed. Concentration of the fissile material beyond its design concentration could result from either the degradation of the waste form resulting from water infiltration or a disruptive event. However, removal of the neutron absorber materials from a DOE SNF waste package would require a breach of the waste package and a removal mechanism. The most likely neutron absorber material removal mechanism is through water infiltration resulting in degradation of the waste package internal components, dissolving of the neutron absorber material in the water, and flushing of the material from the waste package. Since water infiltration does not occur, fast criticality can be excluded based on low probability.

The probability of criticality estimate accounts for factors such as early failures, manufacturing defects, fuel assembly misloads, etc. However, it may not be necessary to directly account for these factors if the total probability of criticality is calculated to be sufficiently below the regulatory probability criterion without utilizing them. For example, if the calculated probability of waste package flooding is below the regulatory probability criterion, incorporation of the probability of a waste package misload would only result in a lower probability than has already been calculated.

Fuel assembly misloads (enrichment and/or burnup) could result in more (or less) fissile material being loaded into the waste package than permitted by the design loading curves. Additional fissile material in the waste package results in a higher criticality potential of the in-package degraded configurations. However, because the probability of removing sufficient neutron absorber material from the waste package is below the regulatory probability threshold for the seismic criticality FEPs, the additional fissile material that could result from a fuel assembly misload cannot result in the formation of a critical configuration.

A seismic event results in a probability of drip shield and waste package failure of 1.0, allowing an advective flow to enter the waste package. However, the probability of sufficient seepage flux penetrating at least one waste package, degrading the waste package internals, and flushing the neutron absorber material from the waste package is only 3.03×10^{-7} during the performance period (refer to Table 6.7-2 of this report). Based on assumptions requiring confirmation, this result is applicable to all waste form / waste package types. However, it should be noted that the 44-BWR waste package type is the only nonzero contributor to this total probability.

TSPA Disposition: Not Applicable

Supporting Reports:

- *Configuration Generator Model for In-Package Criticality* (BSC 2003 [DIRS 165629])
- *Stress Corrosion Cracking of the Drip Shield, the Waste Package Outer Barrier, and the Stainless Steel Structural Material* (BSC 2003 [DIRS 161234])
- *General Corrosion and Localized Corrosion of the Drip Shield* (BSC 2003 [DIRS 161236])
- *Analysis of Mechanisms for Early Waste Package/Drip Shield Failure* (BSC 2003 [DIRS 164475])
- *WAPDEG Analysis of Waste Package and Drip Shield Degradation* (BSC 2003 [DIRS 161317])
- *EBS Radionuclide Transport Abstraction* (BSC 2003 [DIRS 166466])

- *Abstraction of Drift Seepage* (BSC 2003 [DIRS 165564])
- *Analysis of Infiltration Uncertainty* (BSC 2003 [DIRS 165991])
- *Seismic Consequence Abstraction* (BSC 2003 [DIRS 161812])
- *Criticality Model Report* (BSC 2003 [DIRS 165733])
- *Project Functional and Operational Requirements* (Siddoway 2003 [DIRS 163904])
- *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505])

6.8.7 FEP 2.1.14.20.0A Screening Discussion

Name: Near-field criticality resulting from a seismic event

Number: 2.1.14.20.0A

Description: Either during, or as a result of, a seismic disruptive event, near-field criticality occurs when fissile material-bearing solution from the waste package is transported into the drift and the fissile material is precipitated into a critical configuration. Potential near-field critical configurations are defined in Figure 3.3a of *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505]).

Descriptor Phrases: Criticality (in drift), Criticality (from a seismic event)

Screening Decision: Excluded based on low probability.

Screening Argument: For a criticality event to occur, the proper combination of materials (neutron moderators, neutron absorbers, fissile) and geometric configuration must exist. A critical system for the geological repository is defined as one having an effective neutron multiplication factor (k_{eff}), larger than the critical limit. The critical limit is the value of k_{eff} at which a system (configuration of fissile material) is considered critical as characterized by statistical tolerance limits (BSC 2003 [DIRS 165733], Section 6.2.1).

All base case (i.e., nominal scenario class, no disruptive events) postclosure criticality FEPs, internal and external, require water infiltration to degrade the waste package internals and waste form. Neutron absorber material loss and a flooded waste package condition for neutron moderation is the most likely scenario that could result in a potentially critical configuration in any of the in situ criticality FEPs. External criticality FEPs (near-field and far-field) also require the separation of neutron absorber materials from the waste form, transport of fissile material from the waste package, and accumulation of the fissile material within the drift invert or beyond.

Water, silica, and carbon are the only potential moderating materials for both internal and external configurations. Water is the most effective neutron-moderating material, which can enter the waste package as percolation flow or be present in the pores of the rock. Silica is present in appreciable quantities in the high-level radioactive waste glass canisters and in the rock. Silica can also be introduced into the waste package through precipitation from the percolation flow. Carbon is present in only limited amounts in select DOE SNF types and, therefore, has a limited impact on the potential for criticality. The loading of the DOE-standardized SNF canisters, the design of the basket structure inside the canisters, and the addition of neutron absorbers take into account the presence and effect of glass in DOE SNF codisposal waste packages. Silica from the high-level radioactive waste glass canisters has no impact on the potential for criticality in DOE SNF codisposal waste packages. Silica is a much less effective moderator than water and its introduction into commercial SNF waste packages will displace water and effectively reduce the reactivity of the system, thus reducing the potential for criticality.

In addition, criticality without water infiltration is unlikely for the geologic repository because the waste package is designed such that a criticality event in an intact waste package configuration is not possible. This satisfies a preclosure operations requirement that the MGR provide means to ensure criticality control during SNF/HLW handling operations, including waste package loading (Siddoway 2003 [DIRS 163904], Requirement 1.1.6-4).

Some of the DOE SNF waste forms have highly enriched fuel or waste form that could potentially support unmoderated (fast) criticality if (1) the (fissile) material is concentrated beyond its design concentration in the waste form and (2) the neutron absorber materials are removed. Concentration of the fissile material beyond its design concentration could result from either the degradation of the waste form resulting from water infiltration or a disruptive event. However, removal of the neutron absorber materials from a DOE SNF waste package would require a breach of the waste package and a removal mechanism. The most likely neutron absorber material removal mechanism is through water infiltration resulting in degradation of the waste package internal components, dissolving of the neutron absorber material in the water, and flushing of the material from the waste package. Since water infiltration does not occur, fast criticality can be excluded based on low probability.

The probability of criticality estimate accounts for factors such as early failures, manufacturing defects, fuel assembly misloads, etc. However, it may not be necessary to directly account for these factors if the total probability of criticality is calculated to be sufficiently below the regulatory probability criterion without utilizing them. For example, if

the calculated probability of waste package flooding is below the regulatory probability criterion, incorporation of the probability of a waste package misload would only result in a lower probability than has already been calculated.

Fuel assembly misloads (enrichment and/or burnup) could result in more (or less) fissile material being loaded into the waste package than permitted by the design loading curves. Additional fissile material in the waste package results in a higher criticality potential of the in-package degraded configurations. However, because the probability of removing sufficient neutron absorber material from the waste package is below the regulatory probability threshold for the seismic criticality FEPs' conditions, the additional fissile material that could result from a fuel assembly misload cannot result in the formation of a critical configuration.

It then follows that the probability of external criticality must be less than the probability of waste package flooding. This is because, in addition to the events evaluated to calculate the probability of water entering a failed waste package, the probability of the following events must also be considered for external criticality:

- Waste form degradation over the performance period;
- Separating the fissile materials from the degraded waste form;
- Removing the fissile materials from the waste package;
- Accumulating sufficient fissile material into a potentially critical configuration in the near-field or far-field environments; and
- Having sufficient neutron moderator available.

The probability of waste package flooding for a seismic disruptive event is below the regulatory probability criterion. Given the considerations listed above, the probability of criticality in the near-field environment will be even smaller. Therefore, this seismic disruptive event FEP can be excluded based on low probability (refer to Section 6.4.4 of this report). Based on assumptions requiring confirmation, this result is applicable for all waste form / waste package types.

TSPA Disposition: Not Applicable

Supporting Reports:

- *Geochemistry Model Abstraction and Sensitivity Studies for the 21 PWR CSNF Waste Packages* (BSC 2002 [DIRS 160638])
- *External Accumulation of Fissile Material from DOE Co-Disposal Waste Packages* (BSC 2002 [DIRS 159913])
- *Criticality Model Report* (BSC 2003 [DIRS 165733])
- *Project Functional and Operational Requirements* (Siddoway 2003 [DIRS 163904])
- *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505])

6.8.8 FEP 2.2.14.10.0A Screening Discussion

<i>Name:</i>	Far-field criticality resulting from a seismic event
<i>Number:</i>	2.2.14.10.0A
<i>Description:</i>	Either during, or as a result of, a seismic disruptive event, far-field criticality occurs when fissile material-bearing solution from the waste package is transported beyond the drift and the fissile material is precipitated into a critical configuration. Potential far-field critical configurations are defined in Figure 3.3b of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]).
<i>Descriptor Phrases:</i>	Criticality (in the geosphere), Criticality (from a seismic event)
<i>Screening Decision:</i>	Excluded based on low probability.
<i>Screening Argument:</i>	For a criticality event to occur, the proper combination of materials (neutron moderators, neutron absorbers, fissile) and geometric configuration must exist. A critical system for the geological repository is defined as one having an effective neutron multiplication factor (k_{eff}), larger than the critical limit. The critical limit is the value of k_{eff} at which a system (configuration of fissile material) is considered critical as characterized by statistical tolerance limits (BSC 2003 [DIRS 165733], Section 6.2.1).

All base case (i.e., nominal scenario class, no disruptive events) postclosure criticality FEPs, internal and external, require water infiltration to degrade the waste package internals and waste form. Neutron absorber material loss and a flooded waste package condition for neutron moderation is the most likely scenario that could result in a potentially critical configuration in any of the in situ criticality FEPs. External criticality FEPs (near-field and far-field) also require the separation of neutron absorber materials from the waste form, transport of fissile material from the waste package, and accumulation of the fissile material within the drift invert or beyond.

Water, silica, and carbon are the only potential moderating materials for both internal and external configurations. Water is the most effective neutron-moderating material, which can enter the waste package as percolation flow or be present in the pores of the rock. Silica is present in appreciable quantities in the high-level radioactive waste glass canisters and in the rock. Silica can also be introduced into the waste package through precipitation from the percolation flow. Carbon is present in only limited amounts in select DOE SNF types and, therefore, has a limited impact on the potential for criticality. The loading of the DOE-standardized SNF canisters, the design of the basket structure inside the canisters, and the addition of neutron absorbers take into

account the presence and effect of glass in DOE SNF codisposal waste packages. Silica from the high-level radioactive waste glass canisters has no impact on the potential for criticality in DOE SNF codisposal waste packages. Silica is a much less effective moderator than water and its introduction into commercial SNF waste packages will displace water and effectively reduce the reactivity of the system, thus reducing the potential for criticality.

In addition, criticality without water infiltration is unlikely for the geologic repository because the waste package is designed such that a criticality event in an intact waste package configuration is not possible. This satisfies a preclosure operations requirement that the MGR provide means to ensure criticality control during SNF/HLW handling operations, including waste package loading (Siddoway 2003 [DIRS 163904], Requirement 1.1.6-4).

Some of the DOE SNF waste forms have highly enriched fuel or waste form that could potentially support unmoderated (fast) criticality if (1) the (fissile) material is concentrated beyond its design concentration in the waste form and (2) the neutron absorber materials are removed. Concentration of the fissile material beyond its design concentration could result from either the degradation of the waste form resulting from water infiltration or a disruptive event. However, removal of the neutron absorber materials from a DOE SNF waste package would require a breach of the waste package and a removal mechanism. The most likely neutron absorber material removal mechanism is through water infiltration resulting in degradation of the waste package internal components, dissolving of the neutron absorber material in the water, and flushing of the material from the waste package. Since water infiltration does not occur, fast criticality can be excluded based on low probability.

The probability of criticality estimate accounts for factors such as early failures, manufacturing defects, fuel assembly misloads, etc. However, it may not be necessary to directly account for these factors if the total probability of criticality is calculated to be sufficiently below the regulatory probability criterion without utilizing them. For example, if the calculated probability of waste package flooding is below the regulatory probability criterion, incorporation of the probability of a waste package misload would only result in a lower probability than has already been calculated.

Fuel assembly misloads (enrichment and/or burnup) could result in more (or less) fissile material being loaded into the waste package than permitted by the design loading curves. Additional fissile material in the waste package results in a higher criticality potential of the in-package degraded configurations. However, because the probability of

removing sufficient neutron absorber material from the waste package is below the regulatory probability threshold for the seismic criticality FEPs' conditions, the additional fissile material that could result from a fuel assembly misload cannot result in the formation of a critical configuration.

It then follows that the probability of external criticality must be less than the probability of waste package flooding. This is because, in addition to the events evaluated to calculate the probability of water entering a failed waste package, the probability of the following events must also be considered for external criticality:

- Waste form degradation over the performance period;
- Separating the fissile materials from the degraded waste form;
- the probability of removing the fissile materials from the waste package;
- Accumulating sufficient fissile material into a potentially critical configuration in the near-field or far-field environments; and
- Having sufficient neutron moderator available.

The probability of waste package flooding for a seismic disruptive event is below the regulatory probability criterion. Given the considerations listed above, the probability of criticality in the far-field environment will be even smaller. Therefore, this seismic disruptive event FEP can be excluded based on low probability (refer to Section 6.4.4 of this report). Based on assumptions requiring confirmation, this result is applicable for all waste form / waste package types.

TSPA Disposition: Not Applicable

Supporting Reports:

- *Geochemistry Model Abstraction and Sensitivity Studies for the 21 PWR CSNF Waste Packages* (BSC 2002 [DIRS 160638])
- *External Accumulation of Fissile Material from DOE Co-Disposal Waste Packages* (BSC 2002 [DIRS 159913])
- *Criticality Model Report* (BSC 2003 [DIRS 165733])
- *Project Functional and Operational Requirements* (Siddoway 2003 [DIRS 163904])
- *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505])

6.8.9 FEP 2.1.14.21.0A Screening Discussion

Name: In-package criticality resulting from rockfall (intact configuration)

Number: 2.1.14.21.0A

Description: The waste package internal structures and the waste form remain intact either during or after a rockfall event. A breach (or breaches) in the waste package allow(s) water to either accumulate or flow-through the waste package. Criticality then occurs in situ.

Descriptor Phrases: Criticality (in waste package), Criticality (from a rockfall event)

Screening Decision: Excluded based on low probability.

Screening Argument: For a criticality event to occur, the proper combination of materials (neutron moderators, neutron absorbers, fissile) and geometric configuration must exist. A critical system for the geological repository is defined as one having an effective neutron multiplication factor (k_{eff}), larger than the critical limit. The critical limit is the value of k_{eff} at which a system (configuration of fissile material) is considered critical as characterized by statistical tolerance limits (BSC 2003 [DIRS 165733], Section 6.2.1).

Waste form criticality analyses demonstrate that an intact, fully flooded with water (a neutron moderator), waste package configuration cannot achieve criticality (CRWMS M&O 1999 [DIRS 125206], CRWMS M&O 2000 [DIRS 147650], CRWMS M&O 2000 [DIRS 147651], BSC 2003 [DIRS 166610], CRWMS M&O 2000 [DIRS 151742], CRWMS M&O 2000 [DIRS 151743], CRWMS M&O 2001 [DIRS 154194], BSC 2001 [DIRS 157733], BSC 2001 [DIRS 157734], BSC 2001 [DIRS 161125]). Additionally, intact, fully loaded, fully flooded waste packages are precluded from achieving criticality by design to satisfy a preclosure operations requirement that the MGR provide means to ensure criticality control during SNF/HLW handling operations, including waste package loading (Siddoway 2003 [DIRS 163904], Requirement 1.1.6-4).

Therefore, the probability of criticality for a nominal waste package configuration during a rockfall disruptive event is zero. This result is applicable for all waste form / waste package types

TSPA Disposition: Not Applicable

Supporting Reports:

- *21 PWR Waste Package with Absorber Plates Loading Curve Evaluation* (BSC 2003 [DIRS 166610])
- *44-BWR Waste Package Loading Curve Evaluation* (BSC 2001 [DIRS 161125])

- *Evaluation of Codisposal Viability for MOX (FFTF) DOE-Owned Fuel* (CRWMS M&O 1999 [DIRS 125206])
- *Evaluation of Codisposal Viability for U₂Si (TRIGA) DOE-Owned Fuel* (CRWMS M&O 2000 [DIRS 147650])
- *Evaluation of Codisposal Viability for HEU Oxide (Shippingport PWR) DOE-Owned Fuel* (CRWMS M&O 2000 [DIRS 147651])
- *Evaluation of Codisposal Viability for U-Zr/U-Mo (Enrico Fermi) DOE-Owned Fuel* (CRWMS M&O 2000 [DIRS 151742])
- *Evaluation of Codisposal Viability for Th/U Oxide (Shippingport LWBR) DOE-Owned Fuel* (CRWMS M&O 2000 [DIRS 151743])
- *Evaluation of Codisposal Viability for U-Metal (N Reactor) DOE-Owned Fuel* (CRWMS M&O 2001 [DIRS 154194])
- *Evaluation of Codisposal Viability for Melt and Dilute DOE-Owned Fuel* (BSC 2001 [DIRS 157733])
- *Evaluation of Codisposal Viability for Th/U Carbide (Fort Saint Vrain HTGR) DOE-Owned Fuel* (BSC 2001 [DIRS 157734])
- *Criticality Model Report* (BSC 2003 [DIRS 165733])
- *Project Functional and Operational Requirements* (Siddoway 2003 [DIRS 163904])
- *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505])

6.8.10 FEP 2.1.14.22.0A Screening Discussion

Name: In-package criticality resulting from rockfall (degraded configuration)

Number: 2.1.14.22.0A

Description: Either during, or as a result of, a rockfall event, the waste package internal structures and the waste form degrade. A critical configuration develops and criticality occurs in situ. Potential in situ critical configurations are defined in Figures 3.2a and 3.2b of *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505]).

Descriptor Phrases: Criticality (in waste package), Criticality (from a rockfall event)

Screening Decision: Excluded based on low probability.

Screening Argument: For a criticality event to occur, the proper combination of materials (neutron moderators, neutron absorbers, fissile) and geometric configuration must exist. A critical system for the geological repository is defined as one having an effective neutron multiplication factor (k_{eff}), larger than the critical limit. The critical limit is the value of k_{eff} at which a system (configuration of fissile material) is considered critical

as characterized by statistical tolerance limits (BSC 2003 [DIRS 165733], Section 6.2.1).

All base case (i.e., nominal scenario class, no disruptive events) postclosure criticality FEPs, internal and external, require water infiltration to degrade the waste package internals and waste form. Neutron absorber material loss and a flooded waste package condition for neutron moderation is the most likely scenario that could result in a potentially critical configuration in any of the in situ criticality FEPs. External criticality FEPs (near-field and far-field) also require the separation of neutron absorber materials from the waste form, transport of fissile material from the waste package, and accumulation of the fissile material within the drift invert or beyond.

Water, silica, and carbon are the only potential moderating materials for both internal and external configurations. Water is the most effective neutron-moderating material, which can enter the waste package as percolation flow or be present in the pores of the rock. Silica is present in appreciable quantities in the high-level radioactive waste glass canisters and in the rock. Silica can also be introduced into the waste package through precipitation from the percolation flow. Carbon is present in only limited amounts in select DOE SNF types and, therefore, has a limited impact on the potential for criticality. The loading of the DOE-standardized SNF canisters, the design of the basket structure inside the canisters, and the addition of neutron absorbers take into account the presence and effect of glass in DOE SNF codisposal waste packages. Silica from the high-level radioactive waste glass canisters has no impact on the potential for criticality in DOE SNF codisposal waste packages. Silica is a much less effective moderator than water and its introduction into commercial SNF waste packages will displace water and effectively reduce the reactivity of the system, thus reducing the potential for criticality.

In addition, criticality without water infiltration is unlikely for the geologic repository because the waste package is designed such that a criticality event in an intact waste package configuration is not possible. This satisfies a preclosure operations requirement that the MGR provide means to ensure criticality control during SNF/HLW handling operations, including waste package loading (Siddoway 2003 [DIRS 163904], Requirement 1.1.6-4).

Some of the DOE SNF waste forms have highly enriched fuel or waste form that could potentially support unmoderated (fast) criticality if (1) the (fissile) material is concentrated beyond its design concentration in the waste form and (2) the neutron absorber materials are removed. Concentration of the fissile material beyond its design concentration could result from either the degradation of the waste form resulting from

water infiltration or a disruptive event. However, removal of the neutron absorber materials from a DOE SNF waste package would require a breach of the waste package and a removal mechanism. The most likely neutron absorber material removal mechanism is through water infiltration resulting in degradation of the waste package internal components, dissolving of the neutron absorber material in the water, and flushing of the material from the waste package. Since water infiltration does not occur, fast criticality can be excluded based on low probability.

The probability of criticality estimate accounts for factors such as early failures, manufacturing defects, fuel assembly misloads, etc. However, it may not be necessary to directly account for these factors if the total probability of criticality is calculated to be sufficiently below the regulatory probability criterion without utilizing them. For example, if the calculated probability of waste package flooding is below the regulatory probability criterion, incorporation of the probability of a waste package misload would only result in a lower probability than has already been calculated.

Fuel assembly misloads (enrichment and/or burnup) could result in more (or less) fissile material being loaded into the waste package than permitted by the design loading curves. Additional fissile material in the waste package results in a higher criticality potential of the in-package degraded configurations. However, because no water (i.e., neutron moderator) enters the waste package for the rockfall criticality FEPs' conditions, the additional fissile material that could result from a fuel assembly misload cannot result in the formation of a critical configuration.

The rockfall disruptive event does not result in the formation of an advective flow path for water through the drip shield and into the waste package. This is because there is no mechanism for drip shield failure during this event (refer to Section 6.5.1 of this report). Waste package failures result only from early waste package failure mechanisms (refer to Section 6.3.3.3 of this report). Therefore, the screening argument for the rockfall disruptive event is the same as for the base case criticality FEP 2.1.14.16.0A. The probability of waste package flooding is zero and the probability of criticality for this rockfall disruptive event FEP is zero (refer to Table 6.7-2 of this report). Based on assumptions requiring confirmation, this result is applicable for all waste form / waste package types.

TSPA Disposition: Not Applicable

- Supporting Reports:*
- *Configuration Generator Model for In-Package Criticality* (BSC 2003 [DIRS 165629])
 - *Stress Corrosion Cracking of the Drip Shield, the Waste Package Outer Barrier, and the Stainless Steel Structural Material* (BSC 2003 [DIRS 161234])
 - *General Corrosion and Localized Corrosion of the Drip Shield* (BSC 2003 [DIRS 161236])
 - *Analysis of Mechanisms for Early Waste Package/Drip Shield Failure* (BSC 2003 [DIRS 164475])
 - *WAPDEG Analysis of Waste Package and Drip Shield Degradation* (BSC 2003 [DIRS 161317])
 - *EBS Radionuclide Transport Abstraction* (BSC 2003 [DIRS 166466])
 - *Seismic Consequence Abstraction* (BSC 2003 [DIRS 161812])
 - *Criticality Model Report* (BSC 2003 [DIRS 165733])
 - *Project Functional and Operational Requirements* (Siddoway 2003 [DIRS 163904])
 - *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505])

6.8.11 FEP 2.1.14.23.0A Screening Discussion

Name: Near-field criticality resulting from rockfall

Number: 2.1.14.23.0A

Description: Either during, or as a result of, a rockfall event, near-field criticality occurs when fissile material-bearing solution from the waste package is transported into the drift and the fissile material is precipitated into a critical configuration. Potential near-field critical configurations are defined in Figure 3.3a of *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505]).

Descriptor Phrases: Criticality (in drift), Criticality (from a rockfall event)

Screening Decision: Excluded based on low probability.

Screening Argument: For a criticality event to occur, the proper combination of materials (neutron moderators, neutron absorbers, fissile) and geometric configuration must exist. A critical system for the geological repository is defined as one having an effective neutron multiplication factor (k_{eff}), larger than the critical limit. The critical limit is the value of k_{eff} at which a system (configuration of fissile material) is considered critical as characterized by statistical tolerance limits (BSC 2003 [DIRS 165733], Section 6.2.1).

All base case (i.e., nominal scenario class, no disruptive events) postclosure criticality FEPs, internal and external, require water infiltration to degrade the waste package internals and waste form. Neutron absorber material loss and a flooded waste package condition for neutron moderation is the most likely scenario that could result in a potentially critical configuration in any of the in situ criticality FEPs. External criticality FEPs (near-field and far-field) also require the separation of neutron absorber materials from the waste form, transport of fissile material from the waste package, and accumulation of the fissile material within the drift invert or beyond.

Water, silica, and carbon are the only potential moderating materials for both internal and external configurations. Water is the most effective neutron-moderating material, which can enter the waste package as percolation flow or be present in the pores of the rock. Silica is present in appreciable quantities in the high-level radioactive waste glass canisters and in the rock. Silica can also be introduced into the waste package through precipitation from the percolation flow. Carbon is present in only limited amounts in select DOE SNF types and, therefore, has a limited impact on the potential for criticality. The loading of the DOE-standardized SNF canisters, the design of the basket structure inside the canisters, and the addition of neutron absorbers take into account the presence and effect of glass in DOE SNF codisposal waste packages. Silica from the high-level radioactive waste glass canisters has no impact on the potential for criticality in DOE SNF codisposal waste packages. Silica is a much less effective moderator than water and its introduction into commercial SNF waste packages will displace water and effectively reduce the reactivity of the system, thus reducing the potential for criticality.

In addition, criticality without water infiltration is unlikely for the geologic repository because the waste package is designed such that a criticality event in an intact waste package configuration is not possible. This satisfies a preclosure operations requirement that the MGR provide means to ensure criticality control during SNF/HLW handling operations, including waste package loading (Siddoway 2003 [DIRS 163904], Requirement 1.1.6-4).

Some of the DOE SNF waste forms have highly enriched fuel or waste form that could potentially support unmoderated (fast) criticality if (1) the (fissile) material is concentrated beyond its design concentration in the waste form and (2) the neutron absorber materials are removed. Concentration of the fissile material beyond its design concentration could result from either the degradation of the waste form resulting from water infiltration or a disruptive event. However, removal of the neutron absorber materials from a DOE SNF waste package would require a breach of the waste package and a removal mechanism. The

most likely neutron absorber material removal mechanism is through water infiltration resulting in degradation of the waste package internal components, dissolving of the neutron absorber material in the water, and flushing of the material from the waste package. Since water infiltration does not occur, fast criticality can be excluded based on low probability.

The probability of criticality estimate accounts for factors such as early failures, manufacturing defects, fuel assembly misloads, etc. However, it may not be necessary to directly account for these factors if the total probability of criticality is calculated to be sufficiently below the regulatory probability criterion without utilizing them. For example, if the calculated probability of waste package flooding is below the regulatory probability criterion, incorporation of the probability of a waste package misload would only result in a lower probability than has already been calculated.

Fuel assembly misloads (enrichment and/or burnup) could result in more (or less) fissile material being loaded into the waste package than permitted by the design loading curves. Additional fissile material in the waste package results in a higher criticality potential of the in-package degraded configurations. However, because no water (i.e., neutron moderator) enters the waste package for the rockfall criticality FEPs' conditions, the additional fissile material that could result from a fuel assembly misload cannot result in the formation of a critical configuration.

It then follows that the probability of external criticality must be less than the probability of waste package flooding. This is because, in addition to the events evaluated to calculate the probability of water entering a failed waste package, the probability of the following events must also be considered for external criticality:

- Waste form degradation over the performance period;
- Separating the fissile materials from the degraded waste form;
- Removing the fissile materials from the waste package;
- Accumulating sufficient fissile material into a potentially critical configuration in the near-field or far-field environments; and
- Having sufficient neutron moderator available.

Because the probability function for drip shield damage areas is zero for the rockfall disruptive event (i.e., no drip shield failures [refer to Section 6.5.1 of this report]), the probability of waste package flooding is zero for the rockfall disruptive event (refer to Table 6.7-2 of this report). Since no water can enter the waste package to degrade the waste package internals and waste form, no fissile material can be transported from the waste package and into the near-field environment.

Therefore, the probability of criticality for this rockfall disruptive event FEP is zero (refer to Section 6.5.5 of this report). Based on assumptions requiring confirmation, this result is applicable for all waste form / waste package types.

TSPA Disposition: Not Applicable

Supporting Reports:

- *Geochemistry Model Abstraction and Sensitivity Studies for the 21 PWR CSNF Waste Packages* (BSC 2002 [DIRS 160638])
- *External Accumulation of Fissile Material from DOE Co-Disposal Waste Packages* (BSC 2002 [DIRS 159913])
- *Criticality Model Report* (BSC 2003 [DIRS 165733])
- *Project Functional and Operational Requirements* (Siddoway 2003 [DIRS 163904])
- *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505])

6.8.12 FEP 2.2.14.11.0A Screening Discussion

Name: Far-field criticality resulting from rockfall

Number: 2.2.14.11.0A

Description: Either during, or as a result of, a rockfall event, far-field criticality occurs when fissile material-bearing solution from the waste package is transported beyond the drift and the fissile material is precipitated into a critical configuration. Potential far-field critical configurations are defined in Figure 3.3b of *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505]).

Descriptor Phrases: Criticality (in the geosphere), Criticality (from a rockfall event)

Screening Decision: Excluded based on low probability.

Screening Argument: For a criticality event to occur, the proper combination of materials (neutron moderators, neutron absorbers, fissile) and geometric configuration must exist. A critical system for the geological repository is defined as one having an effective neutron multiplication factor (k_{eff}), larger than the critical limit. The critical limit is the value of k_{eff} at which a system (configuration of fissile material) is considered critical as characterized by statistical tolerance limits (BSC 2003 [DIRS 165733], Section 6.2.1).

All base case (i.e., nominal scenario class, no disruptive events) postclosure criticality FEPs, internal and external, require water infiltration to degrade the waste package internals and waste form.

Neutron absorber material loss and a flooded waste package condition for neutron moderation is the most likely scenario that could result in a potentially critical configuration in any of the in situ criticality FEPs. External criticality FEPs (near-field and far-field) also require the separation of neutron absorber materials from the waste form, transport of fissile material from the waste package, and accumulation of the fissile material within the drift invert or beyond.

Water, silica, and carbon are the only potential moderating materials for both internal and external configurations. Water is the most effective neutron-moderating material, which can enter the waste package as percolation flow or be present in the pores of the rock. Silica is present in appreciable quantities in the high-level radioactive waste glass canisters and in the rock. Silica can also be introduced into the waste package through precipitation from the percolation flow. Carbon is present in only limited amounts in select DOE SNF types and, therefore, has a limited impact on the potential for criticality. The loading of the DOE-standardized SNF canisters, the design of the basket structure inside the canisters, and the addition of neutron absorbers take into account the presence and effect of glass in DOE SNF codisposal waste packages. Silica from the high-level radioactive waste glass canisters has no impact on the potential for criticality in DOE SNF codisposal waste packages. Silica is a much less effective moderator than water and its introduction into commercial SNF waste packages will displace water and effectively reduce the reactivity of the system, thus reducing the potential for criticality.

In addition, criticality without water infiltration is unlikely for the geologic repository because the waste package is designed such that a criticality event in an intact waste package configuration is not possible. This satisfies a preclosure operations requirement that the MGR provide means to ensure criticality control during SNF/HLW handling operations, including waste package loading (Siddoway 2003 [DIRS 163904], Requirement 1.1.6-4).

Some of the DOE SNF waste forms have highly enriched fuel or waste form that could potentially support unmoderated (fast) criticality if (1) the (fissile) material is concentrated beyond its design concentration in the waste form and (2) the neutron absorber materials are removed. Concentration of the fissile material beyond its design concentration could result from either the degradation of the waste form resulting from water infiltration or a disruptive event. However, removal of the neutron absorber materials from a DOE SNF waste package would require a breach of the waste package and a removal mechanism. The most likely neutron absorber material removal mechanism is through water infiltration resulting in degradation of the waste package internal components, dissolving of the neutron absorber material in the water,

and flushing of the material from the waste package. Since water infiltration does not occur, fast criticality can be excluded based on low probability.

The probability of criticality estimate accounts for factors such as early failures, manufacturing defects, fuel assembly misloads, etc. However, it may not be necessary to directly account for these factors if the total probability of criticality is calculated to be sufficiently below the regulatory probability criterion without utilizing them. For example, if the calculated probability of waste package flooding is below the regulatory probability criterion, incorporation of the probability of a waste package misload would only result in a lower probability than has already been calculated.

Fuel assembly misloads (enrichment and/or burnup) could result in more (or less) fissile material being loaded into the waste package than permitted by the design loading curves. Additional fissile material in the waste package results in a higher criticality potential of the in-package degraded configurations. However, because no water (i.e., neutron moderator) enters the waste package for the rockfall criticality FEPs' conditions, the additional fissile material that could result from a fuel assembly misload cannot result in the formation of a critical configuration.

It then follows that the probability of external criticality must be less than the probability of waste package flooding. This is because, in addition to the events evaluated to calculate the probability of water entering a failed waste package, the probability of the following events must also be considered for external criticality:

- Waste form degradation over the performance period;
- Separating the fissile materials from the degraded waste form;
- Removing the fissile materials from the waste package;
- Accumulating sufficient fissile material into a potentially critical configuration in the near-field or far-field environments; and
- Having sufficient neutron moderator available.

Because the probability function for drip shield damage areas is zero for the rockfall disruptive event (i.e., no drip shield failures [refer to Section 6.5.1 of this report]), the probability of waste package flooding is zero for the rockfall disruptive event (refer to Table 6.7-2 of this report). Since water cannot enter the waste package to degrade the waste package internals and waste form, no fissile material can be transported from the waste package and into the far-field environment. Therefore, the probability of criticality for this rockfall disruptive event FEP is zero (refer to Section 6.5.5 of this report). Based on assumptions requiring confirmation, this result is applicable for all waste form / waste package types.

TSPA Disposition: Not Applicable

Supporting Reports:

- *Geochemistry Model Abstraction and Sensitivity Studies for the 21 PWR CSNF Waste Packages* (BSC 2002 [DIRS 160638])
- *External Accumulation of Fissile Material from DOE Co-Disposal Waste Packages* (BSC 2002 [DIRS 159913])
- *Criticality Model Report* (BSC 2003 [DIRS 165733])
- *Project Functional and Operational Requirements* (Siddoway 2003 [DIRS 163904])
- *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505])

6.8.13 FEP 2.1.14.24.0A Screening Discussion

Name: In-package criticality resulting from an igneous event (intact configuration)

Number: 2.1.14.24.0A

Description: The waste package internal structures and the waste form remain intact either during or after an igneous disruptive event. A breach (or breaches) in the waste package allow(s) water to either accumulate or flow-through the waste package. Criticality then occurs in situ.

Descriptor Phrases: Criticality (in waste package), Criticality (from an igneous event)

Screening Decision: Excluded based on low probability.

Screening Argument: For a criticality event to occur, the proper combination of materials (neutron moderators, neutron absorbers, fissile) and geometric configuration must exist. A critical system for the geological repository is defined as one having an effective neutron multiplication factor (k_{eff}), larger than the critical limit. The critical limit is the value of k_{eff} at which a system (configuration of fissile material) is considered critical as characterized by statistical tolerance limits (BSC 2003 [DIRS 165733], Section 6.2.1).

Waste form criticality analyses demonstrate that an intact, fully flooded with water (a neutron moderator), waste package configuration cannot achieve criticality (CRWMS M&O 1999 [DIRS 125206], CRWMS M&O 2000 [DIRS 147650], CRWMS M&O 2000 [DIRS 147651], BSC 2003 [DIRS 166610], CRWMS M&O 2000 [DIRS 151742], CRWMS M&O 2000 [DIRS 151743], CRWMS M&O 2001 [DIRS 154194], BSC 2001 [DIRS 157733], BSC 2001 [DIRS 157734], BSC 2001 [DIRS 161125]). Additionally, intact, fully loaded, fully flooded waste

packages are precluded from achieving criticality by design to satisfy a preclosure operations requirement that the MGR provide means to ensure criticality control during SNF/HLW handling operations, including waste package loading (Siddoway 2003 [DIRS 163904], Requirement 1.1.6-4).

For the igneous disruptive event, waste packages have been segregated into two zones defined by the impact of the igneous event (refer to Section 6.6.1 of this report). In Zone 1, the waste packages are completely disassembled. In Zone 2, the waste packages remain intact (nominal waste package configuration). Therefore, for Zone 2 waste packages, the probability of criticality for this igneous disrupt event FEP is zero. This result is applicable for all waste form / waste package types

TSPA Disposition: Not Applicable

Supporting Reports:

- *21 PWR Waste Package with Absorber Plates Loading Curve Evaluation* (BSC 2003 [DIRS 166610])
- *44-BWR Waste Package Loading Curve Evaluation* (BSC 2001 [DIRS 161125])
- *Evaluation of Codisposal Viability for MOX (FFTF) DOE-Owned Fuel* (CRWMS M&O 1999 [DIRS 125206])
- *Evaluation of Codisposal Viability for U₂38 (TRIGA) DOE-Owned Fuel* (CRWMS M&O 2000 [DIRS 147650])
- *Evaluation of Codisposal Viability for HEU Oxide (Shippingport PWR) DOE-Owned Fuel* (CRWMS M&O 2000 [DIRS 147651])
- *Evaluation of Codisposal Viability for U-Zr/U-Mo (Enrico Fermi) DOE-Owned Fuel* (CRWMS M&O 2000 [DIRS 151742])
- *Evaluation of Codisposal Viability for Th/U Oxide (Shippingport LWBR) DOE-Owned Fuel* (CRWMS M&O 2000 [DIRS 151743])
- *Evaluation of Codisposal Viability for U-Metal (N Reactor) DOE-Owned Fuel* (CRWMS M&O 2001 [DIRS 154194])
- *Evaluation of Codisposal Viability for Melt and Dilute DOE-Owned Fuel* (BSC 2001 [DIRS 157733])
- *Evaluation of Codisposal Viability for Th/U Carbide (Fort Saint Vrain HTGR) DOE-Owned Fuel* (BSC 2001 [DIRS 157734])
- *Criticality Model Report* (BSC 2003 [DIRS 165733])
- *Project Functional and Operational Requirements* (Siddoway 2003 [DIRS 163904])
- *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505])

6.8.14 FEP 2.1.14.25.0A Screening Discussion

Name: In-package criticality resulting from an igneous event (degraded configuration)

Number: 2.1.14.25.0A

Description: Either during, or as a result of, an igneous disruptive event, the waste package internal structures and the waste form degrade. A critical configuration develops and criticality occurs in situ. Potential in situ critical configurations are defined in Figures 3.2a and 3.2b of *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505]).

Descriptor Phrases: Criticality (in waste package), Criticality (from an igneous event)

Screening Decision: Excluded based on low probability.

Screening Argument: For a criticality event to occur, the proper combination of materials (neutron moderators, neutron absorbers, fissile) and geometric configuration must exist. A critical system for the geological repository is defined as one having an effective neutron multiplication factor (k_{eff}), larger than the critical limit. The critical limit is the value of k_{eff} at which a system (configuration of fissile material) is considered critical as characterized by statistical tolerance limits (BSC 2003 [DIRS 165733], Section 6.2.1).

All base case (i.e., nominal scenario class, no disruptive events) postclosure criticality FEPs, internal and external, require water infiltration to degrade the waste package internals and waste form. Neutron absorber material loss and a flooded waste package condition for neutron moderation is the most likely scenario that could result in a potentially critical configuration in any of the in situ criticality FEPs. External criticality FEPs (near-field and far-field) also require the separation of neutron absorber materials from the waste form, transport of fissile material from the waste package, and accumulation of the fissile material within the drift invert or beyond.

Water, silica, and carbon are the only potential moderating materials for both internal and external configurations. Water is the most effective neutron-moderating material, which can enter the waste package as percolation flow or be present in the pores of the rock. Silica is present in appreciable quantities in the high-level radioactive waste glass canisters and in the rock. Silica can also be introduced into the waste package through precipitation from the percolation flow. Carbon is present in only limited amounts in select DOE SNF types and, therefore, has a limited impact on the potential for criticality. The loading of the DOE-standardized SNF canisters, the design of the basket structure

inside the canisters, and the addition of neutron absorbers take into account the presence and effect of glass in DOE SNF codisposal waste packages. Silica from the high-level radioactive waste glass canisters has no impact on the potential for criticality in DOE SNF codisposal waste packages. Silica is a much less effective moderator than water and its introduction into commercial SNF waste packages will displace water and effectively reduce the reactivity of the system, thus reducing the potential for criticality.

In addition, criticality without water infiltration is unlikely for the geologic repository because the waste package is designed such that a criticality event in an intact waste package configuration is not possible. This satisfies a preclosure operations requirement that the MGR provide means to ensure criticality control during SNF/HLW handling operations, including waste package loading (Siddoway 2003 [DIRS 163904], Requirement 1.1.6-4).

Some of the DOE SNF waste forms have highly enriched fuel or waste form that could potentially support unmoderated (fast) criticality if (1) the (fissile) material is concentrated beyond its design concentration in the waste form and (2) the neutron absorber materials are removed. Concentration of the fissile material beyond its design concentration could result from either the degradation of the waste form resulting from water infiltration or a disruptive event. However, removal of the neutron absorber materials from a DOE SNF waste package would require a breach of the waste package and a removal mechanism. The most likely neutron absorber material removal mechanism is through water infiltration resulting in degradation of the waste package internal components, dissolving of the neutron absorber material in the water, and flushing of the material from the waste package. Since water infiltration does not occur, fast criticality can be excluded based on low probability.

The probability of criticality estimate accounts for factors such as early failures, manufacturing defects, fuel assembly misloads, etc. However, it may not be necessary to directly account for these factors if the total probability of criticality is calculated to be sufficiently below the regulatory probability criterion without utilizing them. For example, if the calculated probability of waste package flooding is below the regulatory probability criterion, incorporation of the probability of a waste package misload would only result in a lower probability than has already been calculated.

Fuel assembly misloads (enrichment and/or burnup) could result in more (or less) fissile material being loaded into the waste package than permitted by the design loading curves. Additional fissile material in the waste package results in a higher criticality potential of the in-

package degraded configurations. However, because of the waste package / waste form configuration resulting from the igneous disruptive event, the additional fissile material that could result from a fuel assembly misload cannot result in the formation of a critical configuration.

For the igneous disruptive event, waste packages have been segregated into two zones defined by the impact of the igneous event (refer to Section 6.6.1 of this report). In Zone 1, the waste packages are completely disassembled. For Zone 1 waste packages, no in-package criticality event is possible since the waste package has been disassembled. The screening argument of Zone 1 waste packages is provided in FEP 2.1.14.26.0A. In Zone 2, the waste packages remain intact. For those waste packages in Zone 2, the screening argument of FEP 2.1.14.24.0A applies. The probability of criticality for this igneous disruptive event FEP is zero. This result is applicable for all waste form / waste package types.

TSPA Disposition: Not Applicable

Supporting Reports:

- *Dike Propagation Near Drifts* (CRWMS M&O 2000 [DIRS 151552])
- *Waste Package Behavior in Magma* (CRWMS M&O 1999 [DIRS 121300])
- *Characterize Eruptive Processes at Yucca Mountain, Nevada* (BSC 2003 [DIRS 166407])
- *Igneous Intrusion Impacts on Waste Package and Waste Forms* (BSC 2003 [DIRS 165002])
- *Criticality Model Report* (BSC 2003 [DIRS 165733])
- *Project Functional and Operational Requirements* (Siddoway 2003 [DIRS 163904])
- *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505])

6.8.15 FEP 2.1.14.26.0A Screening Discussion

Name: Near-field criticality resulting from an igneous event

Number: 2.1.14.26.0A

Description: Either during, or as a result of, an igneous disruptive event, near-field criticality occurs when fissile material-bearing solution from the waste package is transported into the drift and the fissile material is precipitated into a critical configuration. Potential near-field critical configurations are defined in Figure 3.3a of *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505]).

Descriptor Phrases: Criticality (in drift), Criticality (from an igneous event)

Screening Decision: Excluded based on low probability.

Screening Argument: For a criticality event to occur, the proper combination of materials (neutron moderators, neutron absorbers, fissile) and geometric configuration must exist. A critical system for the geological repository is defined as one having an effective neutron multiplication factor (k_{eff}), larger than the critical limit. The critical limit is the value of k_{eff} at which a system (configuration of fissile material) is considered critical as characterized by statistical tolerance limits (BSC 2003 [DIRS 165733], Section 6.2.1).

For the igneous disruptive event, waste packages have been segregated into two zones defined by the impact of the igneous event (refer to Section 6.6.1 of this report). In Zone 1, the waste packages are disassembled. In Zone 2, the waste packages remain intact. It is expected that the drip shields, invert and waste packages in Zone 1 will be compressed and damaged, allowing the magma to occupy the entire emplacement drift. The igneous intrusion temperature may be as high as 1169°C (BSC 2003 [DIRS 166407], Table 38). The melting points of waste packages made of Alloy C-22 and Stainless Steel Type 316NG are approximately 1,357°C and 1,375°C, respectively (CRWMS M&O 1999 [DIRS 121300], Section 5.1). Although the intrusive igneous temperature is lower than the melting points of steel and alloy, these engineered materials could be severely damaged at the intrusive temperature (e.g., through softening, creeping and breaking down) and in combination with the shear forces of the viscous magma moving at the assumed velocity.

When the waste packages are damaged, the waste forms will be exposed and are likely to be enveloped and fused by the flowing magma. The fuel assemblies will be crushed and fragmented, introducing different size fragments and granules of UO₂ pellets/cladding, neutron absorber, and control rods. The crushed material may form radionuclide-bearing minerals by incorporating crystallizing silicates minerals.

Water, silica, and carbon are the only potential moderating materials for both internal and external configurations. Water is the most effective neutron-moderating material, which can be present in the pores of the rock or within the magma. Carbon is present in only limited amounts in select DOE SNF types and, therefore, has a limited impact on the potential for criticality. Silica is present in appreciable quantities in the high-level radioactive waste glass canisters, in the rock, or, in the case of an igneous event, in the magma. The loading of the DOE-standardized SNF canisters, the design of the basket structure inside the canisters, and the addition of neutron absorbers take into account the

presence and effect of glass in DOE SNF codisposal waste packages. Silica from the high-level radioactive waste glass canisters has no impact on the potential for criticality in DOE SNF codisposal waste packages. Silica is a much less effective moderator than water and its introduction into commercial SNF waste packages will displace water and effectively reduce the reactivity of the system, thus reducing the potential for criticality.

Criticality evaluations have been performed to determine the k_{eff} of an assumed igneous event configuration in the near-field environment. From these criticality evaluations, the probability of criticality for this igneous disruptive event FEP is determined to be sufficiently below the regulatory probability criterion that it is negligible and therefore set to zero (refer to Section 6.6.3 of this report). Through the use of assumptions requiring confirmation, this result is applicable for all waste form / waste package types.

TSPA Disposition: Not Applicable

Supporting Reports:

- *Geochemistry Model Abstraction and Sensitivity Studies for the 21 PWR CSNF Waste Packages* (BSC 2002 [DIRS 160638])
- *External Accumulation of Fissile Material from DOE Co-Disposal Waste Packages* (BSC 2002 [DIRS 159913])
- *Dike Propagation Near Drifts* (CRWMS M&O 2000 [DIRS 151552])
- *Waste Package Behavior in Magma* (CRWMS M&O 1999 [DIRS 121300])
- *Characterize Eruptive Processes at Yucca Mountain, Nevada* (BSC 2003 [DIRS 166407])
- *Igneous Intrusion Impacts on Waste Package and Waste Forms* (BSC 2003 [DIRS 165002])
- *Criticality Model Report* (BSC 2003 [DIRS 165733])
- *Project Functional and Operational Requirements* (Siddoway 2003 [DIRS 163904])
- *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505])

6.8.16 FEP 2.2.14.12.0A Screening Discussion

Name: Far-field criticality resulting from an igneous event

Number: 2.2.14.12.0A

Description: Either during, or as a result of, an igneous disruptive event, far-field criticality occurs when fissile material-bearing solution from the waste

package is transported beyond the drift and the fissile material is precipitated into a critical configuration. Potential far-field critical configurations are defined in Figure 3.3b of *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505]).

Descriptor Phrases: Criticality (in the geosphere), Criticality (from an igneous event)

Screening Decision: Excluded based on low probability.

Screening Argument: For a criticality event to occur, the proper combination of materials (neutron moderators, neutron absorbers, fissile) and geometric configuration must exist. A critical system for the geological repository is defined as one having an effective neutron multiplication factor (k_{eff}), larger than the critical limit. The critical limit is the value of k_{eff} at which a system (configuration of fissile material) is considered critical as characterized by statistical tolerance limits (BSC 2003 [DIRS 165733], Section 6.2.1).

For the igneous disruptive event, waste packages have been segregated into two zones defined by the impact of the igneous event (refer to Section 6.6.1 of this report). In Zone 1, the waste packages are disassembled. In Zone 2, the waste packages remain intact. It is expected that the drip shields, invert and waste packages in Zone 1 will be compressed and damaged, allowing the magma to occupy the entire emplacement drift. The igneous intrusion temperature may be as high as 1169°C (BSC 2003 [DIRS 166407], Table 38). The melting points of waste packages made of Alloy C-22 and Stainless Steel Type 316NG are approximately 1,357°C and 1,375°C, respectively (CRWMS M&O 1999 [DIRS 121300], Section 5.1). Although the intrusive igneous temperature is lower than the melting points of steel and alloy, these engineered materials could be severely damaged at the intrusive temperature (e.g., through softening, creeping and breaking down) and in combination with the shear forces of the viscous magma moving at the assumed velocity.

When the waste packages are damaged, the waste forms will be exposed and are likely to be enveloped and fused by the flowing magma. The fuel assemblies will be crushed and fragmented, introducing different size fragments and granules of UO₂ pellets/cladding, neutron absorber, and control rods. The crushed material may form radionuclide-bearing minerals by incorporating crystallizing silicates minerals.

Water, silica, and carbon are the only potential moderating materials for both internal and external configurations. Water is the most effective neutron-moderating material, which can be present in the pores of the rock or in the magma. Carbon is present in only limited amounts in select DOE SNF types and, therefore, has a limited impact on the

potential for criticality. Silica is present in appreciable quantities in the high-level radioactive waste glass canisters, in the rock, or, in the case of an igneous event, in the magma. The loading of the DOE-standardized SNF canisters, the design of the basket structure inside the canisters, and the addition of neutron absorbers take into account the presence and effect of glass in DOE SNF codisposal waste packages. Silica from the high-level radioactive waste glass canisters has no impact on the potential for criticality in DOE SNF codisposal waste packages. Silica is a much less effective moderator than water and its introduction into commercial SNF waste packages will displace water and effectively reduce the reactivity of the system, thus reducing the potential for criticality.

The probability of criticality in the far-field environment must be less than the probability of accumulating sufficient fissile material in the near-field environment. This is because, once the fissile material is in the near-field environment, the probability of the following events must be considered for far-field criticality:

- The probability of transporting and accumulating sufficient fissile material into a potentially critical configuration in the far-field environments; and
- The probability of having sufficient neutron moderator available.

Because the probability of near-field criticality is below the regulatory probability criterion for an igneous disruptive event (refer to Section 6.6.3 of this report), given the considerations listed above, the probability of criticality in the far-field environment will be even smaller. Therefore, the probability of criticality for this igneous disruptive event FEP is considered negligible and is set to zero. Based on assumptions requiring confirmation, this result is applicable for all waste form / waste package types.

TSPA Disposition: Not Applicable

- Supporting Reports:*
- *Geochemistry Model Abstraction and Sensitivity Studies for the 21 PWR CSNF Waste Packages* (BSC 2002 [DIRS 160638])
 - *External Accumulation of Fissile Material from DOE Co-Disposal Waste Packages* (BSC 2002 [DIRS 159913])
 - *Dike Propagation Near Drifts* (CRWMS M&O 2000 [DIRS 151552])
 - *Waste Package Behavior in Magma* (CRWMS M&O 1999 [DIRS 121300])
 - *Characterize Eruptive Processes at Yucca Mountain, Nevada* (BSC 2003 [DIRS 166407])
 - *Igneous Intrusion Impacts on Waste Package and Waste Forms* (BSC 2003 [DIRS 165002])

- *Criticality Model Report* (BSC 2003 [DIRS 165733])
- *Project Functional and Operational Requirements* (Siddoway 2003 [DIRS 163904])
- *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505])

INTENTIONALLY LEFT BLANK

7. CONCLUSIONS

Using the geologic repository and engineered barrier systems information currently available and several assumptions requiring confirmation (including the modification of the 44-BWR Waste Package absorber plate thickness to 7 mm), criticality can be screened from further consideration in TSPA on the sole basis of the probability of waste package flooding and neutron absorber material removal. The results of this analysis indicate that, for all waste package types, the calculated total probability of waste package flooding and neutron absorber material removal is below the regulatory probability criterion (10 CFR 63.114(d) [DIRS 156605]). This conclusion is based on the binomial distribution evaluation of the calculated probability results (refer to Table 6.7-2).

Information currently being updated that could influence the results of this analysis is the failure potential of the drip shield and waste package due to the various corrosion mechanisms (i.e., general, localized, and stress corrosion cracking). Although the models for these failure mechanisms have been developed, evaluation of these models is dependent on the drift environment to be modeled in the TSPA-LA analyses. Future results in these areas have the potential to impact the analysis results. Also having the potential to impact the analysis results are updates to the qualified data, product outputs and technical information used in this analysis and the results from the testing, design and analysis required for the confirmation of assumptions in Section 5.

7.1 SUMMARY

The safety strategy for the monitored geologic repository relies on a multiple barrier system for the long-term isolation of the emplaced waste packages from the general environment. Over time, waste packages emplaced in the geologic repository as part of the engineered barrier systems can undergo various degradation processes that modify the waste package structural and mineral content and, thus, affect the potential for a criticality event. These degradation processes have major effects on the waste package's isotopic content (through flushing) and spatial distribution of the waste form within the affected waste package (through component degradation). Separation of neutron absorbers from fissile material, volume changes, shape changes, loss of fissile and/or absorber material from the waste package, and rearrangement of degraded components are potential effects of the degradation processes.

For a criticality to occur, multiple changes in conditions must occur (waste package breach, water intrusion, water retention, and removal of neutron absorbers). Should a criticality occur, geological and engineered barriers prevent and reduce the release of energy and the rate of radionuclide transport to the accessible environment.

This screening analysis report:

1. Contributes to the Yucca Mountain scenario development methodology by screening the FEPs related to criticality.
2. Develops screening arguments for these FEPs.
3. Provides information for the YMP FEP database and guidance to Total System Performance Assessment for the License Application analyses applicable to the license application document.

Screening decisions reached in this report are summarized in Table 7.2-1.

7.2 CRITICALITY FEPS SCREENING RECOMMENDATIONS FOR THE LICENSE APPLICATION

Recommendations for the criticality FEPs and their reference section are provided in Table 7.2-1. These recommendations for the base case in situ and external criticality FEPs evaluations are applicable to all waste package/waste form combinations. This is because the probability of water entering any waste package during the performance period is calculated to be 0.0 for all base case criticality FEPs because there are no drip shield failures predicted during the performance period.

The evaluation of the rockfall and igneous disruptive event criticality FEPs are applicable to all waste package/waste form combinations. This is because the probability of water entering any waste package during the performance period is 0.0 for the rockfall disruptive event (no drip shield failures) and because it is improbable that a critical configuration could be formed during an igneous disruptive event.

For the evaluation of the seismic disruptive event criticality FEPs, it is necessary to calculate the analysis results for the individual commercial and DOE SNF waste package types. This is because of the differences in the waste package types internal configurations and compositions that degrade at different rates. Additionally, the seismic criticality results are based on the increase of the 44-BWR waste package basket thickness to 7 mm from 5 mm to allow sufficient retention of boron in the waste package during the performance period. The result of the FEPs evaluation is the calculation of a total probability of waste package flooding and the neutron absorber material removal below the regulatory probability criterion (10 CFR 63.114(d) [DIRS 156605]). Because the total probability of flooding and degrading the waste package internals is below the regulatory probability criterion, the total probability of criticality is also below the regulatory probability criterion.

The Naval Nuclear Propulsion Program is responsible for the assessment of criticality potential of the naval SNF Short and naval SNF Long waste package types in accordance with an Addendum (Mowbray 1999 [DIRS 149585]) to the *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505]).

Table 7.2-1. Screening Decisions for Criticality FEPs

FEP Number	FEP Name	FEP Description	TSPA-LA Screening Decision	Section Screening Addressed
2.1.14.15.0A	In-package criticality (intact configuration)	The waste package internal structures and the waste form remain intact. A breach (or breaches) in the waste package allow(s) water to either accumulate or flow-through the waste package. Criticality then occurs in situ. In-package criticality resulting from disruptive events is addressed in separate FEPs.	Excluded – Low Probability	Section 6.8.1
2.1.14.16.0A	In-package criticality (degraded configurations)	The waste package internal structures and the waste form degrade. A critical configuration (sufficient fissile material and neutron moderator, lack of neutron absorbers) develops and criticality occurs in situ. Potential in situ critical configurations are defined in Figures 3.2a and 3.2b of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]). In-package criticality resulting from disruptive events is addressed in separate FEPs.	Excluded – Low Probability	Section 6.8.2
2.1.14.17.0A	Near-field criticality	Near-field criticality occurs when fissile material-bearing solution from the waste package is transported into the drift and the fissile material is precipitated into a critical configuration. Potential near-field critical configurations are defined in Figure 3.3a of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]). In-package criticality resulting from disruptive events is addressed in separate FEPs.	Excluded – Low Probability	Section 6.8.3
2.2.14.09.0A	Far-field criticality	Far-field criticality occurs when fissile material-bearing solution from the waste package is transported beyond the drift and the fissile material is precipitated into a critical configuration. Potential far-field critical configurations are defined in Figure 3.3b of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]). In-package criticality resulting from disruptive events is addressed in separate FEPs.	Excluded – Low Probability	Section 6.8.4
2.1.14.18.0A	In-package criticality resulting from a seismic event (intact configuration)	The waste package internal structures and the waste form remain intact either during or after a seismic disruptive event. A breach (or breaches) in the waste package allow(s) water to either accumulate or flow-through the waste package. Criticality then occurs in situ.	Excluded – Low Probability	Section 6.8.5
2.1.14.19.0A	In-package criticality resulting from a seismic event (degraded configurations)	Either during, or as a result of, a seismic disruptive event, the waste package internal structures and the waste form degrade. A critical configuration develops and criticality occurs in situ. Potential in situ critical configurations are defined in Figures 3.2a and 3.2b of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]).	Excluded – Low Probability	Section 6.8.6

Table 7.2-1. Screening Decisions for Criticality FEPs (Continued)

FEP Number	FEP Name	FEP Description	TSPA-LA Screening Decision	Section Screening Addressed
2.1.14.20.0A	Near-field criticality resulting from a seismic event	Either during, or as a result of, a seismic disruptive event, near-field criticality occurs when fissile material-bearing solution from the waste package is transported into the drift and the fissile material is precipitated into a critical configuration. Potential near-field critical configurations are defined in Figure 3.3a of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]).	Excluded – Low Probability	Section 6.8.7
2.2.14.10.0A	Far-field criticality resulting from a seismic event	Either during, or as a result of, a seismic disruptive event, far-field criticality occurs when fissile material-bearing solution from the waste package is transported beyond the drift and the fissile material is precipitated into a critical configuration. Potential far-field critical configurations are defined in Figure 3.3b of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]).	Excluded – Low Probability	Section 6.8.8
2.1.14.21.0A	In-package criticality resulting from rockfall (intact configuration)	The waste package internal structures and the waste form remain intact either during or after a rockfall event. A breach (or breaches) in the waste package allow(s) water to either accumulate or flow-through the waste package. Criticality then occurs in situ.	Excluded – Low Probability	Section 6.8.9
2.1.14.22.0A	In-package criticality resulting from rockfall (degraded configurations)	Either during, or as a result of, a rockfall event, the waste package internal structures and the waste form degrade. A critical configuration develops and criticality occurs in situ. Potential in situ critical configurations are defined in Figures 3.2a and 3.2b of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]).	Excluded – Low Probability	Section 6.8.10
2.1.14.23.0A	Near-field criticality resulting from rockfall	Either during, or as a result of, a rockfall event, near-field criticality occurs when fissile material-bearing solution from the waste package is transported into the drift and the fissile material is precipitated into a critical configuration. Potential near-field critical configurations are defined in Figure 3.3a of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]).	Excluded – Low Probability	Section 6.8.11
2.2.14.11.0A	Far-field criticality resulting from rockfall	Either during, or as a result of, a rockfall event, far-field criticality occurs when fissile material-bearing solution from the waste package is transported beyond the drift and the fissile material is precipitated into a critical configuration. Potential far-field critical configurations are defined in Figure 3.3b of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]).	Excluded – Low Probability	Section 6.8.12
2.1.14.24.0A	In-package criticality resulting from an igneous event (intact configuration)	The waste package internal structures and the waste form remain intact either during or after an igneous disruptive event. A breach (or breaches) in the waste package allow(s) water to either accumulate or flow-through the waste package. Criticality then occurs in situ.	Excluded – Low Probability	Section 6.8.13

Table 7.2-1. Screening Decisions for Criticality FEPs (Continued)

FEP Number	FEP Name	FEP Description	TSPA-LA Screening Decision	Section Screening Addressed
2.1.14.25.0A	In-package criticality resulting from an igneous event (degraded configurations)	Either during, or as a result of, an igneous disruptive event, the waste package internal structures and the waste form degrade. A critical configuration develops and criticality occurs in situ. Potential in situ critical configurations are defined in Figures 3.2a and 3.2b of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]).	Excluded – Low Probability	Section 6.8.14
2.1.14.26.0A	Near-field criticality resulting from an igneous event	Either during, or as a result of, an igneous disruptive event, near-field criticality occurs when fissile material-bearing solution from the waste package is transported into the drift and the fissile material is precipitated into a critical configuration. Potential near-field critical configurations are defined in Figure 3.3a of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]).	Excluded – Low Probability	Section 6.8.15
2.2.14.12.0A	Far-field criticality resulting from an igneous event	Either during, or as a result of, an igneous disruptive event, far-field criticality occurs when fissile material-bearing solution from the waste package is transported beyond the drift and the fissile material is precipitated into a critical configuration. Potential far-field critical configurations are defined in Figure 3.3b of <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]).	Excluded – Low Probability	Section 6.8.16

7.3 UNCERTAINTIES AND RESTRICTIONS

This document may be affected by technical product input information that requires confirmation. Any changes to the document that may occur as a result of completing the confirmation activities will be reflected in subsequent revisions. The status of the input information quality may be confirmed by review of the Document Input Reference System database.

7.3.1 Restriction #1: This Screening Analysis Is a Draft Demonstration of the Screening Methodology

Waste package specific information has been utilized for the evaluation of 12-PWR Long, 44-BWR, and 24-BWR Waste Package types. However, the necessary model reports have not been developed or validated for use with BWR fuel and, therefore, strict adherence to the methodology outlined in *Disposal Criticality Analysis Methodology Topic Report* (YMP 2003 [DIRS 165505]) was not possible.

Although an assumption has been made extending the 21-PWR with Absorber Plates Waste Package inputs to the DOE SNF waste package types (Assumption 5.1.7) and an additional assumption has been made regarding the 21-PWR with Control Rods Waste Package type (Assumption 5.1.6), both of these assumptions require confirmation through additional analysis.

7.3.2 Restriction #2: Time-Dependent Corrosion Will Not be Available Until the TSPA-LA Is Performed

Because of the use of corrosion-resistant materials, it is important to assume for this screening analysis, corrosion damage to the drip shields and the waste packages is caused only by an early failure mechanism (improper heat treatment) and not by the time-dependent corrosion mechanisms typically resulting from water dripping onto the drip shield and the waste package (Assumption 5.1.1). Additionally, the detailed time-dependent corrosion information for (1) general corrosion, (2) localized corrosion (crevice corrosion and pitting corrosion), and (3) stress corrosion cracking, will not be available until the TSPA-LA is performed.

This assumption requires further verification and confirmation when the TSPA-LA calculations are published.

7.3.3 Restriction #3: Evaluation Does Not Account for Variations In Waste Package Design.

The FEPs screening analyses assume the waste package is fabricated, loaded, closed, and emplaced as designed (Assumption 5.1.3). Once fabrication and operational processes and procedures are developed and approved, evaluations of off-normal waste package configurations may be performed.

7.3.4 Restriction #4: Assumptions Regarding Neutron Absorber Material Corrosion Rate and Retention in Waste Package

The corrosion rate of the waste package neutron absorber material (Assumptions 5.1.4, 5.1.6, and 5.1.7) and the amount of neutron absorber material that must be retained in a degraded waste package to prevent a criticality event (Assumption 5.1.5) must be confirmed through measurements and analyses, respectively. These parameters are important as they determine the rate of neutron absorber material loss from a breached, flooded waste package. A slow corrosion rate or low required retention amount will possibly prolong a subcritical condition within the waste package to well beyond the performance period.

7.3.5 Restriction #5: Assumptions Regarding Igneous Event Configuration and External Critical Limit

The high fissile material enrichment of some DOE SNF waste forms could facilitate the formation of critical configurations in low or no neutron moderator environments such as is expected during an igneous disruptive event. It is assumed that configurations formed due to igneous events involving DOE SNF waste packages will not result in the formation of a critical system (Assumption 5.4.3).

In addition, a critical limit will need to be determined using the methodology to be developed in the external criticality model for comparison to the calculated igneous event configuration k_{eff} values (Assumption 5.4.4). This is necessary for assessing the criticality potential of the configurations resulting from the igneous disruptive event.

Both of these assumptions require confirmation by analysis.

7.3.6 Restriction #6: Evaluation Does Not Account for Condensation

Water entering a failed waste package may occur from two primary pathways: (1) water dripping from the drift crown through a failed drip shield and into a failed waste package, and (2) water dripping from the underside of a drip shield due to evaporation and condensation into a failed waste package. The first pathway is evaluated in the FEPs screening analysis. However, the model to account for the second pathway is not yet available. Evaluation of this pathway will be necessary once this model is available.

7.4 ADDRESSING OF REQUIREMENTS AND CRITERIA

This section discusses how the criteria and requirements listed in Section 4.2 were addressed in this analysis report. Table 7.4-1 discusses how the applicable project requirements from *Project Requirements Document* (Canori and Leitner 2003 [DIRS 166275]) were addressed. Tables 7.4-2 and 7.4-3 address how the applicable *Yucca Mountain Review Plan* (NRC 2003 [DIRS 163274]) acceptance criteria were addressed.

Table 7.4-1. Addressing Project Requirements

Requirement Number and Title	Requirement Text	How Requirement Addressed
PRD-002/T-015 ^a ; Requirements for Performance Assessment	For complete requirement text, see 10 CFR 63.114 [DIRS 156605]	This report provides the technical bases for excluding criticality FEPs. The technical basis is provided in Section 6.
PRD-002/T-034 ^b ; Limits on Performance Assessments	For complete requirement text, see 10 CFR 63.342 [DIRS 156605]	This report provides the screening so as to not include very unlikely FEPs, defined as those that are estimated to have less than one chance in 10,000 of occurring within 10,000 years of disposal, in the performance assessments. The screening is provided in Section 6.
PRD-013/T-016 ^c ; Postclosure [of DOE SNF Canister Criticality Potential]	The methodology defined in the <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]) shall be used to demonstrate acceptable criticality control for canisters and the waste packages in which they are disposed.	This report documents the partial implementation of the methodology from the from <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]). The complete methodology is not used because the partial application excludes criticality. The implementation is provided in Section 6.
PRD-013/T-023 ^d ; Postclosure [of Naval SNF Canister Criticality Potential]	The methodology in the NNPP addendum (Mowbray 1999 [DIRS 149585]) to the <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]) shall be used to demonstrate acceptable criticality control for canisters and the waste packages in which they are disposed.	This report does not effect how acceptable criticality control is demonstrated in the NNPP addendum (Mowbray 1999 [DIRS 149585]). The external configurations which would require isotopic concentrations for naval SNF from the NNPP are screen out in Section 6.3.
PRD-013/T-038 ^e ; Postclosure.[of Commercial- Origin DOE SNF Canister Criticality Potential]	The methodology defined in the <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]) shall be used to demonstrate acceptable criticality control for canisters and the waste packages in which they are disposed.	This report documents the partial implementation of the methodology from <i>Disposal Criticality Analysis Methodology Topical Report</i> (YMP 2003 [DIRS 165505]). The complete methodology is not used because the partial application excludes criticality. The implementation is provided in Section 6.

Source: Canori and Leitner 2003 [DIRS 166275]

NOTES: ^a Requirement basis is 10 CFR 63.114 and 63.113 [DIRS 156605] & YMP-RD 3.3.4.19 (YMP 2001).

^b Requirement basis is 10 CFR 63.342 [DIRS 156605] (Reference 40 CFR 197.36 [DIRS 155238])

^c Requirement basis is WASRD 4.3.12.B (DOE 2002 [DIRS 158873])

^d Requirement basis is WASRD 4.4.13.B (DOE 2002 [DIRS 158873])

^e Requirement basis is WASRD 4.5.13.B (DOE 2002 [DIRS 158873])

Table 7.4-2. Addressing Acceptance Criteria for Scenario Identification and Screening

Acceptance Criteria Name	How Acceptance Criteria is Addressed
Acceptance Criterion 1: The Identification of a List of Features, Events, and Processes Is Adequate.	(1) The report contains a complete list of criticality features, events and processes that have the potential to influence repository performance. The list is consistent with the site characterization data and includes potentially disruptive events (i.e., igneous; seismic, and rockfall); and criticality. This list is provided in Table 6.1-3.
Acceptance Criterion 2: Screening of the List of Features, Events, and Processes Is Appropriate.	(1) The report identifies all the criticality features, events, and processes that have been excluded in Section 6.8, (2) The report provides justification for excluding the criticality features, events, and processes in Section 6.8; and (3) The report provides an adequate technical basis for excluding each criticality feature, event, and process based on low-probability in Sections 6.3 through 6.6.

Source: NRC 2003 [DIRS 163274], Section 2.2.1.2.1.3

Table 7.4-3. Addressing Acceptance Criteria for Uncertainty in Event Probability

Acceptance Criterion Number and Title	How Acceptance Criteria is Addressed
<p>Acceptance Criterion 1: Events Are Adequately Defined.</p>	<p>(1) The report identifies criticality events and estimates the probabilities of each criticality event separately, so that criticality events are defined without ambiguity and used consistently in probability models. The criticality events and their correlation with individual FEPs are provided in Sections 6.3 through 6.6 of the report; and</p> <p>(2) The probabilities of criticality events are calculated separately by location (internal and external) as appropriate in Sections 6.3 through 6.6.</p>
<p>Acceptance Criterion 2: Probability Estimates for Future Events Are Supported by Appropriate Technical Bases.</p>	<p>(1) The inputs used in the report to estimate the probabilities for future criticality events come from models which consider past patterns of the natural events in the Yucca Mountain region (e.g., seismic) in estimating the likely future conditions and interactions of the natural and engineered repository system. The inputs and their sources are listed in Sections 4.1.2 and 4.1.3.</p>
<p>Acceptance Criterion 3: Probability Model Support Is Adequate.</p>	<p>(1) The report's probability models use the outputs from validated, detailed process level models as inputs. These inputs are discussed in Sections 4.1.2 and 4.1.3. The specific means of validating the models are described in the separate reports.</p>
<p>Acceptance Criterion 4: Probability Model Parameters Have Been Adequately Established.</p>	<p>(1) The report provides the technical justification for the parameters used in the probability models in Sections 4.1.2, 4.1.3 and 6.3 through 6.6. Specifically:</p> <p>(a) Parameters used in the probability models are from the outputs from models of the natural and engineered systems for a repository at Yucca Mountain (Sections 4.1.2 and 4.1.3);</p> <p>(b) The report establishes reasonable and consistent correlations between parameters (discussed in Sections 6.3 through 6.6) ; and</p> <p>(c) Where updated models of natural and engineered systems are not available to generate parameters for the probability models, other appropriate sources are noted and confirmation of this appropriateness is noted in Section 5.</p>
<p>Acceptance Criterion 5: Uncertainty in Event Probability Is Adequately Evaluated.</p>	<p>(1) The report addresses uncertainty in probability values by accounting for uncertainty in the model outputs used to develop the probability values. The uncertainty in model outputs used to develop probabilities is discussed in Section 6.4. Specifically:</p> <p>(a) The report provides a technical basis for probability values used (Sections 6.4 and Attachment III), and the values account for the uncertainty in the probability estimates; and</p> <p>(b) The uncertainties are not reported separately for probability values. The probability values are based on results that incorporate the parameter uncertainty from the model results and model uncertainty.</p>

Source: NRC 2003 [DIRS 163274], Section 2.2.1.2.2.3

8. INPUTS AND REFERENCES

8.1 DOCUMENTS CITED

- 104317 ASM (American Society for Metals) 1980. *Properties and Selection: Stainless Steels, Tool Materials and Special-Purpose Metals*. Volume 3 of *Metals Handbook*. 9th Edition. Benjamin, D., ed. Metals Park, Ohio: American Society for Metals. TIC: 209801.
- 103289 Batchelor, G.K. 1967. *An Introduction to Fluid Dynamics*. New York, New York: Cambridge University Press. TIC: 241827.
- 103897 Briesmeister, J.F., ed. 1997. *MCNP-A General Monte Carlo N-Particle Transport Code*. LA-12625-M, Version 4B. Los Alamos, New Mexico: Los Alamos National Laboratory. ACC: MOL.19980624.0328.
- 157733 BSC (Bechtel SAIC Company) 2001. *Evaluation of Codisposal Viability for Melt and Dilute DOE-Owned Fuel*. TDR-EDC-NU-000006 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20010809.0070.
- 157734 BSC 2001. *Evaluation of Codisposal Viability for Th/U Carbide (Fort Saint Vrain HTGR) DOE-Owned Fuel*. TDR-EDC-NU-000007 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20011017.0092.
- 161125 BSC 2001. *44 BWR Waste Package Loading Curve Evaluation*. CAL-UDC-NU-000005 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20011114.0132.
- 158966 BSC 2002. *The Enhanced Plan for Features, Events, and Processes (FEPs) at Yucca Mountain*. TDR-WIS-PA-000005 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20020417.0385.
- 159913 BSC 2002. *External Accumulation of Fissile Material from DOE Co-Disposal Waste Packages*. ###-3OR-DSD#-001##-###-#A#. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20020920.0163.
- 160313 BSC 2002. *Scientific Processes Guidelines Manual*. MIS-WIS-MD-000001 REV 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20020923.0176.
- 160638 BSC 2002. *Geochemistry Model Abstraction and Sensitivity Studies for the 21 PWR CSNF Waste Packages*. MDL-DSU-MD-000001 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20021107.0154.
- 161234 BSC 2003. *Stress Corrosion Cracking of the Drip Shield, the Waste Package Outer Barrier, and the Stainless Steel Structural Material*. ANL-EBS-MD-000005 REV 01 ICN 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20030717.0001.

- 161236 BSC 2003. *General Corrosion and Localized Corrosion of the Drip Shield*. ANL-EBS-MD-000004 REV 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20030626.0001.
- 161317 BSC 2003. *WAPDEG Analysis of Waste Package and Drip Shield Degradation*. ANL-EBS-PA-000001 REV 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20031208.0004.
- 165002 BSC 2003. *Igneous Intrusion Impacts on Waste Package and Waste Form*. MDL-EBS-GS-000002 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20030819.0003.
- 161812 BSC 2003. *Seismic Consequence Abstraction*. MDL-WIS-PA-000003 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20030818.0006.
- 166407 BSC 2003. *Characterize Eruptive Processes at Yucca Mountain, Nevada*. ANL-MGR-GS-000002 REV 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20031218.0003.
- 161851 BSC 2003. *Number of Waste Packages Hit by Igneous Intrusion*. ANL-MGR-GS-000003 REV 00C. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20030711.0099.
- 163769 BSC 2003. *Characterize Framework for Igneous Activity at Yucca Mountain, Nevada*. ANL-MGR-GS-000001 REV 01. Las Vegas, Nevada: Bechtel SAIC Company. URN 1106.
- 163855 BSC 2003. *Repository Design Project, RDP/PA IED Typical Waste Package Components Assembly (2)*. 800-IED-WIS0-00202-000-00A. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20030702.0002.
- 164475 BSC 2003. *Analysis of Mechanisms for Early Waste Package/Drip Shield Failure*. CAL-EBS-MD-000030 REV 00B. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20031001.0012.
- 166466 BSC 2003. *EBS Radionuclide Transport Abstraction*. ANL-WIS-PA-000001 REV 01F. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20031210.0361. TBV-5644.
- 164490 BSC 2003. *RDP/PA IED Subsurface Facilities*. 800-IED-WIS0-00102-000-00Ab. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20030828.0148. TBV-5547.
- 164491 BSC 2003. *Repository Design Project, Repository/PA IED Subsurface Facilities*. 800-IED-WIS0-00103-000-00Ab. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20030813.0178. TBV-5397.
- 165179 BSC 2003. *Q-List*. TDR-MGR-RL-000005 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20030930.0002.

- 165559 BSC 2003. *Technical Work Plan for: Risk and Criticality Department*. TWP-EBS-MD-000014 REV 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20031002.0003.
- 165564 BSC 2003. *Abstraction of Drift Seepage*. MDL-NBS-HS-000019 REV 00 ICN 1. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20031112.0002.
- 165629 BSC 2003. *Configuration Generator Model for In-Package Criticality*. MDL-EBS-NU-000001 REV 01 ICN 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20030908.0004.
- 166463 BSC 2003. *Multiscale Thermohydrologic Model Report*. ANL-EBS-MD-000049 REV 01G. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20031212.0037.
- 165732 BSC 2003. *Isotopic Model Report for Commercial SNF Burnup Credit*. MDL-DSU-NU-000001 REV 00 ICN 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20030904.0003.
- 165733 BSC 2003. *Criticality Model Report*. MDL-EBS-NU-000003 REV 02. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20031013.0002.
- 165890 BSC 2003. *Boron Loss from CSNF Waste Packages*. ANL-DSU-MD-000001 REV 0. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20031002.0004.
- 165991 BSC 2003. *Analysis of Infiltration Uncertainty*. ANL-NBS-HS-000027 REV 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20031030.0003.
- 166464 BSC 2003. *Engineered Barrier System Features, Events, and Processes*. ANL-WIS-PA-000002 REV 02E. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20031212.0038. TBV-5642
- 166610 BSC 2003. *21-PWR Waste Package with Absorber Plates Loading Curve Evaluation*. CAL-DSU-NU-000006 REV 00A. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20031222.0007.
- 167309 BSC 2004. *D&E / PA/C IED Interlocking Drip Shield and Emplacement Pallet*. 800-IED-WIS0-00401-000-00C. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20040202.0022.
- 167207 BSC 2004. *D&E/PA/C IED Typical Waste Package Components Assembly*. 800-IED-WIS0-00202-000-00B. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20040202.0010.
- 166275 Canori, G.F. and Leitner, M.M. 2003. *Project Requirements Document*. TER-MGR-MD-000001 REV 02. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20031222.0006.

- 100224 CRWMS M&O (Civilain Radioactive Waste Management System Management & Operating Contractor) 1997. *Determination of Waste Package Design Configurations*. BBAA00000-01717-0200-00017 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19970805.0310.
- 102836 CRWMS M&O 1998. *Software Qualification Report for MCNP Version 4B2, A General Monte Carlo N-Particle Transport Code*. CSCI: 30033 V4B2LV. DI: 30033-2003, Rev. 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980622.0637.
- 121300 CRWMS M&O 1999. *Waste Package Behavior in Magma*. CAL-EBS-ME-000002 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19991022.0201.
- 125206 CRWMS M&O 1999. *Evaluation of Codisposal Viability for MOX (FFTF) DOE-Owned Fuel*. BBA000000-01717-5705-00023 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19991014.0235.
- 157731 CRWMS M&O 1999. *Summary Report of Laboratory Critical Experiment Analyses Performed for the Disposal Criticality Analysis Methodology*. B00000000-01717-5705-00076 REV 02. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19990920.0167.
- 144180 CRWMS M&O 2000. *Features, Events, and Processes: System-Level and Criticality*. ANL-WIS-MD-000019 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20010108.0012.
- 147650 CRWMS M&O 2000. *Evaluation of Codisposal Viability for UZrH (TRIGA) DOE-Owned Fuel*. TDR-EDC-NU-000001 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000207.0689.
- 147651 CRWMS M&O 2000. *Evaluation of Codisposal Viability for HEU Oxide (Shippingport PWR) DOE-Owned Fuel*. TDR-EDC-NU-000003 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000227.0240.
- 149939 CRWMS M&O 2000. *Probability of Criticality Before 10,000 Years*. CAL-EBS-NU-000014 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20001107.0303.
- 151552 CRWMS M&O 2000. *Dike Propagation Near Drifts*. ANL-WIS-MD-000015 REV 00 ICN 1. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20001213.0061.
- 151566 CRWMS M&O 2000. *WAPDEG Analysis of Waste Package and Drip Shield Degradation*. ANL-EBS-PA-000001 REV 00 ICN 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20001208.0063.
- 151742 CRWMS M&O 2000. *Evaluation of Codisposal Viability for U-Zr/U-Mo Alloy (Enrico Fermi) DOE-Owned Fuel*. TDR-EDC-NU-000002 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000815.0317.

- 151743 CRWMS M&O 2000. *Evaluation of Codisposal Viability for Th/U Oxide (Shippingport LWBR) DOE-Owned Fuel*. TDR-EDC-NU-000005 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20001023.0055.
- 153246 CRWMS M&O 2000. *Total System Performance Assessment for the Site Recommendation*. TDR-WIS-PA-000001 REV 00 ICN 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20001220.0045.
- 154194 CRWMS M&O 2001. *Evaluation of Codisposal Viability for U-Metal (N Reactor) DOE-Owned Fuel*. TDR-EDC-NU-000004 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20010314.0004.
- 160320 D'Agostino, R.B. and Stephens, M.A., eds. 1986. *Goodness-Of-Fit Techniques*. Statistics, Textbooks and Monographs Volume 68. New York, New York: Marcel Dekker. TIC: 253256.
- 132333 DOE 1987. *Appendix 2A. Physical Descriptions of LWR Fuel Assemblies. Volume 3 of Characteristics of Spent Fuel, High-Level Waste, and Other Radioactive Wastes Which May Require Long-Term Isolation*. DOE/RW-0184. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: HQX.19880405.0024.
- 155943 DOE 2002. *Yucca Mountain Science and Engineering Report*. DOE/RW-0539, Rev. 1. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.20020404.0042
- 158873 DOE 2002. *Waste Acceptance System Requirements Document*. DOE/RW-0351, Rev. 4. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.20020326.0056.
- 162903 DOE 2003. *Quality Assurance Requirements and Description*. DOE/RW-0333P, Rev. 13. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: DOC.20030422.0003.
- 106070 Duderstadt, J.J. and Hamilton L.J. 1976. *Nuclear Reactor Analysis*. New York, New York: John Wiley & Sons. TIC: 245454.
- 154365 Freeze, G.A.; Brodsky, N.S.; and Swift, P.N. 2001. *The Development of Information Catalogued in REV00 of the YMP FEP Database*. TDR-WIS-MD-000003 REV 00 ICN 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20010301.0237.
- 165394 Freeze, G. 2003. *KTI Letter Report, Response to Additional Information Needs on TSPAI 2.05 and TSPAI 2.06*. REG-WIS-PA-000003 REV 00 ICN 04. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20030825.0003.
- 100455 Hillner, E.; Franklin, D.G.; and Smee, J.D. 1998. *The Corrosion of Zircaloy-Clad Fuel Assemblies in a Geologic Repository Environment*. WAPD-T-3173. West Mifflin, Pennsylvania: Bettis Atomic Power Laboratory. TIC: 237127.

- 134327 Kügler, A. 1997. *Sheet and Plate for Nuclear Engineering, Böhler Neutronit A976*. Houston, Texas: Böhler Bleche GmbH. TIC: 246410.
- 104667 Modarres, M. 1993. *What Every Engineer Should Know About Reliability and Risk Analysis*. New York, New York: Marcel Dekker. TIC: 238168.
- 149585 Mowbray, G.E. 1999. *Transmittal of the Naval Nuclear Propulsion Program Addendum to the Yucca Mountain Site Characterization Office "Disposal Criticality Analysis Methodology Topical Report."* Letter from G.E. Mowbray (Department of the Navy) to C.W. Reamer (NRC), October 29, 1999. ACC: MOL.20000316.0531.
- 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.
- 100479 Nuclear Energy Agency 1992. *Systematic Approaches to Scenario Development: A Report of the NEA Working Group on Identification and Selection of Scenarios for Performance Assessment of Radioactive Waste Disposal*. Paris, France: Nuclear Energy Agency, Organisation for Economic Co-operation and Development. TIC: 8083.
- 103896 Parrington, J.R.; Knox, H.D.; Breneman, S.L.; Baum, E.M.; and Feiner, F. 1996. *Nuclides and Isotopes, Chart of the Nuclides*. 15th Edition. San Jose, California: General Electric Company and KAPL, Inc. TIC: 233705.
- 155635 Punatar, M.K. 2001. *Summary Report of Commercial Reactor Criticality Data for Crystal River Unit 3*. TDR-UDC-NU-000001 REV 02. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20010702.0087.
- 163904 Siddoway, D.W. 2003. *Project Functional and Operational Requirements*. TDR-MGR-ME-000003 REV 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20030630.0001.
- 158378 USGS (U.S. Geological Survey) 2001. *Future Climate Analysis*. ANL-NBS-GS-000008 REV 00 ICN 01. Denver, Colorado: U.S. Geological Survey. ACC: MOL.20011107.0004.
- 152180 Walpole, R.E.; Myers, R.H.; and Myers, S.L. 1998. *Probability and Statistics for Engineers and Scientists*. 6th Edition. Upper Saddle River, New Jersey: Prentice Hall. TIC: 242020.
- 157283 Wark, K. 1983. *Thermodynamics*. 4th Edition. New York, New York: McGraw-Hill. TIC: 243020.
- 111561 Weast, R.C., ed. 1985. *CRC Handbook of Chemistry and Physics*. 66th Edition. Boca Raton, Florida: CRC Press. TIC: 216054.

- 156713 YMP 2001. *Yucca Mountain Site Characterization Project Requirements Document (YMP-RD)*. YMP/CM-0025, Rev. 4, DCN 02. Las Vegas, Nevada: Yucca Mountain Site Characterization Office. ACC: MOL.20010322.0491; MOL.20011107.0002.
- 165505 YMP 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

- 156605 10 CFR 63. Energy: Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada. Readily available.
- 155238 40 CFR 197. 2001. Protection of Environment: Public Health and Environmental Radiation Protection Standards for Yucca Mountain, Nevada. Readily available.
- 165023 AP-SI.1Q, Rev. 5, ICN 2. *Software Management*. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: DOC.20030902.0003.
- 166252 AP-SIII.9Q, Rev. 1, ICN 2. *Scientific Analyses*. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: DOC.20031126.0001.
- 165687 AP-SV.1Q, Rev. 1, ICN 0. *Control of the Electronic Management of Information*. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: DOC.20030929.0004.
- 164786 AP-2.22Q, Rev. 1, ICN 0. *Classification Analyses and Maintenance of the Q-List*. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: DOC.20030807.0002.
- 154062 ASTM A 887-89 (Reapproved 2000). 2000. *Standard Specification for Borated Stainless Steel Plate, Sheet, and Strip for Nuclear Application*. West Conshohocken, Pennsylvania: American Society for Testing and Materials. TIC: 249544.

8.3 SOURCE DATA, LISTED BY DATA TRACKING NUMBER

- 163906 LB0104AMRU0185.012. Section 6.4.2 Focusing and Discrete Flow Paths in the TSW - Data Summary. Submittal date: 05/15/2001.
- 163687 LB0304SMDCREV2.002. Seepage Modeling for Performance Assessment, Including Drift Collapse: Summary Plot Files and Tables. Submittal date: 04/11/2003.
- 164337 LB0307SEEPDRCL.002. Seepage Into Collapsed Drift: Data Summary. Submittal date: 07/21/2003.
- 166116 LB0310AMRU0120.002. Mathcad 11 Spreadsheets for Probabilistic Seepage Evaluation. Submittal date: 10/23/2003.

- 163531 MO0210MWDEXC01.008. CSNF Results in Excel Spreadsheets - CSNF_Spreadsheets. Submittal date: 10/22/2002.
- 166801 MO0401SPAMCRAE.000. Materials Corrosion Rates in Aqueous Environments. Submittal date: 01/16/2004.
- 164527 MO0307SEPFEPS4.000. LA FEP List. Submittal date: 07/31/2003
- 164822 MO0308SPACALSS.002. Computational Algorithm for the Seismic Scenario for TSPA. Submittal date: 8/13/2003.
- 165892 MO0309SPABRNAM.001. Calculated Parameters for Boron Abstraction Model for CSNF Waste Packages. Submittal date: 09/25/2003.
- 147618 MO9906RIB00048.000. Waste Package Material Properties: Waste Form Materials. Submittal date: 6/9/1999.

8.4 SOFTWARE CODES

- 154060 CRWMS M&O 1998. *Software Code: MCNP. V4B2LV. HP, HPUX 9.07 and 10.20; PC, Windows 95; Sun, Solaris 2.6. 30033 V4B2LV.*
- 160873 BSC 2002. *Software Code: SAPHIRE. V7.18. PC - Windows 2000/NT 4.0. 10325-7.18-00.*

9. ATTACHMENTS

ATTACHMENT	Title
I.	Glossary
II.	SAPHIRE Model Used for Criticality FEPs Screening Analysis
III.	Seismic Calculations Spreadsheets (Output from MATHCAD Files)
IV.	Seepage Analysis Spreadsheets (Output from MATHCAD Files)
V.	Neutron Corrosion Spreadsheets (Output from MATHCAD Files)
VI.	Listing of Files on CD-ROM
VII.	Read-Only Compact Disc (CD-ROM)

INTENTIONALLY LEFT BLANK

ATTACHMENT I

GLOSSARY

INTENTIONALLY LEFT BLANK

ATTACHMENT I - GLOSSARY

Absorption	(1) To take in and make part of an existent whole. (2) To receive without recoil.
Advection	(1) The usually horizontal movement of a mass of fluid (as air or an ocean current). (2) The process in which solutes are transported by groundwater movement.
Aleatory	Having a random character, in the sense that the likelihood of taking place over various intervals of time can be estimated, but it is not possible to determine whether or not, they will actually occur. See <i>epistemic</i> .
Burnup¹	A measure of nuclear reactor fuel consumption expressed either as the percentage of fuel atoms that have undergone fission or as the amount of energy produced per unit weight of fuel.
Chain reaction¹	A continuing series of nuclear fission events. Neutrons produced by a split nucleus collide with and split other nuclei causing a chain of fission events.
Cladding¹	The metal outer sheath of a fuel rod generally made of a zirconium alloy, and in the early nuclear power reactors, of stainless steel. Intended to protect the uranium dioxide pellets, which are the nuclear fuel, from dissolution by exposure to high temperature water under operating conditions in a reactor.
Critical condition	A self-sustaining nuclear fission chain reaction: When the number of neutrons resulting from fission in each generation equals the number of neutrons lost by both absorption and leakage in the preceding generation. In this circumstance the effective neutron multiplication factor equals one ($k_{\text{eff}}= 1$).
Critical limit	The value of k_{eff} at which a configuration is considered potentially critical, as characterized by statistical tolerance limits.
Criticality¹	(1) A condition that would require the original waste form, which is part of the waste package, to be exposed to degradation, followed by conditions that would allow concentration of sufficient nuclear fuel, the presence of neutron moderators, the absence of neutron absorbers, and favorable geometry. (2) The condition in which a fissile material sustains a chain reaction. It occurs when the number of neutrons present in one generation cycle equals the number generated in the previous cycle. The state is considered critical when a self-sustaining nuclear chain reaction is ongoing.

Criticality analysis	A mathematical analysis, usually performed with a computer, of the neutron multiplication factor of a system or configuration that contains material capable of undergoing a self-sustaining chain reaction.
Criticality control	The suite of measures taken to control the occurrence of self-sustaining nuclear chain reactions in fissionable materials, including spent nuclear fuel. For postclosure disposal applications, criticality control is ensuring that the probability of a criticality event is so small that the occurrence is unlikely, and the risk that any criticality will violate repository performance objectives is negligible.
Criticality, fast	A critical condition where fast (high-energy) neutrons sustain the fission process.
Criticality, thermal	A critical condition where thermal (low-energy) neutrons sustain the fission process.
Disposal²	The emplacement of radioactive waste in a geological repository with the intent of leaving it in there permanently.
Disruptive event¹	An off-normal event that, in the case of the repository, includes volcanic activity, seismic activity, and nuclear criticality. Disruptive events have two possible effects: (1) direct release of radioactivity to the surface, or (2) alteration of the nominal behavior of the system. For the purposes of screening features, events, and processes for total system performance assessment, a disruptive event is defined as an event that has a significant effect on the expected annual dose and that has a probability of occurrence during the 10,000 year period of performance less than 1.0, but greater than a cutoff of 0.0001.
Drift¹	From mining terminology, a horizontal, underground, passage. The nearly horizontal underground passageways from the shaft(s) to the alcoves and rooms. Drifts includes excavations for emplacement (emplacement drifts) and access (access mains).
Effective neutron multiplication factor	See <i>critical condition</i> .
Engineered barrier system²	The waste packages, including engineered components and systems other than the waste package (e.g., drip shields), and the underground facility.
Epistemic	Refers to the state of knowledge about a parameter because the data may be limited or because there may be alternative interpretations of the available data. The state of knowledge about the exact value of the parameter can increase through testing and data collection such that the uncertainty is “reducible.” See <i>aleatory</i> .

Events¹	(1) Occurrences that have a specific starting time and, usually, a duration shorter than the time being simulated in a model. (2) Uncertain occurrences that take place within a short time relative to the time frame of the model. For the purposes of screening features, events, and processes for total system performance assessment, an event is defined to be a natural or human-caused phenomenon that has a potential to affect disposal system performance and that occurs during an interval that is short compared with the period of performance.
Far-field	With reference to processes, those occurring at the scale of the mountain. The area of the geosphere and biosphere far enough away from the geological repository that, when numerically modeled, represents releases from the geological repository as a homogeneous, single-source effect.
Far-field for criticality	Far-field for criticality is defined as the space beyond the drift wall (i.e., in the host rock of the geological repository).
Features¹	Physical, chemical, thermal or temporal characteristics of the site or repository system. For the purpose of screening features, events, and processes for total system performance assessment, a feature is defined to be an object, structure or condition that has a potential to affect disposal system performance.
Fissile materials	Fissile materials are those materials that will undergo fission with thermal (slow) neutrons. The three primary fissile materials are uranium-233, uranium-235, and plutonium-239.
Fissionable materials	Fissionable materials are those materials that will undergo fission by neutrons with sufficient energy. Note that while all fissile materials are fissionable, the reverse is not true. Although “fissile,” rather than “fissionable,” is used in most places in this report, “fissionable” may be applicable in some configurations.
High-level waste	See <i>high-level radioactive waste</i> .
High-level radioactive waste	(1) The highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing, and any solid material derived from such liquid waste that contains fission products in sufficient concentration. (2) Other highly radioactive materials that the U.S. Nuclear Regulatory Commission, consistent with existing law, determines by rule require permanent isolation.
Initiating event²	A natural or human induced event that causes an event sequence.
k_{eff}	Effective neutron multiplication factor.
License application¹	An application to the U.S. Nuclear Regulatory Commission for a license to construct and operate a repository.

Lithophysae	Voids having concentric shells of finely crystalline alkali feldspar, quartz, and other materials that were formed by entrapped gas that later escaped.
Lithophysal	Pertaining to tuff units with <i>lithophysae</i> .
Near-field¹	The area and conditions within the geological repository including the drifts and waste packages and the rock immediately surrounding the drifts. The region around the repository where the natural hydrogeologic system has been significantly impacted by the excavation of the repository and the emplacement of waste.
Near-field for criticality	The area outside the waste package and inside the drift wall (including the drift liner and invert).
Neutron, fast	A neutron with kinetic energy greater than its surroundings when released during fission.
Neutron, thermal	A neutron that has (by collision with other particles) been slowed to an energy state equal to that of its surroundings, typically on the order of 0.025 eV (electron volts) and having a velocity of approximately 2,200 m/s.
Neutron leakage	The fraction of neutrons lost as result of escape from a fissile system.
Neutron moderator	A material such as ordinary water, heavy water, or graphite that is used to slow down fast (high-energy) neutrons to thermal (low-energy) neutrons, thus increasing the likelihood of fission.
Nuclear fission	The act of splitting a nucleus into two or more nuclei, resulting in the release of two or more neutrons and a relatively large amount of energy.
Performance assessment²	A probabilistic analysis that: (1) Identifies the features, events, and processes that might affect the performance of the geological repository; (2) Examines the effects of those features, events, and processes on the performance of the geological repository; and (3) Estimates the consequences (e.g., radiological exposures to the reasonably maximally exposed individual, radionuclide releases to the accessible environment) of releases from the geologic repository.
Period of performance	10,000 years after permanent closure of the geologic repository.
Permanent closure²	Final back-filling of the underground facility, if appropriate, and the sealing of shafts, ramps, and boreholes.

Probabilistic¹	(1) Based on or subject to probability. (2) Involving a variate, such as temperature or porosity. At each instance of time, the variate may take on any of the values of a specified set with a certain probability. Data from a probabilistic process are an ordered set of observations, each of which is one item from a probability distribution.
Probability¹	The chance that an outcome will occur from the set of possible outcomes. Statistical probability examines actual events and can be verified by observation or sampling. Knowledge of the exact probability of an event is usually limited by the inability to know, or compile, the complete set of possible outcomes over time or space, a degree of belief.
Probability distribution¹	The set of outcomes (values) and their corresponding probabilities for a random variable.
Processes¹	Phenomena and activities that have gradual, continuous interactions with the system being modeled. For purposes of screening features, events, and processes for total system performance assessment, a process is defined as a natural or human-caused phenomenon that has a potential to affect disposal system performance and that operates during all or a significant part of the period of performance.
Pyroclastic	Of or relating to individual particles or fragments of elastic rock material of any size formed by volcanic explosion or ejected from a volcanic vent.
Safety analysis, preclosure²	A systematic examination of the site; the design; and the potential hazards, initiating events, and event sequences and their consequences (e.g., radiological exposures to workers and the public). The analysis identifies structures, systems, and components important to safety.
Saturated zone²	That part of the earth's crust beneath the regional water table in which all voids, large and small, are ideally filled with water under pressure greater than atmospheric. See also <i>unsaturated zone</i> .
Scenario¹	A well-defined, connected sequence of features, events, and processes that can be thought of as an outline of a future condition of the repository system. Scenarios can be undisturbed, in which case the performance would be expected, or nominal, behavior for the system. Scenarios can also be disturbed, if altered by disruptive events such as human intrusion or natural phenomena such as volcanism or nuclear criticality.
Scenario class¹	A set of related scenarios that share sufficient similarities that they can usefully be aggregated for the purposes of screening or analysis. The number and breadth of scenario classes depends on the resolution at which scenarios have been defined. Coarsely defined scenarios result in fewer, broad scenario classes, whereas narrowly defined scenarios result in many narrow scenario classes. Scenario classes (and scenarios) should be aggregated at the coarsest level at which a technically sound argument can be made, while still retaining adequate detail for the purposes of analysis.

Seepage¹	The inflow of groundwater moving in fractures or pore spaces of permeable rock to an open space in the rock such as a drift. Seepage rate is the percolation flux that enters the drift. Seepage is an important factor in waste package degradation and mobilization and migration of radionuclides out of the repository.
Seismic¹	Pertaining to, characteristic of, or produced by earthquakes or earth vibrations.
Spent nuclear fuel¹	Fuel that has been withdrawn from a nuclear reactor following irradiation, the constituent elements of which have not been separated by reprocessing. Spent fuel that has been burned (irradiated) in a reactor to the extent that it no longer makes an efficient contribution to a nuclear chain reaction. This fuel is more radioactive than it was before irradiation, and releases significant amounts of heat from the decay of its fission product radionuclides. See <i>burnup</i> .
Uncertainty¹	A measure of how much a calculated or estimated value varies from the unknown true value.
Unsaturated zone²	The zone between the land surface and the regional water table. Generally, fluid pressure in this zone is less than atmospheric pressure, and some of the voids may contain air or other gases at atmospheric pressure. Beneath flooded areas or in perched water bodies, the fluid pressure locally may be greater than atmospheric.
Variability (statistical)¹	A measure of how a quantity varies over time or space.
Waste form²	The radioactive waste materials and any encapsulating or stabilizing matrix.
Water table²	That surface in a groundwater body, separating the unsaturated zone from the saturated zone, at which the water pressure is atmospheric.

¹ Definition cited from glossary of *Yucca Mountain Review Plan* (NRC 2003).

² Definition cited from 10 CFR 63.2 (10 CFR 63).

ATTACHMENT II

SAPHIRE MODEL USED FOR CRITICALITY FEPS SCREENING ANALYSIS

INTENTIONALLY LEFT BLANK

ATTACHMENT II - SAPHIRE MODEL USED FOR CRITICALITY FEPS SCREENING ANALYSIS

The SAPHIRE model used for the evaluation of the criticality FEPs screening analysis is based on the configuration generator model (BSC 2003 [DIRS 165629]). The event trees and fault trees used in the SAPHIRE criticality FEPs analysis are presented and discussed in Section II.1. The logic rules used to assign the basic event probabilities and direct the evaluation of the event trees are presented in Sections II.2 through II.5. The basic event values used in this analysis are presented in Section II.6 and the SAPHIRE-calculated end-state results are presented in Section II.7.

II.1 SAPHIRE EVENT TREES AND FAULT TREES

Figures II-1 through II-4 present the event trees used in the criticality FEPs screening analysis. The fault trees supporting the top events of the FEPS event trees are presented in Figures II-5 through II-8.

Figure II-1 presents the “WP_TYPE” event tree used for determining the waste form and waste package type inventory fraction. Figure II-2 presents the 21-PWR with Absorber Plates Waste Package, an example of the eight waste package type event trees. These event trees are used to initiate the calculation of the waste package flooding probabilities on a per waste package type basis. Figure II-3 presents the “CASE” event tree for directing the SAPHIRE evaluation of the criticality FEPs cases – base case, seismic disruptive event, and rockfall disruptive event (the igneous disruptive event is not evaluated by SAPHIRE). Finally, Figure II-4 presents the “FEPS” event tree for processing the events that determine the probability of waste package flooding.

Figure II-5 through II-8 present the fault trees and their supporting basic events used to quantify top events MS-IC-1, MS-IC-2, MS-IC-3, and MS-IC-4, respectively, of the “FEPS” event tree. Fault tree MS-IC-1 contains the basic event defining the probability of achieving the minimum required seepage rate. Fault tree MS-IC-2 contains the basic events and their relational logic to define the probability of drip shield failure. Fault tree MC-IC-3 contains the basic events and their relational logic to define the probability of waste package failure. Finally, fault tree MS-IC-4 contains the basic events and their relational logic to define the probability of bathtub configuration forming and enduring over the period of performance.

Waste Package Fraction	Waste Form Type Percentages by Originator		Waste Form Sub-Type Percentages		Waste Package Type Percent Breakdown		#	END-STATE-NAMES	FRACTION
	WP-SOURCE	WP-IND	WP-IND	WP-TYPE					
Waste Package Fraction	Commercial CSNF (66.8% of total inventory)	PWR (40.7% of total inventory)	BWR (26.1% of total inventory)	21-PWR Absorber Plate (38.4% of total inventory)	1	CSNF-21PWR-ABS-WP	3.840E-001		
				21-PWR Control Rod (0.8% of total inventory)	2	CSNF-21PWR-CR-WP	8.000E-003		
				12-PWR Long (1.5% of total inventory)	3	CSNF-12PWR-LONG-WP	1.500E-002		
				44-BWR (25.3% of total inventory)	4	CSNF-44BWR-WP	2.53E-001		
				24-BWR (0.8% of total inventory)	5	CSNF-24BWR-WP	8.000E-003		
				DOE Long (10.3% of total inventory)	6	DOESNF-LONG-WP	1.030E-001		
				DOE Short (18.9% of total inventory)	7	DOESNF-SHORT-WP	1.890E-001		
				DOE MCO (1.3% of total inventory)	8	DOESNF-MCO-WP	1.300E-002		
				Naval Short (1.3% of total inventory)	9	NAVAL-SHORT-WP	1.300E-002		
				Naval Long (1.4% of total inventory)	10	NAVAL-LONG-WP	1.400E-002		

Figure II-1. Waste Form and Waste Package Type Inventory Fraction Event Tree

Initiate Evaluation of 21-PWR with Absorber Plates Waste Package Type	WP01-21-PWR-AP	<PASS>	#	END_STATE_NAMES
		<p>1 T</p> <hr/> <p>CASE</p>		

Figure II-2. Waste Package Type Event Tree

Incoming Waste Package Type Identifier	FEPs Initiating Event	Rock Type of Drift	#	END-STATE	
	FEP	DRIFT			
IE1	Base Case Probability = 1.0	Nonlithophysal (15%)		1 T	FEPS
		Lithophysal (85%)		2 T	FEPS
	Seismic Disruptive Event Probability = 1.0	Nonlithophysal		3 T	FEPS
		Lithophysal		4 T	FEPS
	Rock Fall Disruptive Event Probability = 1.0	Nonlithophysal		5 T	FEPS
		Lithophysal		6 T	FEPS
	Igneous Disruptive Event Probability = 1.6E-4			7	OK

Figure II-3. Criticality FEPs Case Assignment Event Tree

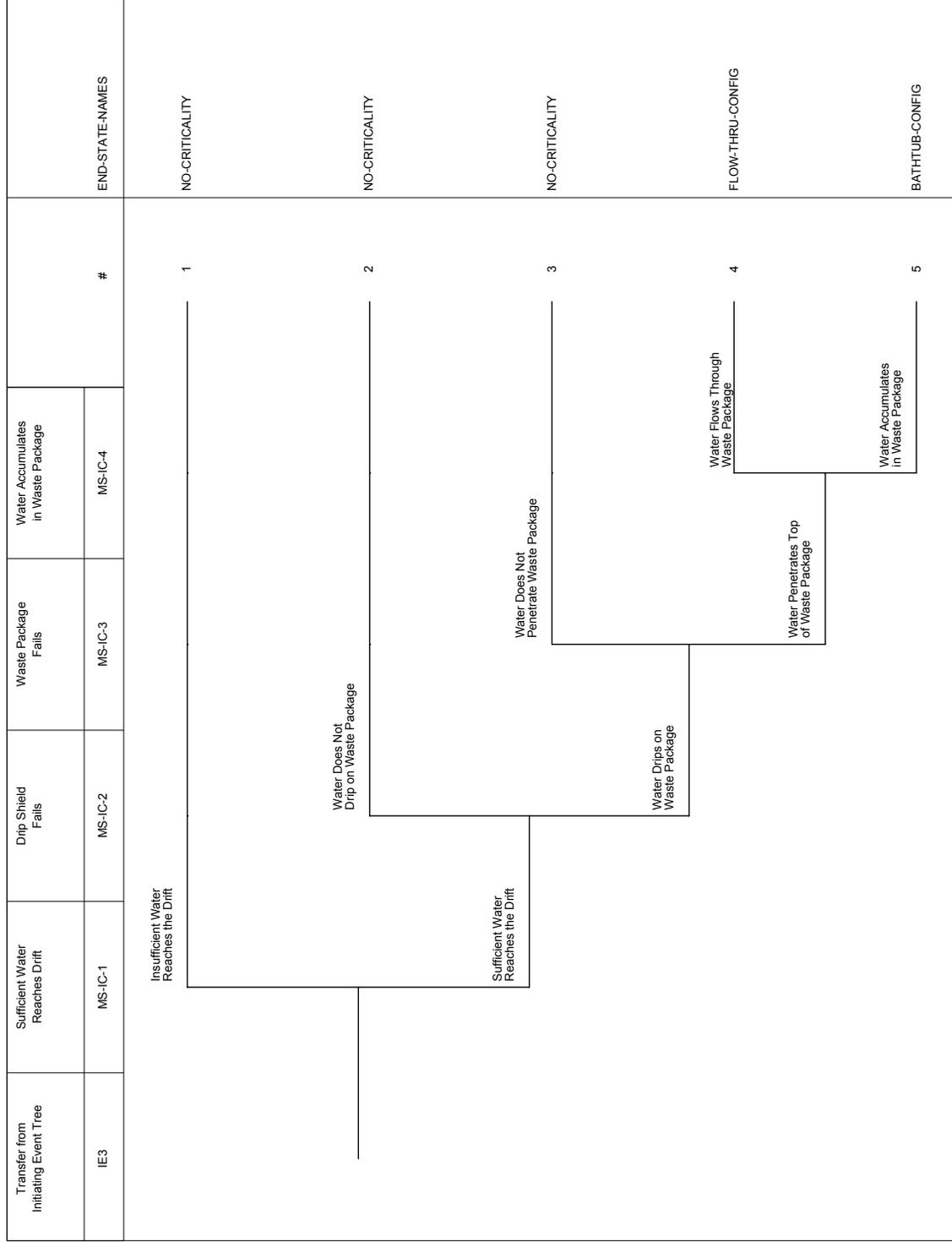


Figure II-4. Probability of Waste Package Flooding Event Tree

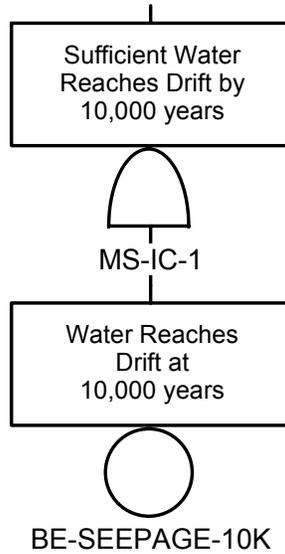


Figure II-5. MS-IC-1 Fault Tree (Minimum Required Seepage Rate)

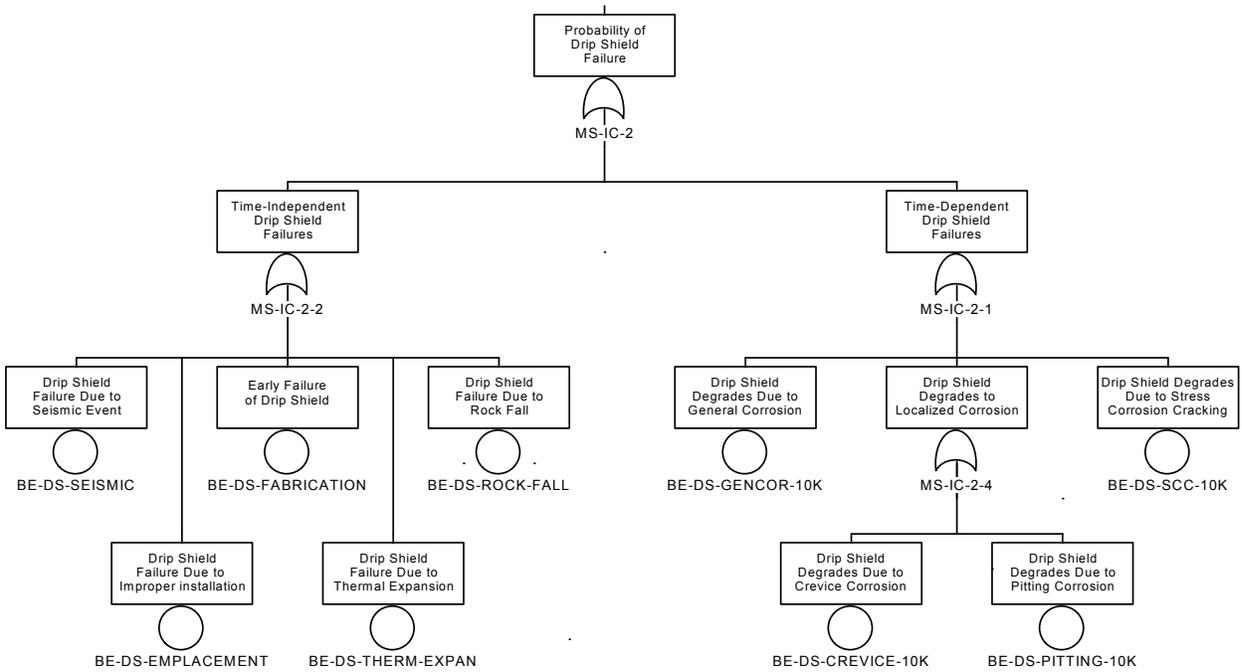


Figure II-6. MS-IC-2 Fault Tree (Drip Shield Failure)

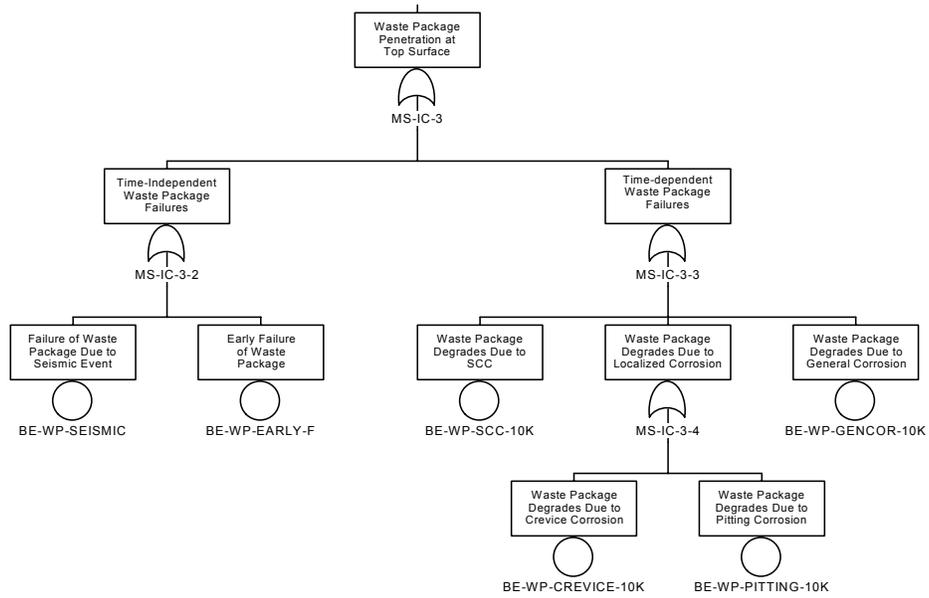


Figure II-7. MS-IC-3 Fault Tree (Waste Package Failure)

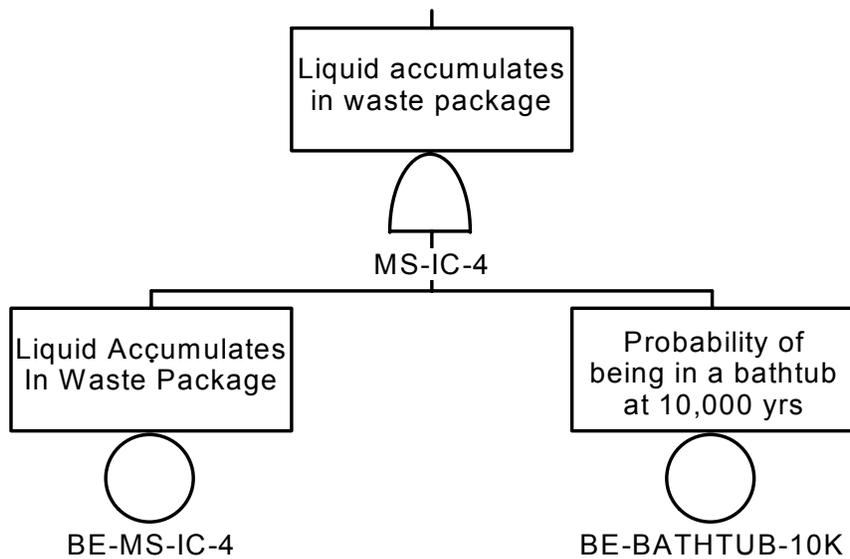


Figure II-8. MS-IC-4 Fault Tree (Bathtub Configuration)

II.2 LINKAGE RULES FOR THE WP_TYPE EVENT TREE (FIGURE II-1)

The following linkage rules are used to assign the basic event values representing the percentage of total waste package inventory for the various waste form types, waste form subtypes, and waste package types.

```
IF ALWAYS THEN
  /WP-SOURCE = WP-SOURCE-CSNF;
  WP-SOURCE[1] = WP-SOURCE-DOE;
  WP-SOURCE[2] = WP-SOURCE-NAVAL;
ENDIF;
|
IF /WP-SOURCE THEN
  /WP-IND = WP-PWR;
  WP-IND = WP-BWR;
ENDIF;
|
IF (/WP-SOURCE * /WP-IND) THEN
  /WP-TYPE = WP-TYPE-21ABS;
  WP-TYPE[1] = WP-TYPE-21CR;
  WP-TYPE[2] = WP-TYPE-12LONG;
ENDIF;
|
IF (/WP-SOURCE * WP-IND) THEN
  /WP-TYPE = WP-TYPE-44BWR;
  WP-TYPE = WP-TYPE-24BWR;
ENDIF;
|
IF WP-SOURCE[1] THEN
  /WP-TYPE = WP-DOE-LONG;
  WP-TYPE[1] = WP-DOE-SHORT;
  WP-TYPE[2] = WP-DOE-MCO;
ENDIF;
|
IF WP-SOURCE[2] THEN
  /WP-TYPE = WP-NAVAL-SHORT;
  WP-TYPE = WP-NAVAL-LONG;
ENDIF;
```

II.3 LINKAGE RULES FOR THE CASE EVENT TREE (FIGURE II-3)

The following linkage rules are used to substitute the basic event value for the four criticality FEPs cases considered in the SAPHIRE analysis – (1) Base Case (probability = 1.0), (2) Seismic Disruptive Event (probability = 1.0); (3) Rock Fall Disruptive Event (probability = 1.0), , and Igneous Disruptive Event (probability = 1.7E-4).

```
SET FEP INITIATING EVENTS
IF ALWAYS THEN
  /FEP = FEP_NOMINAL;
  FEP [1] = FEP_SEISMIC;
  FEP [2] = FEP_ROCKFALL;
  FEP [3] = FEP_IGNEOUS;
ENDIF
```

II.4 PROJECT RECOVERY RULES

The following recovery rules are used to substitute basic events in the event tree sequences and to prevent mutually exclusive events from occurring within a sequence.

```

Basic event substitution rules for MS-IC-1 Fault Tree
if (FEP_SEISMIC * BE-SEEPAGE-10K * WP01-21-PWR-AP * DRIFT) then
  DeleteEvent = BE-SEEPAGE-10K;
  AddEvent    = BE-SEEPAGE-WP1-L;
elseif (FEP_SEISMIC * BE-SEEPAGE-10K * WP01-21-PWR-AP * /DRIFT) then
  DeleteEvent = BE-SEEPAGE-10K;
  AddEvent    = BE-SEEPAGE-WP1-NL;
elseif (FEP_SEISMIC * BE-SEEPAGE-10K * WP02-21-PWR-CR * DRIFT) then
  DeleteEvent = BE-SEEPAGE-10K;
  AddEvent    = BE-SEEPAGE-WP2-L;
elseif (FEP_SEISMIC * BE-SEEPAGE-10K * WP02-21-PWR-CR * /DRIFT) then
  DeleteEvent = BE-SEEPAGE-10K;
  AddEvent    = BE-SEEPAGE-WP2-NL;
elseif (FEP_SEISMIC * BE-SEEPAGE-10K * WP03-12-PWR-LONG * DRIFT) then
  DeleteEvent = BE-SEEPAGE-10K;
  AddEvent    = BE-SEEPAGE-WP3-L;
elseif (FEP_SEISMIC * BE-SEEPAGE-10K * WP03-12-PWR-LONG * /DRIFT) then
  DeleteEvent = BE-SEEPAGE-10K;
  AddEvent    = BE-SEEPAGE-WP3-NL;
elseif (FEP_SEISMIC * BE-SEEPAGE-10K * WP04-44-BWR * DRIFT) then
  DeleteEvent = BE-SEEPAGE-10K;
  AddEvent    = BE-SEEPAGE-WP4-L;
elseif (FEP_SEISMIC * BE-SEEPAGE-10K * WP04-44-BWR * /DRIFT) then
  DeleteEvent = BE-SEEPAGE-10K;
  AddEvent    = BE-SEEPAGE-WP4-NL;
elseif (FEP_SEISMIC * BE-SEEPAGE-10K * WP05-24-BWR * DRIFT) then
  DeleteEvent = BE-SEEPAGE-10K;
  AddEvent    = BE-SEEPAGE-WP5-L;
elseif (FEP_SEISMIC * BE-SEEPAGE-10K * WP05-24-BWR * /DRIFT) then
  DeleteEvent = BE-SEEPAGE-10K;
  AddEvent    = BE-SEEPAGE-WP5-NL;
elseif (FEP_SEISMIC * BE-SEEPAGE-10K * WP06-DOE-LONG * DRIFT) then
  DeleteEvent = BE-SEEPAGE-10K;
  AddEvent    = BE-SEEPAGE-WP6-L;
elseif (FEP_SEISMIC * BE-SEEPAGE-10K * WP06-DOE-LONG * /DRIFT) then
  DeleteEvent = BE-SEEPAGE-10K;
  AddEvent    = BE-SEEPAGE-WP6-NL;
elseif (FEP_SEISMIC * BE-SEEPAGE-10K * WP07-DOE-SHORT * DRIFT) then
  DeleteEvent = BE-SEEPAGE-10K;
  AddEvent    = BE-SEEPAGE-WP7-L;
elseif (FEP_SEISMIC * BE-SEEPAGE-10K * WP07-DOE-SHORT * /DRIFT) then
  DeleteEvent = BE-SEEPAGE-10K;
  AddEvent    = BE-SEEPAGE-WP7-NL;
elseif (FEP_SEISMIC * BE-SEEPAGE-10K * WP08-DOE-MCO * DRIFT) then
  DeleteEvent = BE-SEEPAGE-10K;
  AddEvent    = BE-SEEPAGE-WP8-L;
elseif (FEP_SEISMIC * BE-SEEPAGE-10K * WP08-DOE-MCO * /DRIFT) then
  DeleteEvent = BE-SEEPAGE-10K;
  AddEvent    = BE-SEEPAGE-WP8-NL;
endif;

```

```
Basic event substitution rules for MS-IC-2 Fault Tree
if (BE-DS-SEISMIC * FEP_SEISMIC) then
  DeleteEvent = BE-DS-SEISMIC;
  AddEvent    = BE-DS-SEISMIC1;
endif;

Basic event substitution rules for MS-IC-3 Fault Tree
if (BE-WP-EARLY-F * FEP_SEISMIC) then
  DeleteEvent = BE-WP-EARLY-F;
  AddEvent    = BE-WP-EARLY-F1;
elseif (BE-WP-SEISMIC * FEP_SEISMIC) then
  DeleteEvent = BE-WP-SEISMIC;
  AddEvent    = BE-WP-SEISMIC1;
endif;

Recovery Rules for MS-IC-4 Fault Tree
if (BE-WP-EARLY-F + BE-WP-SEISMIC1) * BE-MS-IC-4 then
  DeleteEvent = BE-MS-IC-4;
endif;
```

II.5 PROJECT PARTITION RULES

The following partition rules are used to create encoded end states for the FEPS event tree sequences that result in either a bathtub or flow-through configuration. These encoded end states represent sequences for the three SAPHIRE evaluated criticality FEPs cases (igneous disruptive event not evaluated in SAPHIRE), eight of the ten waste package types (naval waste package types are not considered in this evaluation), and the two geological zones (lithophysal and nonlithophysal) considered in this analysis.

```

DEFINE VARIABLES
FEPIE1      = /FEP_BASECASE;
FEPIE2_    = FEP_ROCKFALL;
FEPIE3_    = FEP_SEISMIC;
BATHTUB_   = ~/MS-IC-4;
NOBATHTUB_ = /MS-IC-4;
LITH_      = DRIFT;
NONLITH_   = /DRIFT;
SORT_      = (~/MS-IC-1 * ~/MS-IC-2 * ~/MS-IC-3 * (DRIFT + /DRIFT));

if FEPIE1 * SORT then
  GlobalPartition="N-?????????";
elseif FEPIE2 * SORT then
  GlobalPartition="R-????????????";
elseif FEPIE3 * SORT then
  GlobalPartition="S-????????????";
endif;

if init(WP01-21-PWR-AP) * SORT then
  GlobalPartition="??PWR1?????";
elseif init(WP02-21-PWR-CR) * SORT then
  GlobalPartition="??PWR2?????";
elseif init(WP03-12-PWR-LONG) * SORT then
  GlobalPartition="??PWR3?????";
elseif init(WP04-44-BWR) * SORT then
  GlobalPartition="??BWR1?????";
elseif init(WP05-24-BWR) * SORT then
  GlobalPartition="??BWR2?????";
elseif init(WP06-DOE-LONG) * SORT then
  GlobalPartition="??DOE0?????";
elseif init(WP07-DOE-SHORT) * SORT then
  GlobalPartition="??DOE0?????";
elseif init(WP08-DOE-MCO) * SORT then
  GlobalPartition="??DOE0?????";
endif;

if BATHTUB * SORT then
  GlobalPartition="??????-BT???";
elseif NOBATHTUB * SORT then
  GlobalPartition="??????-FT???";
endif;

if LITH * SORT then
  GlobalPartition="?????????-LI";
elseif NONLITH * SORT then
  GlobalPartition="?????????-NL";
endif;

```

II.6 BASIC EVENTS FOR SAPHIRE ANALYSIS

Table II-1 lists the basic event values used in the Criticality FEPs evaluations.

Table II-1. Basic Events For SAPHIRE Criticality FEPs Analysis

Basic Event Name	Description	Probability
BASIC EVENTS FOR THE MS-IC-1 TOP EVENT OF THE FEPS EVENT TREE		
BE-SEEPAGE-10K	Water Reaches Drift at 10,000 years	0.000E+000
BE-SEEPAGE-WP1-L	minimum water flux at 10K yrs - 21-PWR AP WP - seismic lith	0.000E+000
BE-SEEPAGE-WP1-NL	minimum water flux at 10K yrs - 21-PWR AP WP - seismic nonlith	0.000E+000
BE-SEEPAGE-WP2-L	minimum water flux at 10K yrs - 21-PWR CR WP - seismic lith	0.000E+000
BE-SEEPAGE-WP2-NL	minimum water flux at 10K yrs - 21-PWR CR WP - seismic nonlith	0.000E+000
BE-SEEPAGE-WP3-L	minimum water flux at 10K yrs - 12-PWR WP - seismic lith	0.000E+000
BE-SEEPAGE-WP3-NL	minimum water flux at 10K yrs - 12-PWR WP - seismic nonlith	0.000E+000
BE-SEEPAGE-WP4-NL	minimum water flux at 10K yrs - 44-BWR WP - seismic nonlith	9.740E-007
BE-SEEPAGE-WP4-L	minimum water flux at 10K yrs - 44-BWR WP - seismic lith	1.525E-006
BE-SEEPAGE-WP5-L	minimum water flux at 10K yrs - 24-BWR WP - seismic lith	0.000E+000
BE-SEEPAGE-WP5-NL	minimum water flux at 10K yrs - 24-BWR WP - seismic nonlith	0.000E+000
BE-SEEPAGE-WP6-L	minimum water flux at 10K yrs - DOE Long WP - seismic lith	0.000E+000
BE-SEEPAGE-WP6-NL	minimum water flux at 10K yrs - DOE Long WP - seismic nonlith	0.000E+000
BE-SEEPAGE-WP7-L	minimum water flux at 10K yrs - DOE Short WP - seismic lith	0.000E+000
BE-SEEPAGE-WP7-NL	minimum water flux at 10K yrs - DOE Short WP - seismic nonlith	0.000E+000
BE-SEEPAGE-WP8-L	minimum water flux at 10K yrs - DOE MCO WP - seismic lith	0.000E+000
BE-SEEPAGE-WP8-NL	minimum water flux at 10K yrs - DOE MCO WP - seismic nonlith	0.000E+000
BASIC EVENTS FOR THE MS-IC-1 TOP EVENT OF THE FEPS EVENT TREE FOR THE SEISMIC SENSITIVITY CASE		
BE-SEEPAGE-WP4-NL	minimum water flux at 10K yrs - 44-BWR WP - seismic nonlith	9.924E-012
BE-SEEPAGE-WP4-L	minimum water flux at 10K yrs - 44-BWR WP - seismic lith	1.242E-010
BASIC EVENTS FOR THE MS-IC-2 TOP EVENT OF THE FEPS EVENT TREE		
BE-DS-CREVICE-10K	Drip Shield Degrades Due to Crevice Corrosion	0.000E+000
BE-DS-EMPLACEMENT	Drip Shield Failure Due to Improper installation	0.000E+000
BE-DS-FABRICATION	Early Failure of Drip Shield	0.000E+000
BE-DS-GENCOR-10K	Drip Shield Degrades Due to General Corrosion	0.000E+000
BE-DS-PITTING-10K	Drip Shield Degrades Due to Pitting Corrosion	0.000E+000
BE-DS-ROCK-FALL	Drip Shield Failure Due to Rock Fall - Lithophysal Zone	0.000E+000
BE-DS-ROCK-FALL1	Drip Shield Failure Due to Rock Fall - Nonlithophysal Zone	3.310E-002
BE-DS-SCC-10K	Drip Shield Degrades Due to Stress Corrosion Cracking	0.000E+000
BE-DS-SEISMIC	Drip Shield Failure Due to Seismic Event - Base Case	0.000E+000
BE-DS-SEISMIC1	Drip Shield Failure Due to Seismic Event - Seismic Event	1.000E+000
BE-DS-THERM-EXPAN	Drip Shield Failure Due to Thermal Expansion	0.000E+000
BASIC EVENTS FOR THE MS-IC-3 TOP EVENT OF THE FEPS EVENT TREE		
BE-WP-CREVICE-10K	Waste Package Degrades Due to Crevice Corrosion	0.000E+000
BE-WP-EARLY-F	Early Failure of Waste Package	2.800E-005
BE-WP-EARLY-F1	Early Failure of Waste Package - Seismic Event	0.000E+000
BE-WP-GENCOR-10K	Waste Package Degrades Due to General Corrosion	0.000E+000
BE-WP-PITTING-10K	Waste Package Degrades Due to Pitting Corrosion	0.000E+000

Table II-1. Basic Events For SAPHIRE Criticality FEPs Analysis (Continued)

Basic Event Name	Description	Probability
BE-WP-SCC-10K	Waste Package Degrades Due to SCC	0.000E+000
BE-WP-SEISMIC	Failure of Waste Package Due to Seismic Event	0.000E+000
BE-WP-SEISMIC1	Failure of Waste Package Due to Seismic Event - Seismic Event	1.000E+000
BASIC EVENTS FOR THE MS-IC-4 TOP EVENT OF THE FEPS EVENT TREE		
BE-BATHTUB-10K	Probability of Being in a Bathtub at 10,000 yrs	1.000E+000
BE-MS-IC-4	Liquid Accumulates In Waste Package	1.000E+000
BASIC EVENTS FOR THE DRIFT TOP EVENT OF THE INITEVENT EVENT TREE		
DRIFT	Rock Type Fraction in Drifts	8.500E-001
BASIC EVENTS FOR FEP TOP EVENT OF INITEVENT EVENT TREE		
FEP_BASECASE	Base Case Disruptive Event	1.000E+000
FEP_SEISMIC	Seismic Case Disruptive Event	1.000E+000
FEP_ROCKFALL	Rockfall Case Disruptive Event	1.000E+000
FEP_IGNEOUS	Igneous Case Disruptive Event	1.600E-004
BASIC EVENTS FOR THE WP-SOURCE TOP EVENT OF THE WP_TYPE EVENT TREE		
WP-SOURCE-CSNF	Commercial SNF (66.8%)	3.320E-001
WP-SOURCE-DOE	DOE SNF (30.5%)	3.050E-001
WP-SOURCE-NAVAL	Naval SNF (2.7%)	2.700E-002
BASIC EVENTS FOR THE WP-IND TOP EVENT OF THE WP_TYPE EVENT TREE		
WP-BWR	BWR (26.1%)	3.907E-001
WP-PWR	PWR (40.7%)	3.907E-001
BASIC EVENTS FOR THE WP-TYPE TOP EVENT OF THE WP_TYPE EVENT TREE		
WP-TYPE-21ABS	21-PWR Absorber Plate (38.4%)	5.651E-002
WP-TYPE-21CR	21-PWR Control Rod (0.8%)	1.965E-002
WP-TYPE-12LONG	12-PWR Long (1.5%)	3.685E-002
WP-TYPE-44BWR	44-BWR (25.3%)	3.065E-002
WP-TYPE-24BWR	24-BWR (0.8%)	3.065E-002
WP-DOE-SHORT	DOE Short (18.9%)	6.196E-001
WP-DOE-LONG	DOE Long (10.3%)	6.622E-001
WP-DOE-MCO	DOE MCO (1.3%)	4.262E-002
WP-NAVAL-LONG	Naval Long (1.4%)	5.185E-001
WP-NAVAL-SHORT	Naval Short (1.3%)	5.185E-001
INITIATING EVENTS WASTE PACKAGE TYPE EVENT TREES		
WP01-21-PWR-AP	21-PWR With Absorber Plates Waste Package	1.000E+000
WP02-21-PWR-CR	21-PWR With Control Rods Waste Package	1.000E+000
WP03-12-PWR-LONG	12-PWR Long Waste Package	1.000E+000
WP04-44-BWR	44-BWR Waste Package	1.000E+000
WP05-24-BWR	24-BWR Waste Package	1.000E+000
WP06-DOE-LONG	DOE Long Waste Package	1.000E+000
WP07-DOE-SHORT	DOE Short Waste Package	1.000E+000
WP08-DOE-MCO	DOE MCO Waste Package	1.000E+000

II.7 SAPHIRE END STATE RESULTS FOR CRITICALITY FEPS ANALYSIS

Table II-2 presents the criticality FEPs analysis probability results as calculated by SAPHIRE. The 12-character end-state names are encoded to capture the following information:

1. The criticality FEPs analysis case (i.e., base case, seismic, or rockfall)
 - B – base case
 - S – seismic disruptive event
 - R – rockfall disruptive event
2. The waste package type (e.g., 21-PWR with Absorber Plates Waste Package)
 - -PWR1 – 21-PWR with Absorber Plates Waste Package
 - -PWR2 – 21-PWR with Control Rods Waste Package
 - -PWR3 – 12-PWR Long Waste Package
 - -BWR1 – 44-BWR Waste Package
 - -BWR2 – 24-BWR Waste Package
 - -DOE0 – DOE Waste Package (includes results for the DOE-Long, DOE-Short, and DOE-MCO waste package types)
3. The waste package configuration type (i.e., flow or bathtub)
 - -BT – bathtub waste package configuration
 - -FT – flow-through waste package configuration
4. The repository location (i.e., lithophysal or nonlithophysal zone)
 - -LI – lithophysal zone
 - -NL – nonlithophysal zone.

The end states are assigned to each event tree sequence based on the project partition rules documented in Section II.5.

Table II-2. SAPHIRE End State Probabilities

End State Name	Base Case Probability	Sensitivity Case Probability ^a
Base Case Results		
B-BWR1-BT-LI	0.00E+00	NA
B-BWR1-BT-NL	0.00E+00	NA
B-BWR2-BT-LI	0.00E+00	NA
B-BWR2-BT-NL	0.00E+00	NA
B-DOE0-BT-LI	0.00E+00	NA
B-DOE0-BT-NL	0.00E+00	NA
B-PWR1-BT-LI	0.00E+00	NA
B-PWR1-BT-NL	0.00E+00	NA
B-PWR2-BT-LI	0.00E+00	NA
B-PWR2-BT-NL	0.00E+00	NA
B-PWR3-BT-LI	0.00E+00	NA
B-PWR3-BT-NL	0.00E+00	NA
Rock Fall Disruptive Event Results		
R-BWR1-BT-LI	0.00E+00	NA
R-BWR1-BT-NL	0.00E+00	NA
R-BWR2-BT-LI	0.00E+00	NA
R-BWR2-BT-NL	0.00E+00	NA
R-DOE0-BT-LI	0.00E+00	NA
R-DOE0-BT-NL	0.00E+00	NA
R-PWR1-BT-LI	0.00E+00	NA
R-PWR1-BT-NL	0.00E+00	NA
R-PWR2-BT-LI	0.00E+00	NA
R-PWR2-BT-NL	0.00E+00	NA
R-PWR3-BT-LI	0.00E+00	NA
R-PWR3-BT-NL	0.00E+00	NA
Seismic Disruptive Event Results		
S-BWR1-BT-LI	1.30E-06	1.05E-10
S-BWR1-BT-NL	1.46E-07	1.39E-12
S-BWR2-BT-LI	0.00E+00	0.00E+00
S-BWR2-BT-NL	0.00E+00	0.00E+00
S-DOE0-BT-LI	0.00E+00	0.00E+00
S-DOE0-BT-NL	0.00E+00	0.00E+00
S-PWR1-BT-LI	0.00E+00	0.00E+00
S-PWR1-BT-NL	0.00E+00	0.00E+00
S-PWR2-BT-LI	0.00E+00	0.00E+00
S-PWR2-BT-NL	0.00E+00	0.00E+00
S-PWR3-BT-LI	0.00E+00	0.00E+00
S-PWR3-BT-NL	0.00E+00	0.00E+00
TOTALS =	1.44E-06	1.07E-10

^a Neutronit absorber plate thickness of 44-BWR Waste Package increased to 7 mm

ATTACHMENT III

SEISMIC CALCULATIONS SPREADSHEETS (OUTPUT FROM MATHCAD FILES)

INTENTIONALLY LEFT BLANK

ATTACHMENT III - SEISMIC CALCULATIONS SPREADSHEETS (OUTPUT FROM MATHCAD FILES)

The following sections present the Mathcad probability analyses for achieving the minimum required seepage to remove the neutron absorber material from the waste package as a result of a seismic disruptive event. These analyses are performed for a base case scenario (waste package baseline design) and a sensitivity case scenario (absorber plate thickness of the 44-BWR Waste Package is increase to 7 mm).

III.1 SEISMIC BASE CASE ANALYSIS

The following section presents the Mathcad probability analysis for achieving the minimum required seepage to remove the neutron absorber material from the waste package as a result of a seismic disruptive event. This analysis utilizes seepage information from *Abstraction of Drift Seepage* (BSC 2003 [DIRS 165564]), seismic event information and waste package and drip shield damage information from *Seismic Consequence Abstraction* (BSC 2003 [DIRS 161812]), and waste package boron loss information from *Boron Loss From CSNF Waste Packages* (BSC 2003 [DIRS 165890]). The seismic base case is performed assuming that:

- Water cannot enter a failed waste package until at least 700 years when the average drift wall temperature falls below the boiling point (Assumption 5.2.2);
- The neutron absorber material degradation rate is 1.5 times that of stainless steel 316 (Assumption 5.1.4); and
- 90 percent of the boron from the neutron absorber material can be removed from PWR waste packages with absorber plates and 50 percent can be removed from BWR waste packages with absorber plates without criticality concerns (Assumption 5.1.5).

The information contained in this section was obtained from the “Attachment III.mcd” Mathcad file of Attachment VII.

Probability Calculation of Seismic Event Leading to Potential Criticality

This calculation evaluates the damage to a drip shield and a waste package due to a seismic event that has the potential to allow advective flow into a waste package. The equations and data are from *Seismic Consequence Abstraction* (BSC 2003 [DIRS 161812]) and DTN: M0308SPACALSS.002 (BSC 2003 [DIRS 164822]).

Drip Shield Damage Due to Seismic Event & Rockfall

Drip shield damage is based on location within the drift. The drip shields within the lithophysal area can only be damaged by vibratory ground motion and not rockfall because rocks here will crush and during a seismic event (BSC 2003 [DIRS 161812], Section 6.6.2). The drip shields located in the nonlithophysal, however, can be damaged by both rockfall and vibratory ground motion. Approximately 85% of the drift lies in the lithophysal zones.

$$DSU_{dat} := \begin{pmatrix} 0 & 0 \\ 0.55 & 0 \\ 2.44 & 2.68 \\ 5.35 & 50 \\ 20 & 50 \end{pmatrix} \quad \begin{array}{l} \text{Drip shield upper bound} \\ \text{damage from vibratory} \\ \text{ground motion based on} \\ \text{look-up table} \\ \text{DTN:M0308SPACALSS.002} \\ \text{(BSC 2003 [DIRS 164822])}. \end{array}$$

$$DSL_{dat} := \begin{pmatrix} 0 & 0 \\ 2.44 & 0 \\ 5.35 & 10 \end{pmatrix} \quad \begin{array}{l} \text{Drip shield lower bound} \\ \text{damage from vibratory} \\ \text{ground motion based on} \\ \text{look-up table} \\ \text{DTN:M0308SPACALSS.002} \\ \text{(BSC 2003 [DIRS 164822])}. \end{array}$$

$$PGV_{dsu} := DSU_{dat}^{\langle 0 \rangle} \quad DS_{ud} := DSU_{dat}^{\langle 1 \rangle} \quad PGV_{dsl} := DSL_{dat}^{\langle 0 \rangle} \quad DS_{ld} := DSL_{dat}^{\langle 1 \rangle}$$

Seismic Sampling Routine

$$i := 0..8$$

Peak Ground Velocity (m/s)

$$PGV_B := \begin{pmatrix} 0.159 \\ 0.239 \\ 0.398 \\ 0.796 \\ 1.59 \\ 3.98 \\ 5.57 \\ 7.96 \\ 11.9 \end{pmatrix}$$

The peak ground velocity (PGV) and mean annual frequency are from DTN: M0308SPACALSS.002 (BSC 2003 [DIRS 164822]).

$$PGV_n := PGV_B$$

$$PGV_t := \text{reverse}(PGV_B)$$

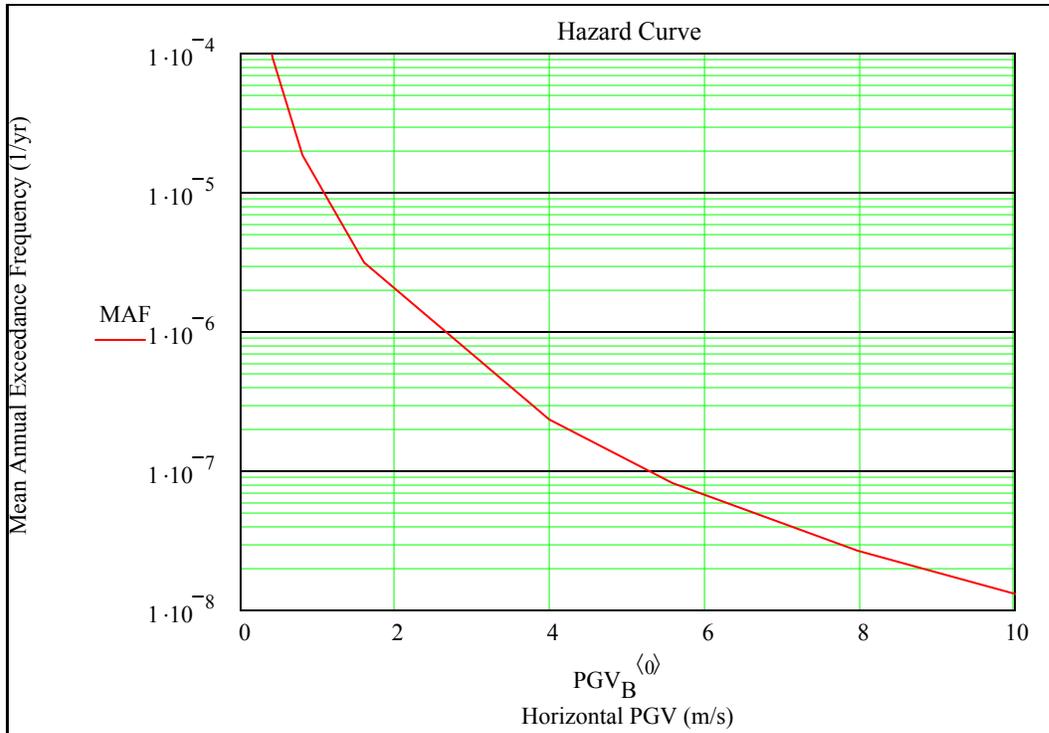
The interpolation between the PGV and mean annual exceedance frequency points is based on a linear interpolation using the value of $\log(MAF)$ at the individual sample points as stated in DTN: M0308SPACALSS.002 (BSC 2003 [DIRS 164822]).

Mean Annual Exceedance Frequency

$$MAF := \begin{pmatrix} 6.26 \times 10^{-4} \\ 2.78 \times 10^{-4} \\ 9.30 \times 10^{-5} \\ 1.84 \times 10^{-5} \\ 3.07 \times 10^{-6} \\ 2.28 \times 10^{-7} \\ 8.15 \times 10^{-8} \\ 2.60 \times 10^{-8} \\ 6.56 \times 10^{-9} \end{pmatrix}$$

$$MAF_n := \log(MAF)$$

$$MAF_t := \text{reverse}(MAF_n)$$



Set up mean annual exceedance frequency versus PGV for sampling (based on seismic event).

$$DAT_{i,0} := MAF_{t_{i,0}} \quad DAT_{i,1} := PGV_{t_{i,0}}$$

$$DAT = \begin{pmatrix} -8.183 & 11.9 \\ -7.585 & 7.96 \\ -7.089 & 5.57 \\ -6.642 & 3.98 \\ -5.513 & 1.59 \\ -4.735 & 0.796 \\ -4.032 & 0.398 \\ -3.556 & 0.239 \\ -3.203 & 0.159 \end{pmatrix}$$

$$IE_V := DAT^{(0)} \quad PGV_V := DAT^{(1)}$$

Seismic exceedance frequencies and time to first occurrence of seismic event follow uniform distributions (BSC 2003 [DIRS 164822])

$$IE_l := 1 \cdot 10^{-8} \quad IE_u := 1 \cdot 10^{-4}$$

The upper and lower bounds are from DTN: M0308SPACALSS.002 (BSC 2003 [DIRS 164822]).

$$T_l := 1 \quad T_u := 10000$$

The lower bound is 1 year based on closure of repository and the upper bound is 10,000 years based on regulatory period (BSC 2003 [DIRS 164822]).

Latin Hypercube Sampling Routine for Evaluation of Seismic Events

The PGV values, damaged areas, and seepage are obtained using Latin Hypercube Sampling.

$n_s := 20000$ **sample size**

$i := 1..n_s$

$RD_{i-1,0} := i$ $RD_{i-1,2} := \text{rnd}(1.0)$ $RD_{i-1,4} := \text{rnd}(1.0)$ $RD_{i-1,6} := \text{rnd}(1.0)$ $RD_{i-1,8} := \text{rnd}(1.0)$

$RD_{i-1,1} := \text{rnd}(1.0)$ $RD_{i-1,3} := \text{rnd}(1.0)$ $RD_{i-1,5} := \text{rnd}(1.0)$ $RD_{i-1,7} := \text{rnd}(1.0)$ $RD_{i-1,9} := \text{rnd}(1.0)$

$RD_{i-1,10} := \text{rnd}(1.0)$ $RD_{i-1,11} := \text{rnd}(1.0)$ $RD_{i-1,12} := \text{rnd}(1.0)$

RKs are matrixes in which the first column contain a permutation on the integers on the interval $[1, n_s]$.

$RK1 := \text{csort}(RD, 1)$ $RK2 := \text{csort}(RD, 2)$ $RK3 := \text{csort}(RD, 3)$ $RK4 := \text{csort}(RD, 4)$

$RK5 := \text{csort}(RD, 5)$ $RK6 := \text{csort}(RD, 6)$ $RK7 := \text{csort}(RD, 7)$ $RK8 := \text{csort}(RD, 8)$

$RK9 := \text{csort}(RD, 9)$ $RK10 := \text{csort}(RD, 10)$ $RK11 := \text{csort}(RD, 11)$ $RK12 := \text{csort}(RD, 12)$

Define sets of random values. Each random value is selected within one of the equiprobable n_s intervals that partition $[0,1]$, one set for each random variable.

$$X^{(0)} := \frac{RK1^{(0)} - 1 + \text{runif}(n_s, 0, 1)}{n_s} \quad X^{(1)} := \frac{RK2^{(0)} - 1 + \text{runif}(n_s, 0, 1)}{n_s} \quad X^{(2)} := \frac{RK3^{(0)} - 1 + \text{runif}(n_s, 0, 1)}{n_s}$$

$$X^{(3)} := \frac{RK4^{(0)} - 1 + \text{runif}(n_s, 0, 1)}{n_s} \quad X^{(4)} := \frac{RK5^{(0)} - 1 + \text{runif}(n_s, 0, 1)}{n_s} \quad X^{(5)} := \frac{RK6^{(0)} - 1 + \text{runif}(n_s, 0, 1)}{n_s}$$

$$X^{(6)} := \frac{RK7^{(0)} - 1 + \text{runif}(n_s, 0, 1)}{n_s} \quad X^{(7)} := \frac{RK8^{(0)} - 1 + \text{runif}(n_s, 0, 1)}{n_s} \quad X^{(8)} := \frac{RK9^{(0)} - 1 + \text{runif}(n_s, 0, 1)}{n_s}$$

$$X^{(9)} := \frac{RK10^{(0)} - 1 + \text{runif}(n_s, 0, 1)}{n_s} \quad X^{(10)} := \frac{RK11^{(0)} - 1 + \text{runif}(n_s, 0, 1)}{n_s} \quad X^{(11)} := \frac{RK12^{(0)} - 1 + \text{runif}(n_s, 0, 1)}{n_s}$$

Calculate a set of sample values for each of the random variables (i.e., seismic exceedance frequency and time to first seismic event.

$i := 0..n_s - 1$

$IE_{S_i} := \text{qunif}(X_{i,0}, IE_l, IE_u)$ **Sample mean annual seismic exceedance frequency**

$T_{S_i} := \text{qunif}(X_{i,9}, T_l, T_u)$ **Sample time (when first seismic event occurred)**

Calculate peak ground velocity based on seismic mean annual frequency.

$$PGV := \text{linterp}(IE_v, PGV_v, \log(IE_s))$$

Drip Shield Damage Due to Seismic Event Only

Calculate drip shield upper bound damage state.

$$DS_{l_i} := \frac{1}{100} \cdot \text{linterp}(PGV_{dsl}, DS_{ld}, PGV_i) \quad DS_{1u_i} := \frac{1}{100} \cdot \text{linterp}(PGV_{dsu}, DS_{ud}, PGV_i)$$

$$DS_{u_i} := \text{if}(DS_{1u_i} \leq 0, 1 \times 10^{-7}, DS_{1u_i})$$

$$DS_{1ds_i} := \text{qunif}(X_{i,1}, DS_{l_i}, DS_{u_i})$$

$$DS_{2ds_i} := \text{if}(DS_{1ds_i} \leq 1 \times 10^{-7}, 0, DS_{1ds_i})$$

$$DS_{ds} := \text{sort}(DS_{2ds}) \quad \text{Sort the drip shield fraction of damage area.}$$

$$CDF_i := \frac{i+1}{n_s} \quad \text{cumulative distribution function}$$

Drip Shield Damage Information

$$\mu_{ds} := \sum_{i=0}^{n_s-1} \frac{DS_{ds_i}}{n_s} \quad \mu_{ds} = 2.234 \times 10^{-3} \quad \text{Mean damage area (fraction of drip shield damaged)}$$

$$\text{linterp}(CDF, DS_{ds}, 0.05) = 0 \quad \text{5th percentile damage area (fraction of drip shield damaged)}$$

$$\text{linterp}(CDF, DS_{ds}, 0.95) = 6.486 \times 10^{-3} \quad \text{95th percentile damage area (fraction of drip shield damaged)}$$

Drip Shield Damage Due to Seismic and Rockfall (Nonlithophysal Only)

$$DS_{1nd} := 0.601 \cdot PGV^{-0.735} \quad \text{Probability of no damage to the drip shield from rockfall}$$

$$DS_{nd_i} := \text{if}(DS_{1nd_i} \geq 1, 1, DS_{1nd_i}) \quad \text{(Maximum value is 1.0)}$$

$$DS_{1drfmd} := 0.00204 PGV^{3.7767} \quad \text{Mode percent failed area of drip shield due to rockfall}$$

$$DS_{drfmin} := 0.001 \quad DS_{drfmax} := 100 \quad \text{Min and max damaged percent of drip shield due to rockfall}$$

$$DS_{drfmd_i} := \text{if}(DS_{1drfmd_i} \leq 1 \times 10^{-3}, 1.001 \times 10^{-3}, DS_{1drfmd_i})$$

Determine which equation to use:

if Random Number < RNtest then use Equation 1 (DSeq1).

if Random Number > RNtest then use Equation 2 (DSeq2).

$$RN_{\text{test}_i} := \frac{(\log(DS_{\text{drfmd}_i}) - \log(DS_{\text{drfmin}}))^2}{(\log(DS_{\text{drfmax}}) - \log(DS_{\text{drfmin}})) \cdot (\log(DS_{\text{drfmd}_i}) - \log(DS_{\text{drfmin}}))}$$

$$DS_{\text{eq1}_i} := \log(DS_{\text{drfmin}}) + \sqrt{X_{i,2} \cdot (\log(DS_{\text{drfmax}}) - \log(DS_{\text{drfmin}})) \cdot (\log(DS_{\text{drfmd}_i}) - \log(DS_{\text{drfmin}}))}$$

$$DS_{\text{eq2}_i} := \log(DS_{\text{drfmax}}) - \sqrt{(1 - X_{i,2}) \cdot (\log(DS_{\text{drfmax}}) - \log(DS_{\text{drfmin}})) \cdot (\log(DS_{\text{drfmax}}) - \log(DS_{\text{drfmd}_i}))}$$

$$DS1_{\text{drf}_i} := \text{if} \left[\left(X_{i,2} \leq RN_{\text{test}_i} \right), DS_{\text{eq1}_i}, DS_{\text{eq2}_i} \right]$$

Percentage of drip shield damaged area due to rockfall

$$DS2_{\text{drf}_i} := 10^{DS1_{\text{drf}_i}}$$

$$DS\%_{\text{drf}_i} := \text{if} \left[\left(X_{i,3} \leq DS_{\text{nd}_i} \right), 0, DS2_{\text{drf}_i} \right]$$

Fraction of drip shield damaged area due to rockfall

$$DS_{\text{drf}_i} := \frac{1}{100} \cdot DS\%_{\text{drf}_i}$$

Total fraction of drip shield damaged area due to seismic event and rockfall

$$DS1_{\text{dnl}} := DS_{\text{drf}} + DS1_{\text{ds}}$$

$$DS_{\text{dnl}_i} := \text{if} \left(DS1_{\text{dnl}_i} \geq 1, 1, DS1_{\text{dnl}_i} \right)$$

$$DS_{\text{nl}} := \text{sort} \left(DS_{\text{dnl}} \right)$$

Drip Shield damage information

$$\mu_{\text{nlds}} := \sum_{i=0}^{n_s-1} \frac{DS_{\text{nl}_i}}{n_s} \quad \mu_{\text{nlds}} = 4.735 \times 10^{-3} \quad \text{Mean damage area (fraction of drip shield damaged)}$$

$$\text{linterp}(\text{CDF}, DS_{\text{nl}}, 0.05) = 9.918 \times 10^{-9} \quad \text{5th percentile damage area (fraction of drip shield damaged)}$$

$$\text{linterp}(\text{CDF}, DS_{\text{nl}}, 0.95) = 1.06 \times 10^{-2} \quad \text{95th percentile damage area (fraction of drip shield damaged)}$$

Rockfall Conversion

Fraction of drip shields damaged due to rockfall

$$n_{rf} := 17110$$

$$\text{frac}_{rf} := \frac{(n_s - 1) - n_{rf}}{n_s}$$

$$\text{frac}_{rf} = 0.144 \quad \text{Fraction of drip shields damaged assuming each realization constitutes a rockfall}$$

Fraction of Damaged Area to Drip Shield From Rockfall Only

$$DS_{rf} := \text{sort}(DS_{drf})$$

Drip shield fraction of damaged area information from rockfall only

$$\mu_{rfd_s} := \sum_{i=0}^{n_s-1} \frac{DS_{drf_i}}{n_s} \quad \mu_{rfd_s} = 2.501 \times 10^{-3} \quad \text{Mean damage area (fraction of drip shield damaged)}$$

$$\text{linterp}(\text{CDF}, DS_{rf}, 0.05) = 0 \quad \text{5th percentile damage area (fraction of drip shield damaged)}$$

$$\text{linterp}(\text{CDF}, DS_{rf}, 0.95) = 1.82 \times 10^{-3} \quad \text{95th percentile damage area (fraction of drip shield damaged)}$$

Waste Package Damage Due to Seismic Event

$$WP_l := 0 \quad WP_{1u} := 0.436 \text{ PGV} - 0.305 \quad \text{Calculate waste package upper bound percent damaged area.}$$

$$WP_{u_i} := \text{if}(WP_{1u_i} \leq 0, 1 \times 10^{-7}, WP_{1u_i}) \quad \text{Sample waste package percent damage between lower (0) and upper (WPu). WPu is set to } 1 \times 10^{-7} \text{ if calculated value is less than zero in order for the uniform distribution to be sampled. Then all damaged areas less than } 1 \times 10^{-7} \text{ are set back to zero. The } 1 \times 10^{-7} \text{ value is determined as being less than the smallest sampled value from WP1u.}$$

$$WP_{1d_i} := \text{qunif}(X_{i,4}, WP_l, WP_{u_i})$$

$$WP_{2d_i} := \text{if}(WP_{1d_i} \leq 1 \times 10^{-7}, 0, WP_{1d_i})$$

$$WP_{3d} := \text{sort}\left(\frac{1}{100} \cdot WP_{2d}\right) \quad \text{Sorted fraction of waste package damaged area.}$$

Waste Package Damage Information

$$\mu_{wp} := \sum_{i=0}^{n_s-1} \frac{WP_{3d_i}}{n_s} \quad \mu_{wp} = 2.577 \times 10^{-4} \quad \text{Mean damage area (fraction of waste package damaged)}$$

$$\text{linterp}(\text{CDF}, WP_{3d}, 0.05) = 0 \quad \text{5th percentile damage area (fraction of waste package damaged)}$$

$$\text{linterp}(\text{CDF}, WP_{3d}, 0.95) = 1.469 \times 10^{-3} \quad \text{95th percentile damage area (fraction of waste package damaged)}$$

Seepage distributions are based on the License Application (LA) seepage abstraction model (BSC [DIRS 165564]). The outputs were fit to Weibull distributions based on the sampling process developed to obtain the seepage rates for the low-, mean-, and upper-glacial transition climate case. The distributions are for both the Tptpl and Tptpmn zones (see Attachment IV). The Tptpl zone uses the collapsed drift seepage rates, while the Tptpmn zone increases the nominal seepage rates by 20 percent.

Tptpl Seepage (Drift Collapse)

$$ST_{l_{ptl}}(r) := 1 - \exp\left[-\left(\frac{r}{8.869 \times 10^{-3}}\right)^{0.52}\right]$$

$$ST_{m_{ptl}}(r) := 1 - \exp\left[-\left(\frac{r}{1.46 \times 10^{-1}}\right)^{0.468}\right]$$

$$ST_{u_{ptl}}(r) := 1 - \exp\left[-\left(\frac{r}{3.83 \times 10^{-1}}\right)^{0.494}\right]$$

Tptpmn Seepage (Degraded Drift)

$$ST_{l_{ptn}}(r) := 1 - \exp\left[-\left(\frac{r}{4.949 \times 10^{-3}}\right)^{0.536}\right]$$

$$ST_{m_{ptn}}(r) := 1 - \exp\left[-\left(\frac{r}{8.559 \times 10^{-2}}\right)^{0.473}\right]$$

$$ST_{u_{ptn}}(r) := 1 - \exp\left[-\left(\frac{r}{2.251 \times 10^{-1}}\right)^{0.501}\right]$$

Boron loss from waste packages based on *Boron Loss from CSNF Waste Packages*(BSC 2003 [DIRS 165890], Section 6).

Input parameters for 21-PWR Absorber Plate waste package are from different sources as listed in Section 5.1 and 6.4.

Corrosion rate of Neutronit is based on 1.5 times the corrosion rate for stainless steel 316 data (see Assumption 5.1.4). The corrosion rate was fit to a Weibull distribution for use in this calculation (see Attachment V). The corrosion rate data for stainless steel 316 can be found in DTN: MO0303SPAMCRAQ.000 [aqueous-316L.xls] (BSC 2003 [DIRS 162353]).

$\alpha_{cr} := 0.314$ Alpha parameter of Weibull distribution

$\beta_{cr} := 3.027$ Beta parameter of Weibull distribution

$cr_{n_i} := \alpha_{cr} \cdot q_{weibull}(X_i, \gamma, \beta_{cr})$ Corrosion rate data fit to a Weibull distribution ($\mu\text{m/yr}$)

$AW := 10.811$ Atomic Weight of boron (g/mole) (see Table 4.1-12)

$n_{21} := 2.06 \times 10^6$ Grams of Neutronit in a 21-PWR Absorber Plate (g) (see Table 6.4-3)

$b_{wf} := 1.245 \times 10^{-2}$ Weight fraction of boron (see Table 6.4-3)

$B_{i_{21}} := \frac{n_{21} \cdot b_{wf}}{AW}$ Initial bor on in a 21-PWR Absorber Plate waste package (moles) (see Table 6.4-3)

$V_{r_{21}} := 4.69 \times 10^3$ Volume of a 21-PWR Absorber Plate (liter) (see Table 5.1-1 [Assumption 5.1.2])

$SA_{21} := 5.29 \times 10^5$ Surface area of Neutronit in a 21-PWR Absorber Plate (cm^2) (see Table 5.1-1 [Assumption 5.1.2])

$con := 1 \times 10^{-4}$ **cm/ μ m conversion factor**

$\rho_{316} := 8$ **Density of stainless steel 316 g/cm³ (see Table 4.1-12)**

$k_{21_i} := cr_{n_1} \cdot \rho_{316} con$ **Degradation rate of Neutronit in moles for a 21-PWR Absorber Plate (g/cm²*yr) (see Table 6.4-3)**

$T1_{s_i} := \text{if}(T_{s_i} < 700, 700, T_{s_i})$ **Assume no water can penetrate the waste package prior to 700 years due to evaporation from the decay heat generation (see Assumption 5.2.2).**

$tdeg_{21_i} := \left(\frac{n_{21}}{k_{21_i} SA_{21}} \right) + T1_{s_i}$ **Time required to degrade all of the Neutronit from a 21-PWR Absorber Plate (years) (see Table 6.4-3)**

$D_{21_i} := \left(\frac{Bi_{21}}{tdeg_{21_i}} \right)$ **Moles of boron released from Neutronit per year (moles/yr) (see Table 6.4-3)**

Develop the time available for boron to degrade and flush from waste package. This time is based on the occurrence of the first seismic event up to the regulatory period. If the time to degrade the Neutronit is longer than the delta time (regulatory period minus time of seismic event), then it is set to the regulatory period and delta time becomes zero.

$t1_i := 10000 - T1_{s_i}$

$t_{21_i} := \text{if}(t1_i < tdeg_{21_i}, tdeg_{21_i}, t1_i)$

$per_B := 0.1$ **fraction of boron remaining in a PWR waste package (10 percent) (see Assumption 5.1.5)**

$B_{21loss} := per_B \cdot Bi_{21}$ $B_{21loss} = 237.231$

$A_i := \text{if}(tdeg_{21_i} \geq 10000, 0, \text{if}(tdeg_{21_i} = t_{21_i}, 0, 1))$ **Parameters required to solve the boron loss equation when the time to degrade is longer than the regulatory period of 10,000 years**

$C_i := \text{if}(tdeg_{21_i} \geq 10000, 1, \text{if}(tdeg_{21_i} = t_{21_i}, 1, 0))$

$E_i := \text{if}(tdeg_{21_i} \geq 10000, 10000, \text{if}(tdeg_{21_i} = t_{21_i}, 10000, 1))$

Boron Loss Equation (BSC 2003 [DIRS 165890], Section 6)

$$NB_{21}(v_{21}, i) := v_{21} \cdot C_i + \left[A_i \cdot \left[\frac{(V_{r21} \cdot D_{21_i,0})}{v_{21}} \right] \cdot \left(1 - \exp\left(-tdeg_{21_i,0} \cdot \frac{v_{21}}{V_{r21}}\right) \right) \cdot \exp\left[\frac{-v_{21} \cdot (t_{21_i,0} - tdeg_{21_i,0})}{V_{r21}}\right] \right] - B_{21loss} \cdot E_i$$

$V_{21_{dr_i}} := \text{root}(NB_{21}(v_{21}, i), v_{21}, 1 \times 10^{-11}, 1 \times 10^{11})$

$req_{21_{dr}} := \frac{V_{21_{dr}}}{1000}$ **Required drip rate (m³/yr) into a 21-PWR Absorber Plate waste package to degrade and flush out the boron based on sampled corrosion rate and time to first seismic event**

The following is the equation used to calculate the probability that the seepage rate can be at or greater than the seepage noted as z_{21} (for lithophysal) and $z1_{21}$ (for nonlithophysal). This seepage is based on the seepage rate making it through the damaged areas of the drip shield and waste package. The drip rate value is based on sampling the corrosion rate of Neutronit and sampling the time to first seismic occurrence, which determines the time to degrade and flush out the Neutronit from a 21-PWR Absorber Plate Waste Package for criticality potential.

$$z_{21_i} := \frac{req_{21dr_i}}{\left(\frac{1}{100} \cdot WP1_{d_i}\right) \cdot DS1_{ds_i}} \quad \mathbf{z_{21} \text{ is amount of seepage rate (m}^3/\text{yr) required to reach the drift for lithophysal zone}}$$

$$z1_{21_i} := \frac{req_{21dr_i}}{\left[\left(\frac{1}{100} \cdot WP1_{d_i}\right) \cdot DS_{dnl_i}\right]} \quad \mathbf{z1_{21} \text{ is amount of seepage rate (m}^3/\text{yr) required to reach the drift for nonlithophysal zone}}$$

Lithophysal Zone

Nonlithophysal Zone

Tptpll Seepage (Collapsed Drift)

Tptpmn Seepage (Degraded Drift)

$$STl_{ptl}(r) := 1 - \exp\left[-\left(\frac{r}{8.869 \times 10^{-3}}\right)^{0.52}\right]$$

$$STl_{ptn}(r) := 1 - \exp\left[-\left(\frac{r}{4.949 \times 10^{-3}}\right)^{0.536}\right]$$

$$STm_{ptl}(r) := 1 - \exp\left[-\left(\frac{r}{1.46 \times 10^{-1}}\right)^{0.468}\right]$$

$$STm_{ptn}(r) := 1 - \exp\left[-\left(\frac{r}{8.559 \times 10^{-2}}\right)^{0.473}\right]$$

$$STu_{ptl}(r) := 1 - \exp\left[-\left(\frac{r}{3.83 \times 10^{-1}}\right)^{0.494}\right]$$

$$STu_{ptn}(r) := 1 - \exp\left[-\left(\frac{r}{2.251 \times 10^{-1}}\right)^{0.501}\right]$$

$$Q21_{spl_i} := 1 - STl_{ptl}(z_{21_i})$$

$$Q21_{spn_i} := 1 - STl_{ptn}(z1_{21_i})$$

$$Q21_{mspl_i} := 1 - STm_{ptl}(z_{21_i})$$

$$Q21_{mspn_i} := 1 - STm_{ptn}(z1_{21_i})$$

$$Q21_{uspl_i} := 1 - STu_{ptl}(z_{21_i})$$

$$Q21_{uspn_i} := 1 - STu_{ptn}(z1_{21_i})$$

The probability of being in the low-, mean- or upper-infiltration scenario for the glacial transition climate is 0.24, 0.41, and 0.35, respectively (BSC 2003 [DIRS 165991], Section 7, Table 7-1).

$$Q21_{sfl_i} := \text{if}\left(X_{i,5} \leq 0.24, Q21_{spl_i} \cdot 0.194, \text{if}\left(0.24 \leq X_{i,5} \leq 0.65, Q21_{mspl_i} \cdot 0.514, Q21_{uspl_i} \cdot 0.637\right)\right)$$

$$Q21_{sfn_i} := \text{if}\left(X_{i,5} \leq 0.24, Q21_{spn_i} \cdot 0.154, \text{if}\left(0.24 \leq X_{i,5} \leq 0.65, Q21_{mspn_i} \cdot 0.524, Q21_{uspn_i} \cdot 0.672\right)\right)$$

The probability of the seismic event causing sufficient damage to allow advective flow to penetrate, degrade, and flush out the Neutronit from a 21-PWR Absorber Plate waste package is calculated using the equations below for both lithophysal and nonlithophysal. The equations are based on the sampling of the probability of sufficient advective flow given a seismic event with magnitude, v , at time, t . This probability will be fed into top event MS-IC-1 of the SAPHIRE model (Section 6.4.2) for seismic event. The probability of a seismic event will be set to 1.0 in the SAPHIRE model since it is accounted for in this calculation.

Lithophysal Zone

$$Pr21_{sfl} := \frac{[(T_u - T_l) \cdot (IE_u - IE_l)]}{n_s} \cdot \sum_{i=0}^{n_s-1} Q21_{sfl_i} \cdot (1 - X_{i,7})$$

$Pr21_{sfl} = 0$ **Mean probability**

Equations based on Equation 6.4-6 of main report, DTN:MO0308SPACALSS.002 (BSC 2003 [DIRS 164822]) and *Seismic Consequence Abstraction* (BSC 2003 [DIRS 161812], Attachment VIII, Eq. VIII.2.11).

Nonlithophysal Zone

$$Pr21_{sfnl} := \frac{[(T_u - T_l) \cdot (IE_u - IE_l)]}{n_s} \cdot \sum_{i=0}^{n_s-1} Q21_{sfnl_i} \cdot (1 - X_{i,7})$$

$Pr21_{sfnl} = 0$ **Mean probability**

Boron loss from waste packages based on *Boron Loss from CSNF Waste Packages* (BSC 2003 [DIRS 165890], Section 6).

Input parameters for 12-PWR Absorber Plate Long waste package are from different sources as listed in Section 5.1 and 6.4.

$n_{12} := 1.15 \times 10^6$ **Grams of Neutronit in a 12-PWR Absorber Plate Long (g) (see Table 6.4-4)**

$Bi_{12} := \frac{n_{12} \cdot b_{wf}}{AW}$ **Initial boron in a 12-PWR Absorber Plate Long (moles) (see Table 6.4-4)**

$Vr_{12} := 3.32 \times 10^3$ **Volume of a 12-PWR Absorber Plate Long (liter) (see Table 5.1-1 [Assumption 5.1.2])**

$SA_{12} := 3.19 \times 10^5$ **Surface area of Neutronit in a 12-PWR Absorber Plate Long (cm²) (see Table 5.1-1 [Assumption 5.1.2])**

$k_{12_i} := cr_{n_i} \cdot \rho_{316}^{con}$ **Degradation rate of Neutronit in moles for a 12-PWR Absorber Plate Long (g/cm²*yr) (see Table 6.4-4)**

$T1_{s_i} := \text{if}(T_{s_i} < 700, 700, T_{s_i})$ **Assume no water can penetrate the waste package prior to 700 years due to evaporation from the decay heat generation (see Assumption 5.2.2).**

$t^{deg}_{12_i} := \left(\frac{n_{12}}{k_{12_i} \cdot SA_{12}} \right) + T1_{s_i}$ **Time required to degrade all of the Neutronit from a 12-PWR Absorber Plate Long (year) (see Table 6.4-4)**

$$D_{12_i} := \left(\frac{Bi_{12}}{tdeg_{12_i}} \right) \quad \text{Moles of boron release from Neutronit per year (moles/yr)} \\ \text{(see Table 6.4-4)}$$

Develop the time available for boron to degrade and flush from waste package. This time is based on the occurrence of the first seismic event up to the regulatory period. If the time to degrade the Neutronit is longer than the delta time (regulatory period minus time of seismic event), then it is set to the regulatory period and delta time becomes zero.

$$t1_i := 10000 - T1_{s_i}$$

$$t_{12_i} := \text{if}(t1_i < tdeg_{12_i}, tdeg_{12_i}, t1_i)$$

Fraction of boron remaining in a PWR waste package (10 percent) (see Assumption 5.1.5)

$$B_{12loss} := \text{per}_B \cdot Bi_{12} \quad B_{12loss} = 132.435$$

$$A_i := \text{if}(tdeg_{12_i} \geq 10000, 0, \text{if}(tdeg_{12_i} = t_{12_i}, 0, 1)) \quad \text{Parameters required to solve the boron loss equation when the time to degrade is longer than the regulatory period of 10,000 years.}$$

$$C_i := \text{if}(tdeg_{12_i} \geq 10000, 1, \text{if}(tdeg_{12_i} = t_{12_i}, 1, 0))$$

$$E_i := \text{if}(tdeg_{12_i} \geq 10000, 10000, \text{if}(tdeg_{12_i} = t_{12_i}, 10000, 1))$$

Boron Loss Equation (BSC 2003 [DIRS 165890] Section 6)

$$NB_{12}(v_{12}, i) := v_{12} \cdot C_i + \left[A_i \cdot \left[\frac{(V_{r12} \cdot D_{12_i,0})}{v_{12}} \right] \cdot \left(1 - \exp\left(-tdeg_{12_i,0} \cdot \frac{v_{12}}{V_{r12}}\right) \right) \cdot \exp\left[\frac{-v_{12} \cdot (t_{12_i,0} - tdeg_{12_i,0})}{V_{r12}}\right] - B_{12loss} \cdot E_i \right]$$

$$V_{12dr_i} := \text{root}(NB_{12}(v_{12}, i), v_{12}, 1 \times 10^{-11}, 1 \times 10^{11})$$

$$\text{req}_{12dr} := \frac{V_{12dr}}{1000} \quad \text{Required drip rate (m}^3\text{/yr) into a 12-PWR Absorber Plate Long waste package to degrade and flush out the boron based on sampled corrosion and time to first seismic event.}$$

The following is the equation used to calculate the probability that the seepage rate can be at or greater than the seepage noted as z_{12} (for lithophysal) and $z1_{12}$ (for nonlithophysal). This seepage is based on the seepage rate making it through the damaged areas of the drip shield and waste package. The drip rate value is based on sampling the corrosion rate of Neutronit and sampling the time to first seismic occurrence, which determines the time to degrade and flush out the Neutronit from a 12-PWR Absorber Plate Long waste package for criticality potential.

$$z_{12_i} := \frac{\text{req}_{12dr_i}}{\left(\frac{1}{100} \cdot WP1_{d_i} \right) \cdot DS1_{ds_i}} \quad z_{12} \text{ is amount of seepage rate (m}^3\text{/yr) required to reach the drift for lithophysal zone}$$

$$z1_{12_i} := \frac{req_{12dr_i}}{\left[\left(\frac{1}{100} \cdot WP1_{d_i} \right) \cdot DS_{dnl_i} \right]}$$

z1₁₂ is amount of seepage rate (m³/yr) required to reach the drift for nonlithophysal zone

Lithophysal Zone

Nonlithophysal Zone

$$Q12_{spl_i} := 1 - STl_{ptl}(z1_{12_i})$$

$$Q12_{spn_i} := 1 - STl_{ptn}(z1_{12_i})$$

$$Q12_{m_{spl_i}} := 1 - STm_{ptl}(z1_{12_i})$$

$$Q12_{m_{spn_i}} := 1 - STm_{ptn}(z1_{12_i})$$

$$Q12_{u_{spl_i}} := 1 - STu_{ptl}(z1_{12_i})$$

$$Q12_{u_{spn_i}} := 1 - STu_{ptn}(z1_{12_i})$$

The probability of being in the low-, mean- or upper-infiltration scenario for the glacial transition climate is 0.24, 0.41, and 0.35, respectively (BSC 2003 [DIRS 165991], Section 7, Table 7-1).

$$Q12_{sfl_i} := \text{if}(X_{i,5} \leq 0.24, Q12_{spl_i} \cdot 0.194, \text{if}(0.24 \leq X_{i,5} \leq 0.65, Q12_{m_{spl_i}} \cdot 0.514, Q12_{u_{spl_i}} \cdot 0.637))$$

$$Q12_{sfn_i} := \text{if}(X_{i,5} \leq 0.24, Q12_{spn_i} \cdot 0.154, \text{if}(0.24 \leq X_{i,5} \leq 0.65, Q12_{m_{spn_i}} \cdot 0.524, Q12_{u_{spn_i}} \cdot 0.672))$$

The probability of the seismic event causing sufficient damage to allow advective flow to penetrate, degrade, and flush out the Neutronit from a 12-PWR Absorber Plate Long waste package is calculated using the equations below for both lithophysal and nonlithophysal. The equations are based on the sampling of the probability of sufficient advective flow given a seismic event with magnitude, v, at time, t. This probability will be fed into top event MS-IC-1 of the SAPHIRE model (Section 6.4.2) for seismic event. The probability of a seismic event will be set to 1.0 in the SAPHIRE model since it is accounted for in this calculation.

Lithophysal Zone

$$Pr12_{sfl} := \frac{[(T_u - T_l) \cdot (IE_u - IE_l)]}{n_s} \cdot \sum_{i=0}^{n_s-1} Q12_{sfl_i} \cdot (1 - X_{i,7})$$

Pr12_{sfl} = 0 **Mean probability**

Nonlithophysal Zone

$$Pr12_{sfnl} := \frac{[(T_u - T_l) \cdot (IE_u - IE_l)]}{n_s} \cdot \sum_{i=0}^{n_s-1} Q12_{sfnl_i} \cdot (1 - X_{i,7})$$

Pr12_{sfnl} = 0 **Mean probability**

Equations based on Equation 6.4-6 of main report, DTN:MO0308SPACALSS.002 (BSC 2003 [DIRS 164822]) and Seismic Consequence Abstraction (BSC 2003 [DIRS 161812], Attachment VIII, Eq. VIII.2.11).

Boron loss from waste packages based on *Boron Loss from CSNF Waste Packages*(BSC 2003 [DIRS 165890], Section 6).

Input parameters for 44-BWR Absorber Plate waste package are from different sources as listed in Section 5.1 and 6.4 .

$$n_{44} := 2.15 \times 10^6 \quad \text{Grams of Neutronit in a 44-BWR Absorber Plate (g) (see Table 6.4-5)}$$

$$Bi_{44} := \frac{n_{44} \cdot b_{wf}}{AW} \quad \text{Initial boron in a 44-BWR Absorber Plate (moles) (see Table 6.4-5)}$$

$$V_{r44} := 4.85 \times 10^3 \quad \text{Volume of a 44-BWR Absorber Plate (liter) (see Table 5.1-1 [Assumption 5.1.2])}$$

$$SA_{44} := 9.55 \times 10^5 \quad \text{Surface area of Neutronit in a 44-BWR Absorber Plate (cm}^2\text{) (see Table 5.1-1 [Assumption 5.1.2])}$$

$$k_{44_i} := cr_{n_i} \cdot \rho_{316}^{con} \quad \text{Degradation rate of Neutronit in moles for a 44-BWR Absorber Plate (g/cm}^2\text{*yr) (see Table 6.4-5)}$$

$$T1_{s_i} := \text{if}(T_{s_i} < 700, 700, T_{s_i}) \quad \text{Assume no water can penetrate the waste package prior to 700 years due to evaporation from the decay heat generation (see Assumption 5.2.2).}$$

$$t_{deg_{44_i}} := \left(\frac{n_{44}}{k_{44_i} \cdot SA_{44}} \right) + T1_{s_i} \quad \text{Time required to degrade all of the Neutronit from a 44-BWR Absorber Plate (years) (see Table 6.4-5)}$$

$$D_{44_i} := \left(\frac{Bi_{44}}{t_{deg_{44_i}}} \right) \quad \text{Moles of boron release from Neutronit per year (moles/yr) (see Table 6.4-5)}$$

Develop the time available for boron to degrade and flush from waste package. This time is based on the occurrence of the first seismic event up to the regulatory period. If the time to degrade the Neutronit is longer than the delta time (regulatory period minus time of seismic event), then it is set to the regulatory period and delta time becomes zero.

$$t1_i := 10000 - T1_{s_i}$$

$$t_{44_i} := \text{if}(t1_i < t_{deg_{44_i}}, t_{deg_{44_i}}, t1_i)$$

$$\text{per}_{BB} := 0.5 \quad \text{Fraction of boron remaining in a BWR waste package (50 percent) (see Assumption 5.1.5)}$$

$$B_{44loss} := \text{per}_{BB} \cdot Bi_{44} \quad B_{44loss} = 1.238 \times 10^3$$

$$A_i := \text{if}(t_{deg_{44_i}} \geq 10000, 0, \text{if}(t_{deg_{44_i}} = t_{44_i}, 0, 1)) \quad \text{Parameters required to solve the boron loss equation when the time to degrade is longer than the regulatory period of 10,000 years}$$

$$C_i := \text{if}(t_{deg_{44_i}} \geq 10000, 1, \text{if}(t_{deg_{44_i}} = t_{44_i}, 1, 0))$$

$$E_i := \text{if}(t_{deg_{44_i}} \geq 10000, 10000, \text{if}(t_{deg_{44_i}} = t_{44_i}, 10000, 1))$$

Boron Loss Equation (BSC 2003 [DIRS 165890], Section 6)

$$NB_{44}(v_{44}, i) := v_{44} \cdot C_i + \left[A_i \cdot \left[\frac{(V_{r44} \cdot D_{44,i,0})}{v_{44}} \right] \cdot \left(1 - \exp \left(-t_{deg_{44,i,0}} \cdot \frac{v_{44}}{V_{r44}} \right) \right) \cdot \exp \left[\frac{-v_{44} \cdot (t_{44,i,0} - t_{deg_{44,i,0}})}{V_{r44}} \right] \right] - B_{44loss} \cdot E_i$$

$$V_{44,dr_i} := \text{root} \left(NB_{44}(v_{44}, i), v_{44}, 1 \times 10^{-11}, 1 \times 10^{11} \right)$$

$$req_{44dr} := \frac{V_{44,dr}}{1000} \quad \text{Required drip rate (m}^3\text{/yr) into a 44-BWR Absorber Plate waste package to degrade and flush out the boron based on sampled corrosion and time to first seismic event}$$

The following is the equation used to calculate the probability that the seepage rate can be at or greater than the seepage noted as z_{44} (for lithophysal) and $z1_{44}$ (for nonlithophysal). This seepage is based on the seepage rate making it through the damaged areas of the drip shield and waste package. The drip rate value is based on sampling the corrosion rate of Neutronit and sampling the time to first seismic occurrence, which determines the time to degrade and flush out the Neutronit from a 44-BWR Absorber Plate waste package for criticality potential.

$$z_{44_i} := \frac{req_{44dr_i}}{\left(\frac{1}{100} \cdot WP1_{d_i} \right) \cdot DS1_{ds_i}} \quad \text{z}_{44} \text{ is amount of seepage rate (m}^3\text{/yr) required to reach the drift for lithophysal zone}$$

$$z1_{44_i} := \frac{req_{44dr_i}}{\left[\left(\frac{1}{100} \cdot WP1_{d_i} \right) \cdot DS_{dnl_i} \right]} \quad \text{z1}_{44} \text{ is amount of seepage rate (m}^3\text{/yr) required to reach the drift for nonlithophysal zone}$$

Lithophysal Zone

$$Q_{44l_{spl_i}} := 1 - STl_{ptl}(z_{44_i})$$

$$Q_{44m_{spl_i}} := 1 - STm_{ptl}(z_{44_i})$$

$$Q_{44u_{spl_i}} := 1 - STu_{ptl}(z_{44_i})$$

Nonlithophysal Zone

$$Q_{44l_{spn_i}} := 1 - STl_{ptn}(z1_{44_i})$$

$$Q_{44m_{spn_i}} := 1 - STm_{ptn}(z1_{44_i})$$

$$Q_{44u_{spn_i}} := 1 - STu_{ptn}(z1_{44_i})$$

The probability of being in the low-, mean- or upper-infiltration scenario for the glacial transition climate is 0.24, 0.41, and 0.35, respectively (BSC 2003 [DIRS 165991], Section 7, Table 7-1).

$$Q_{44sfl_i} := \text{if} \left(X_{i,5} \leq 0.24, Q_{44l_{spl_i}} \cdot 0.194, \text{if} \left(0.24 \leq X_{i,5} \leq 0.65, Q_{44m_{spl_i}} \cdot 0.514, Q_{44u_{spl_i}} \cdot 0.637 \right) \right)$$

$$Q_{44sfn_i} := \text{if} \left(X_{i,5} \leq 0.24, Q_{44l_{spn_i}} \cdot 0.154, \text{if} \left(0.24 \leq X_{i,5} \leq 0.65, Q_{44m_{spn_i}} \cdot 0.524, Q_{44u_{spn_i}} \cdot 0.672 \right) \right)$$

The probability of the seismic event causing sufficient damage to allow advective flow to penetrate, degrade, and flush out the Neutronit from a 44-BWR Absorber Plate waste package is calculated using the equations below for both lithophysal and nonlithophysal. The equations are based on the sampling of the probability of sufficient advective flow given a seismic event with magnitude, v , at time, t . This probability will be fed into top event MS-IC-1 of the SAPHIRE model (Section 6.4.2) for seismic event. The probability of a seismic event will be set to 1.0 in the SAPHIRE model since it is accounted for in this calculation.

Lithophysal Zone

$$Pr_{44_sfl} := \frac{[(T_u - T_l) \cdot (IE_u - IE_l)]}{n_s} \cdot \sum_{i=0}^{n_s-1} Q_{44_sfl_i} \cdot (1 - X_{i,7})$$

$Pr_{44_sfl} = 1.525 \times 10^{-6}$ **Mean probability**

Equations based on Equation 6.4-6 of main report, DTN:MO0308SPACALSS.002 (BSC 2003 [DIRS 164822]) and *Seismic Consequence Abstraction* (BSC 2003 [DIRS 161812], Attachment VIII, Eq. VIII.2.11).

Nonlithophysal Zone

$$Pr_{44_sfnl} := \frac{[(T_u - T_l) \cdot (IE_u - IE_l)]}{n_s} \cdot \sum_{i=0}^{n_s-1} Q_{44_sfnl_i} \cdot (1 - X_{i,7})$$

$Pr_{44_sfnl} = 9.74 \times 10^{-7}$ **Mean probability**

Boron loss from waste packages based on *Boron Loss from CSNF Waste Packages* (BSC 2003 [DIRS 165890], Section 6).

Input parameters for 24-BWR Absorber Plate waste package are from different sources as listed in Section 5.1 and 6.4 .

$n_{24} := 2.63 \times 10^6$ **Grams of Neutronit in a 24-BWR Absorber Plate (g) (see Table 6.4-6)**

$Bi_{24} := \frac{n_{24} \cdot b_{wf}}{AW}$ **Initial boron in a 24-BWR Absorber Plate (moles) (see Table 6.4-6)**

$V_{r24} := 2.64 \times 10^3$ **Volume of a 24-BWR Absorber Plate (liter) (see Table 5.1-1 [Assumption 5.1.2])**

$SA_{24} := 6.93 \times 10^5$ **Surface area of Neutronit in a 24-BWR Absorber Plate (cm²) (see Table 5.1-1 [Assumption 5.1.2])**

$k_{24_i} := cr_{n_i} \cdot \rho_{316}^{con}$ **Degradation rate of Neutronit in moles for a 24-BWR Absorber Plate (g/cm²*yr) (see Table 6.4-6)**

$T1_{s_i} := \text{if}(T_{s_i} < 700, 700, T_{s_i})$ **Assume no water can penetrate the waste package prior to 700 years due to evaporation from the decay heat generation (see Assumption 5.2.2)**

$t_{deg\ 24_i} := \left(\frac{n_{24}}{k_{24_i} \cdot SA_{24}} \right) + T1_{s_i}$ **Time required to degrade all of the Neutronit from a 24-BWR Absorber Plate (years) (see Table 6.4-6)**

$D_{24_i} := \left(\frac{Bi_{24}}{t_{deg\ 24_i}} \right)$ **Moles of boron release from Neutronit per year (moles/yr) (see Table 6.4-6)**

Develop the time available for boron to degrade and flush from waste package. This time is based on the occurrence of the first seismic event up to the regulatory period. If the time to degrade the Neutronit is longer than the delta time (regulatory period minus time of seismic event), then it is set to the regulatory period and delta time becomes zero.

$$t1_i := 10000 - T1_{s_i}$$

$$t24_i := \text{if}(t1_i < tdeg_{24_i}, tdeg_{24_i}, t1_i)$$

Fraction of boron remaining in a BWR waste package (50 percent) (see Assumption 5.1.5)

$$B_{24\text{loss}} := \text{per}_{\text{BB}} \cdot B_{i24} \quad B_{24\text{loss}} = 1.514 \times 10^3$$

$$A_i := \text{if}(tdeg_{24_i} \geq 10000, 0, \text{if}(tdeg_{24_i} = t24_i, 0, 1))$$

Parameters required to solve the boron loss equation when the time to degrade is longer than the regulatory period of 10,000 years

$$C_i := \text{if}(tdeg_{24_i} \geq 10000, 1, \text{if}(tdeg_{24_i} = t24_i, 1, 0))$$

$$E_i := \text{if}(tdeg_{24_i} \geq 10000, 10000, \text{if}(tdeg_{24_i} = t24_i, 10000, 1))$$

Boron Loss Equation (BSC 2003 [DIRS 165890], Section 6)

$$NB_{24}(v24, i) := v24 \cdot C_i + \left[A_i \cdot \left[\frac{(V_{r24} \cdot D_{24_i,0})}{v24} \right] \cdot \left(1 - \exp\left(-tdeg_{24_i,0} \cdot \frac{v24}{V_{r24}}\right) \right) \cdot \exp\left[\frac{-v24 \cdot (t24_{i,0} - tdeg_{24_i,0})}{V_{r24}}\right] \right] - B_{24\text{loss}} \cdot E_i$$

$$V_{24\text{dr}_i} := \text{root}(NB_{24}(v24, i), v24, 1 \times 10^{-11}, 1 \times 10^{11})$$

$$\text{req}_{24\text{dr}} := \frac{V_{24\text{dr}}}{1000}$$

Required drip rate (m³/yr) into a 24-BWR Absorber Plate waste package to degrade and flush out the boron based on sampled corrosion and time to first seismic event.

The following is the equation used to calculate the probability that the seepage rate can be at or greater than the seepage noted as z₂₄ (for lithophysal) and z1₂₄ (for nonlithophysal). This seepage is based on the seepage rate making it through the damaged areas of the drip shield and waste package. The drip rate value is based on sampling the corrosion rate of Neutronit and sampling the time to first seismic occurrence, which determines the time to degrade and flush out the Neutronit from a 24-BWR Absorber Plate waste package for criticality potential.

$$z_{24_i} := \frac{\text{req}_{24\text{dr}_i}}{\left(\frac{1}{100} \cdot \text{WP1}_{d_i}\right) \cdot \text{DS1}_{d_{s_i}}}$$

z₂₄ is amount of seepage rate (m³/yr) required to reach the drift for lithophysal zone

$$z1_{24_i} := \frac{\text{req}_{24\text{dr}_i}}{\left[\left(\frac{1}{100} \cdot \text{WP1}_{d_i}\right) \cdot \text{DS}_{\text{dnl}_i}\right]}$$

z1₂₄ is amount of seepage rate (m³/yr) required to reach the drift for nonlithophysal zone

Lithophysal Zone

$$Q24l_{spl_i} := 1 - STl_{ptl}(z24_i)$$

$$Q24m_{spl_i} := 1 - STm_{ptl}(z24_i)$$

$$Q24u_{spl_i} := 1 - STu_{ptl}(z24_i)$$

Nonlithophysal Zone

$$Q24l_{spn_i} := 1 - STl_{ptn}(z124_i)$$

$$Q24m_{spn_i} := 1 - STm_{ptn}(z124_i)$$

$$Q24u_{spn_i} := 1 - STu_{ptn}(z124_i)$$

The probability of being in the low-, mean- or upper-infiltration scenario for the glacial transition climate is 0.24, 0.41, and 0.35, respectively (BSC 2003 [DIRS 165991], Section 7, Table 7-1).

$$Q24_{sfl_i} := \text{if}(X_{i,5} \leq 0.24, Q24l_{spl_i} \cdot 0.194, \text{if}(0.24 \leq X_{i,5} \leq 0.65, Q24m_{spl_i} \cdot 0.514, Q24u_{spl_i} \cdot 0.637))$$

$$Q24_{sfn_i} := \text{if}(X_{i,5} \leq 0.24, Q24l_{spn_i} \cdot 0.154, \text{if}(0.24 \leq X_{i,5} \leq 0.65, Q24m_{spn_i} \cdot 0.524, Q24u_{spn_i} \cdot 0.672))$$

The probability of the seismic event causing sufficient damage to allow advective flow to penetrate, degrade, and flush out the Neutronit from a 24-BWR Absorber Plate waste package is calculated using the equations below for both lithophysal and nonlithophysal. The equations are based on the sampling of the probability of sufficient advective flow given a seismic event with magnitude, v , at time, t . This probability will be fed into top event MS-IC-1 of the SAPHIRE model (Section 6.4.2) for seismic event. The probability of a seismic event will be set to 1.0 in the SAPHIRE model since it is accounted for in this calculation.

Lithophysal Zone

$$Pr24_{sfl} := \frac{[(T_u - T_l) \cdot (IE_u - IE_l)]}{n_s} \cdot \sum_{i=0}^{n_s-1} Q24_{sfl_i} \cdot (1 - X_{i,7})$$

$Pr24_{sfl} = 0$ **Mean probability**

Equations based on Equation 6.4-6 of main report, DTN:MO0308SPACALSS.002 (BSC 2003 [DIRS 164822]) and *Seismic Consequence Abstraction*(BSC 2003 [DIRS 161812], Attachment VIII, Eq. VIII.2.11).

Nonlithophysal Zone

$$Pr24_{sfnl} := \frac{[(T_u - T_l) \cdot (IE_u - IE_l)]}{n_s} \cdot \sum_{i=0}^{n_s-1} Q24_{sfnl_i} \cdot (1 - X_{i,7})$$

$Pr24_{sfnl} = 0$ **Mean probability**

Final Results of Seismic Base Case

Probability Calculation using the following assumptions :

- Corrosion rate of Neutronit assumed to be 1.5 times the corrosion rate of stainless steel 316, which was fit to a Weibull distribution (Assumption 5.1.4)
- Flushing out 90 percent of the boron from the PWR waste package types (Assumption 5.1.5)
- Flushing out 50 percent of the boron from the BWR waste package types (Assumption 5.1.5)
- No water ingress into a waste package prior to 700 years (Assumption 5.2.2)

The following are the final calculated probabilities of having a seepage rate equal to or greater than $z_{\#}$ (required) along with a corrosion rate of Neutronit equal to or greater than cr_n given a seismic event for the different waste package types in the different repository zones.

Lithophysal Zone

Nonlithophysal Zone

21-PWR Absorber Plate waste package

$$Pr_{21_{sfl}} = 0 \quad (\text{see p. III-13})$$

$$Pr_{21_{sfnl}} = 0 \quad (\text{see p. III-13})$$

12-PWR Absorber Plate Long waste package

$$Pr_{12_{sfl}} = 0 \quad (\text{see p. III-15})$$

$$Pr_{12_{sfnl}} = 0 \quad (\text{see p. III-15})$$

44-BWR Absorber Plate waste package

$$Pr_{44_{sfl}} = 1.525 \times 10^{-6} \quad (\text{see p. III-18})$$

$$Pr_{44_{sfnl}} = 9.74 \times 10^{-7} \quad (\text{see p. III-18})$$

24-BWR Absorber Plate waste package

$$Pr_{24_{sfl}} = 0 \quad (\text{see p. III-20})$$

$$Pr_{24_{sfnl}} = 0 \quad (\text{see p. III-20})$$

III.2 SEISMIC SENSITIVITY CASE ANALYSIS

The seismic sensitivity case analysis is identical to the seismic base case analysis of Section III.1 with the exception that it is assumed that the neutron absorber plate thickness of the 44-BWR Waste Package is increased from 5 mm to 7 mm. A 7 mm plate thickness is identical to the design of the 21-PWR with Absorber Plates and the 12-PWR Long waste packages types, but is less than the absorber plate thickness of the 24-BWR Waste Package design. The information contained in this section was obtained from the “Attachment III.mcd” Mathcad file of Attachment VII.

Seismic Sensitivity Case Analysis (Increase Neutronit plate thickness of the 44-BWR Absorber Plate waste package)

Boron loss from waste packages is based on *Boron Loss from CSNF Waste Packages*(BSC 2003 [DIRS 165890], Section 6).

Input parameters from DTN: MO0309SPABRNAM.001 [DIRS 165892] for 44-BWR Absorber Plate waste package, except the Neutronit plate thickness is increased to 7 mm for a sensitivity analysis (see Section 6.4 for discussion).

$$nt_{44} := 3.152 \times 10^6 \quad \text{Grams of Neutronit in a 44-BWR (g)}$$

$$Bit_{44} := \frac{nt_{44} \cdot b_{wf}}{AW} \quad \text{Initial boron in a 44-BWR Absorber Plate (moles)}$$

$$V_{r44} := 4.85 \times 10^3 \quad \text{Volume of a 44-BWR Absorber Plate (liter)}$$

$$SA_{t44} := 9.837 \times 10^5 \quad \text{Surface area of neutronit in a 44-BWR Absorber Plate (cm}^2\text{)}$$

$$k_{44_1} := cr_{n_1} \cdot p_{316} \cdot con \quad \text{Degradation rate of Neutronit in moles for a 44-BWR Absorber Plate (g/cm}^2\text{*yr)}$$

$$T1_{s_i} := \text{if}(T_{s_i} < 700, 700, T_{s_i}) \quad \text{Assume no water can penetrate the waste package prior to 700 years due to evaporation from the decay heat generation (see Assumption 5.2.2)}$$

$$t_{degt_{44_1}} := \left(\frac{nt_{44}}{k_{44_1} \cdot SA_{t44}} \right) + T1_{s_i} \quad \text{Time required to degrade all of the Neutronit in a 44-BWR Absorber Plate (years)}$$

$$Dt_{44_1} := \left(\frac{Bit_{44}}{t_{degt_{44_1}}} \right) \quad \text{Moles of boron release from Neutronit per year (moles/yr)}$$

Develop the time available for boron to degrade and flush from waste package. This time is based on the occurrence of the first seismic event up to the regulatory period. If the time to degrade the Neutronit is longer than the delta time (regulatory period minus time of seismic event), then it is set to the regulatory period and delta time becomes zero.

$$t1_i := 10000 - T1_{s_i}$$

$$tt_{44_1} := \text{if}(t1_i < t_{degt_{44_1}}, t_{degt_{44_1}}, t1_i)$$

$$per_{BB} := 0.5 \quad \text{Fraction boron remaining in a BWR waste package (50 percent) (see Assumption 5.1.5)}$$

$$Bt_{44loss} := per_{BB} \cdot Bit_{44} \quad Bt_{44loss} = 1.815 \times 10^3$$

$$A_i := \text{if}(t_{degt_{44_1}} \geq 10000, 0, \text{if}(t_{degt_{44_1}} = tt_{44_1}, 0, 1)) \quad \text{Parameters required to solve the boron loss equation when the time to degrade is longer than the regulatory period of 10,000 years}$$

$$C_i := \text{if}(t_{degt_{44_1}} \geq 10000, 1, \text{if}(t_{degt_{44_1}} = tt_{44_1}, 1, 0))$$

$$E_i := \text{if}(t_{degt_{44_1}} \geq 10000, 10000, \text{if}(t_{degt_{44_1}} = tt_{44_1}, 10000, 1))$$

Boron Loss Equation (BSC 2003 [DIRS 165890], Section 6)

$$NBt_{44}(vt_{44}, i) := vt_{44} \cdot C_i + \left[A_i \cdot \left[\frac{(Vr_{44} \cdot Dt_{44,i,0})}{vt_{44}} \right] \cdot \left(1 - \exp\left(-tdegt_{44,i,0} \cdot \frac{vt_{44}}{Vr_{44}}\right) \right) \cdot \exp\left[\frac{-vt_{44} \cdot (tt_{44,i,0} - tdegt_{44,i,0})}{Vr_{44}}\right] \right] - Bt_{44loss} \cdot E_i$$

$$Vt_{44,dr_i} := \text{root}\left(NBt_{44}(vt_{44}, i), vt_{44}, 1 \times 10^{-11}, 1 \times 10^{11}\right)$$

$$reqt_{44dr} := \frac{Vt_{44,dr}}{1000} \quad \text{Required drip rate (m}^3\text{/yr) into a 44-BWR Absorber Plate waste package to degrade and flush out the boron based on sampled corrosion and time to first seismic event.}$$

The following is the equation used to calculate the probability that the seepage rate can be at or greater than the seepage noted as z_{44} (for lithophysal) and $z1_{44}$ (for nonlithophysal). This seepage is based on the seepage rate making it through the damaged areas of the drip shield and waste package. The drip rate value is based on sampling the corrosion rate of Neutronit and sampling the time to first seismic occurrence, which determines the time to degrade and flush out the Neutronit from a 44-BWR Absorber Plate waste package for criticality potential.

$$zt_{44,i} := \frac{reqt_{44dr_i}}{\left(\frac{1}{100} \cdot WP1_{d_i}\right) \cdot DS1_{ds_i}} \quad z_{44} \text{ is the amount of seepage rate (m}^3\text{/yr) required for lithophysal zone.}$$

$$z1t_{44,i} := \frac{reqt_{44dr_i}}{\left[\left(\frac{1}{100} \cdot WP1_{d_i}\right) \cdot DS_{dnl_i}\right]} \quad z1_{44} \text{ is the amount of seepage rate (m}^3\text{/yr) required for nonlithophysal zone.}$$

Lithophysal Zone

$$Qt_{44l_{spl_i}} := 1 - STl_{ptl}(zt_{44,i})$$

$$Qt_{44m_{spl_i}} := 1 - STm_{ptl}(zt_{44,i})$$

$$Qt_{44u_{spl_i}} := 1 - STu_{ptl}(zt_{44,i})$$

Nonlithophysal Zone

$$Qt_{44l_{spn_i}} := 1 - STl_{ptn}(z1t_{44,i})$$

$$Qt_{44m_{spn_i}} := 1 - STm_{ptn}(z1t_{44,i})$$

$$Qt_{44u_{spn_i}} := 1 - STu_{ptn}(z1t_{44,i})$$

The probability of being in the low-, mean- or upper-infiltration scenario for the glacial transition climate is 0.24, 0.41, and 0.35, respectively (BSC 2003 [DIRS 165991], Section 7, Table 7-1).

$$Qt_{44_{sfl_i}} := \text{if}\left(X_{i,5} \leq 0.24, Qt_{44l_{spl_i}} \cdot 0.194, \text{if}\left(0.24 \leq X_{i,5} \leq 0.65, Qt_{44m_{spl_i}} \cdot 0.514, Qt_{44u_{spl_i}} \cdot 0.637\right)\right)$$

$$Qt_{44_{sfn_i}} := \text{if}\left(X_{i,5} \leq 0.24, Qt_{44l_{spn_i}} \cdot 0.154, \text{if}\left(0.24 \leq X_{i,5} \leq 0.65, Qt_{44m_{spn_i}} \cdot 0.524, Qt_{44u_{spn_i}} \cdot 0.672\right)\right)$$

The probability of the seismic event causing sufficient damage to allow advective flow to penetrate, degrade, and flush out the Neutronit from a 44-BWR Absorber Plate waste package is calculated using the equations below for both lithophysal and nonlithophysal. The equations are based on the sampling of the probability of sufficient advective flow given a seismic event with magnitude, v , at time, t . This probability will be fed into top event MS-IC-1 of the SAPHIRE model for seismic event. The probability of a seismic event will be set to 1.0 in the SAPHIRE model since it is accounted for in this calculation.

Lithophysal Zone

$$Prt44_{sfl} := \frac{[(T_u - T_l) \cdot (IE_u - IE_l)]}{n_s} \cdot \sum_{i=0}^{n_s-1} Qt44_{sfl_i} \cdot (1 - X_{i,7})$$

$Prt44_{sfl} = 1.242 \times 10^{-10}$ **Mean probability**

Equations based on Equation 6.4-6 of main report, DTN:MO0308SPACALSS.002 (BSC 2003 [DIRS 164822]) and *Seismic Consequence Abstraction* (BSC 2003 [DIRS 161812], Attachment VIII, Eq. VIII.2.11).

Nonlithophysal Zone

$$Prt44_{sfnl} := \frac{[(T_u - T_l) \cdot (IE_u - IE_l)]}{n_s} \cdot \sum_{i=0}^{n_s-1} Qt44_{sfnl_i} \cdot (1 - X_{i,7})$$

$Prt44_{sfnl} = 9.924 \times 10^{-12}$ **Mean probability**

Final Results of Seismic Sensitivity Case Analysis

Sensitivity Probability Calculation using the following assumptions :

- Corrosion rate of Neutronit assumed to be 1.5 times the corrosion rate of stainless steel 316, which was fit to a Weibull distribution (Assumption 5.1.4)
- Flushing out 90 percent of the boron from the PWR waste package types (Assumption 5.1.5)
- Flushing out 50 percent of the boron from the BWR waste package types (Assumption 5.1.5)
- No water ingress into a waste package prior to 700 years (Assumption 5.2.2)
- 44-BWR Absorber Plate waste package, Neutronit plate thickness increased to 7-mm

Lithophysal Zone

Nonlithophysal Zone

44-BWR Absorber Plate waste package

$Prt44_{sfl} = 1.242 \times 10^{-10}$

$Prt44_{sfnl} = 9.924 \times 10^{-12}$

Probabilities for the remaining waste package types remained the same and are , therefore, not listed.

INTENTIONALLY LEFT BLANK

ATTACHMENT IV

SEEPAGE ANALYSIS SPREADSHEETS (OUTPUT FROM MATHCAD FILES)

INTENTIONALLY LEFT BLANK

ATTACHMENT IV - SEEPAGE ANALYSIS SPREADSHEETS (OUTPUT FROM MATHCAD FILES)

The following sections presents the Mathcad analyses for the lower, mean and upper seepage infiltration rates of the glacial transition climate in both the lithophysal and nonlithophysal zones.

IV.1 SEEPAGE ANALYSIS FOR LOWER INFILTRATION RATE IN THE LITHOPHYSAL ZONE

The following section presents the Mathcad analysis for the lower seepage infiltration rate of the glacial transition climate in the lithophysal zone. The seepage information used in this analysis was obtained from *Abstraction of Drift Seepage* (BSC 2003 [DIRS 165564]). The information contained in the section has been abstracted from the “seepage glac lower Tptpl driftcollapse report.mcd” Mathcad file of Attachment VII.

Seepage rate and seepage fraction calculation followed *Abstraction of Drift Seepage* (BSC 2003 [DIRS 165564], Section 6.7).

Latin Hypercube Sampling Routine to Generate Random Numbers

Sample Size: $n := 20000$

$i := 1..n$

$RD_{i-1,0} := i$ $RD_{i-1,3} := \text{rnd}(1.0)$ $RD_{i-1,6} := \text{rnd}(1.0)$ $RD_{i-1,9} := \text{rnd}(1.0)$ $RD_{i-1,12} := \text{rnd}(1.0)$
 $RD_{i-1,1} := \text{rnd}(1.0)$ $RD_{i-1,4} := \text{rnd}(1.0)$ $RD_{i-1,7} := \text{rnd}(1.0)$ $RD_{i-1,10} := \text{rnd}(1.0)$
 $RD_{i-1,2} := \text{rnd}(1.0)$ $RD_{i-1,5} := \text{rnd}(1.0)$ $RD_{i-1,8} := \text{rnd}(1.0)$ $RD_{i-1,11} := \text{rnd}(1.0)$

RKs are matrixes in which the first column contain a permutation on the integers on the interval [1,n].

$RK1 := \text{csort}(RD, 1)$ $RK4 := \text{csort}(RD, 4)$ $RK7 := \text{csort}(RD, 7)$ $RK10 := \text{csort}(RD, 10)$
 $RK2 := \text{csort}(RD, 2)$ $RK5 := \text{csort}(RD, 5)$ $RK8 := \text{csort}(RD, 8)$ $RK11 := \text{csort}(RD, 11)$
 $RK3 := \text{csort}(RD, 3)$ $RK6 := \text{csort}(RD, 6)$ $RK9 := \text{csort}(RD, 9)$ $RK12 := \text{csort}(RD, 12)$

Define sets of random values. Each random value is selected within one of the equiprobable n intervals that partition [0,1], one set for each random variable.

$$X^{(0)} := \frac{RK1^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} \quad X^{(3)} := \frac{RK4^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} \quad X^{(6)} := \frac{RK7^{(0)} - 1 + \text{runif}(n, 0, 1)}{n}$$

$$X^{(1)} := \frac{RK2^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} \quad X^{(4)} := \frac{RK5^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} \quad X^{(7)} := \frac{RK8^{(0)} - 1 + \text{runif}(n, 0, 1)}{n}$$

$$X^{(2)} := \frac{RK3^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} \quad X^{(5)} := \frac{RK6^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} \quad X^{(8)} := \frac{RK9^{(0)} - 1 + \text{runif}(n, 0, 1)}{n}$$

$$X^{(9)} := \frac{RK10^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} \quad X^{(10)} := \frac{RK11^{(0)} - 1 + \text{runif}(n, 0, 1)}{n}$$

$$X^{(11)} := \frac{RK12^{(0)} - 1 + \text{runif}(n, 0, 1)}{n}$$

$i := 0..n - 1$

Capillary Strength $1/\alpha$ in (Pa)

$\alpha_{1lb} := 402$ $\alpha_{1ub} := 780$ $\alpha_{1\mu} := 591$ **Spatial variability follows a uniform distribution**

$\Delta\alpha_{1l} := -105$ $\Delta\alpha_{1\mu} := 0$ $\Delta\alpha_{1u} := 105$ **Uncertainty follows a triangular distribution**

Sampling from spatial variability to obtain the $1/\alpha$ value

$\alpha_{1i} := \text{qunif}(X_{i,0}, \alpha_{1lb}, \alpha_{1ub})$ **$1/\alpha$ value**

Sample from uncertainty triangular distribution to obtain $\Delta 1/\alpha$

Determine which equation to use:

if Random Number $< \text{RN}_{\Delta\alpha 1}$ then use Equation 1 ($\Delta\alpha 1eq1$).

if Random Number $> \text{RN}_{\Delta\alpha 1}$ then use Equation 2 ($\Delta\alpha 1eq2$).

$$\text{RN}_{\Delta\alpha 1} := \frac{(\Delta\alpha_{1\mu} - \Delta\alpha_{1l})^2}{(\Delta\alpha_{1u} - \Delta\alpha_{1l}) \cdot (\Delta\alpha_{1\mu} - \Delta\alpha_{1l})}$$

$$\Delta\alpha_{1eq1i} := \Delta\alpha_{1l} + \sqrt{X_{i,1} \cdot (\Delta\alpha_{1u} - \Delta\alpha_{1l}) \cdot (\Delta\alpha_{1\mu} - \Delta\alpha_{1l})}$$

$$\Delta\alpha_{1eq2i} := \Delta\alpha_{1u} - \sqrt{(1 - X_{i,1}) \cdot (\Delta\alpha_{1u} - \Delta\alpha_{1l}) \cdot (\Delta\alpha_{1u} - \Delta\alpha_{1\mu})}$$

$$\Delta\alpha_{1i} := \text{if} \left[\left(X_{i,1} \leq \text{RN}_{\Delta\alpha 1} \right), \Delta\alpha_{1eq1i}, \Delta\alpha_{1eq2i} \right] \quad \mathbf{\Delta 1/\alpha \text{ value}}$$

Overall Capillary Strength $1/\alpha + \Delta 1/\alpha$

$$T_{1\alpha_i} := \alpha_{1i} + \Delta\alpha_{1i} \quad \mathbf{1/\alpha \text{ value}}$$

Permeability k in Tptpl Unit (in log 10)

$\mu_{kTl} := -11.5$ **Mean of lognormal distribution**

$\sigma_{kTl} := 0.47$ **Standard deviation of lognormal distribution**

$$k_{Tli} := \ln \left(\text{qlnorm} \left(X_{i,2}, \mu_{kTl}, \sigma_{kTl} \right) \right)$$

$$\text{mean}(k_{Tl}) = -11.5$$

$$\text{Stdev}(k_{Tl}) = 0.47$$

Permeability Δk in Tptpl Unit (in log 10)

$\Delta k_{Tll} := -0.92$ $\Delta k_{Tl\mu} := 0$ $\Delta k_{Tlu} := 0.92$ **Uncertainty follows a triangular distribution**

Sample from uncertainty triangular distribution to obtain Δk

Determine which equation to use:

if Random Number < $RN_{\Delta k_{TI}}$ then use Equation 1 (Δk_{Tleq1}).

if Random Number > $RN_{\Delta k_{TI}}$ then use Equation 2 (Δk_{Tleq2}).

$$RN_{\Delta k_{TI}} := \frac{(\Delta k_{Tl\mu} - \Delta k_{Tll})^2}{(\Delta k_{Tlu} - \Delta k_{Tll}) \cdot (\Delta k_{Tl\mu} - \Delta k_{Tll})}$$

$$\Delta k_{Tleq1_i} := \Delta k_{Tll} + \sqrt{X_{i,3} \cdot (\Delta k_{Tlu} - \Delta k_{Tll}) \cdot (\Delta k_{Tl\mu} - \Delta k_{Tll})}$$

$$\Delta k_{Tleq2_i} := \Delta k_{Tlu} - \sqrt{(1 - X_{i,3}) \cdot (\Delta k_{Tlu} - \Delta k_{Tll}) \cdot (\Delta k_{Tlu} - \Delta k_{Tl\mu})}$$

$$\Delta k_{Tl_i} := \text{if} \left[\left(X_{i,3} \leq RN_{\Delta k_{TI}} \right), \Delta k_{Tleq1_i}, \Delta k_{Tleq2_i} \right] \quad \Delta k \text{ value}$$

Overall Permeability $k + \Delta k$

$$Tl_{k_{TI}_i} := k_{TI_i} + \Delta k_{Tl_i}$$

Permeability must lie between -14 and -10 (bounds of SMPA simulations)

$$T_{k_{TI}_i} := \text{if} \left(Tl_{k_{TI}_i} \geq -10, -10, \text{if} \left(Tl_{k_{TI}_i} \leq -14, -14, Tl_{k_{TI}_i} \right) \right) \quad k \text{ value}$$

Flow Focusing Factor (DTN: LB0104AMRU0185.012 [DIRS 163906])

$$f(x) := -0.3137x^4 + 5.4998x^3 - 35.66x^2 + 102.3x - 11.434$$

$$ff_i := \text{root} \left[f(x) - (X_{i,5} \cdot 100), x, 0, 6 \right]$$

Percolation Flux (mm/yr)

The percolation flux used here is for the glacial transition period only. The percolation flux is based on sampling from the lower bound TSPA repository location only (DTN: LB0310AMRU0120.002 [DIRS 166116]).

$$nnn := 0..468$$

Lower Bound Percolation Flux

$$PF1_i :=$$

	0
0	3.68
1	2.65
2	2.41
3	2.13
4	2.41
5	2.4
6	2.12
7	2.76
8	1.4
9	2.21

$$PFt_{i,nnn} := PF1_{i,nnn,0}$$

$$Z^{(0)} := \text{round}(\text{runif}(n, 0, 468))$$

$$PF_i := PFt_{i,Z_i,0}$$

Adjusted Percolation Flux

Multiply the flow-focusing factor by the percolation flux, which will be used to obtain the seepage rate, seepage fraction, and seepage percentage

$$q1_{pff_i} := PF_i \cdot ff_i$$

Percolation Flux must lie between 1 and 1000 mm/yr (bounds of SMPA simulations)

$$q_{pff_i} := \text{if}(q1_{pff_i} \leq 1, 1, \text{if}(q1_{pff_i} \geq 1000, 1000, q1_{pff_i}))$$

**Seepage Information from SMPA analysis
(DTN: LB0307SEEPDRCL.002 [DIRS 164337])**

SMPA_{data}^{<0>} is permeability value $\log(k [m^2])$

SMPA_{data}^{<1>} is capillary strength $1/\alpha [Pa]$

SMPA_{data}^{<2>} is local percolation flux (mm/yr)

SMPA_{data}^{<3>} is Mean Seepage [kg/yr/WP]

SMPA_{data}^{<4>} is Std. Dev. Seepage [kg/yr/WP]

SMPA_{data}^{<5>} is Mean Seepage [%]

SMPA_{data}^{<6>} is Std. Dev. Seepage [%]

m := 2549 data points

SMPA_{data} :=

	0	1	2	3	4	5	6
0	-14	100	1	56.44	5.47	100.6	9.75
1	-14	100	5	282.63	27.5	100.76	9.8
2	-14	100	10	566.16	55.13	100.92	9.83
3	-14	100	20	1135.12	109.85	101.17	9.79
4	-14	100	50	2849.95	272.25	101.6	9.71
5	-14	100	100	5726.78	535.98	102.08	9.55
6	-14	100	200	11523.63	1064.22	102.71	9.49
7	-14	100	300	17369.22	1583.08	103.2	9.41
8	-14	100	400	23241.94	2086.65	103.57	9.3
9	-14	100	500	29154.54	2552.38	103.94	9.1
10	-14	100	600	35097.8	2992.46	104.27	8.89
11	-14	100	700	41099.26	3411.36	104.66	8.69
12	-14	100	800	47084.03	3860.77	104.91	8.6
13	-14	100	900	53190.45	4145.2	105.35	8.21
14	-14	100	1000	59206.88	4520.61	105.54	8.06
15	-14	200	1	55.25	5.44	98.48	9.69

Develop routine to select correct mean seepage, seepage standard deviation, seepage percent, and seepage percent standard deviation based on sampled value of $1/\alpha$, k, percolation flux.

nx := 14 ny := 9 nz := 16

ii := 0..nx

$x_{ii} := \text{SMPA}_{\text{data}, ii, 2}$ $x_{ii} := ii$

jj := 0..ny

$y_{jj} := 100 \cdot jj + 100$ $y_{jj} := jj$

kk := 0..nz

$z_{kk} := -14 + kk \cdot 0.25$ $z_{kk} := kk$

loc represents the location within the matrix of which value to pick for the interpolation process.

$$\text{loc}_{1_i} := \text{floor}\left(\text{linterp}\left(z, z_k, T_{kTl_i}\right)\right) \cdot (nx + 1) \cdot (ny + 1) + \text{floor}\left(\text{linterp}\left(y, y_j, T_{1\alpha_i}\right)\right) \cdot (nx + 1) \dots \\ + \text{floor}\left(\text{linterp}\left(x, x_i, q_{pff_i}\right)\right)$$

$$s_{ms1_i} := \text{SMPA}_{\text{data}} \text{loc}_{1_i}, 3$$

$$s_{msd1_i} := \text{SMPA}_{\text{data}} \text{loc}_{1_i}, 4$$

$$s_{pms1_i} := \text{SMPA}_{\text{data}} \text{loc}_{1_i}, 5$$

$$s_{psd1_i} := \text{SMPA}_{\text{data}} \text{loc}_{1_i}, 6$$

$$\text{loc}_{2_i} := \left[\text{floor}\left(\text{linterp}\left(z, z_k, T_{kTl_i}\right)\right) \cdot (nx + 1) \cdot (ny + 1) \right] + \text{floor}\left(\text{linterp}\left(y, y_j, T_{1\alpha_i}\right)\right) \cdot (nx + 1) \dots \\ + \text{ceil}\left(\text{linterp}\left(x, x_i, q_{pff_i}\right)\right)$$

$$s_{ms2_i} := \text{SMPA}_{\text{data}} \text{loc}_{2_i}, 3$$

$$s_{msd2_i} := \text{SMPA}_{\text{data}} \text{loc}_{2_i}, 4$$

$$s_{pms2_i} := \text{SMPA}_{\text{data}} \text{loc}_{2_i}, 5$$

$$s_{psd2_i} := \text{SMPA}_{\text{data}} \text{loc}_{2_i}, 6$$

$$\text{loc}_{3_i} := \text{floor}\left(\text{linterp}\left(z, z_k, T_{kTl_i}\right)\right) \cdot (nx + 1) \cdot (ny + 1) + \text{ceil}\left(\text{linterp}\left(y, y_j, T_{1\alpha_i}\right)\right) \cdot (nx + 1) \dots \\ + \text{ceil}\left(\text{linterp}\left(x, x_i, q_{pff_i}\right)\right)$$

$$s_{ms3_i} := \text{SMPA}_{\text{data}} \text{loc}_{3_i}, 3$$

$$s_{msd3_i} := \text{SMPA}_{\text{data}} \text{loc}_{3_i}, 4$$

$$s_{pms3_i} := \text{SMPA}_{\text{data}} \text{loc}_{3_i}, 5$$

$$s_{psd3_i} := \text{SMPA}_{\text{data}} \text{loc}_{3_i}, 6$$

$$\text{loc}_{4_i} := \text{floor}\left(\text{linterp}\left(z, z_k, T_{kTl_i}\right)\right) \cdot (nx + 1) \cdot (ny + 1) + \text{ceil}\left(\text{linterp}\left(y, y_j, T_{1\alpha_i}\right)\right) \cdot (nx + 1) \dots \\ + \text{floor}\left(\text{linterp}\left(x, x_i, q_{pff_i}\right)\right)$$

$$s_{ms4_i} := \text{SMPA}_{\text{data}} \text{loc}_{4_i}, 3$$

$$s_{msd4_i} := \text{SMPA}_{\text{data}} \text{loc}_{4_i}, 4$$

$$s_{pms4_i} := \text{SMPA}_{\text{data}} \text{loc}_{4_i}, 5$$

$$s_{psd4_i} := \text{SMPA}_{\text{data}} \text{loc}_{4_i}, 6$$

$$\text{loc}_{5_i} := \left[\text{ceil} \left(\text{linterp} \left(z, z_k, T_{kTl_i} \right) \right) \cdot (nx + 1) \cdot (ny + 1) \right] + \text{floor} \left(\text{linterp} \left(y, y_j, T_{1\alpha_i} \right) \right) \cdot (nx + 1) \dots \\ + \text{floor} \left(\text{linterp} \left(x, x_i, q_{pff_i} \right) \right)$$

$$s_{ms5_i} := \text{SMPA}_{\text{data}_{\text{loc}_{5_i}, 3}}$$

$$s_{msd5_i} := \text{SMPA}_{\text{data}_{\text{loc}_{5_i}, 4}}$$

$$s_{pms5_i} := \text{SMPA}_{\text{data}_{\text{loc}_{5_i}, 5}}$$

$$s_{psd5_i} := \text{SMPA}_{\text{data}_{\text{loc}_{5_i}, 6}}$$

$$\text{loc}_{6_i} := \text{ceil} \left(\text{linterp} \left(z, z_k, T_{kTl_i} \right) \right) \cdot (nx + 1) \cdot (ny + 1) + \text{floor} \left(\text{linterp} \left(y, y_j, T_{1\alpha_i} \right) \right) \cdot (nx + 1) \dots \\ + \text{ceil} \left(\text{linterp} \left(x, x_i, q_{pff_i} \right) \right)$$

$$s_{ms6_i} := \text{SMPA}_{\text{data}_{\text{loc}_{6_i}, 3}}$$

$$s_{msd6_i} := \text{SMPA}_{\text{data}_{\text{loc}_{6_i}, 4}}$$

$$s_{pms6_i} := \text{SMPA}_{\text{data}_{\text{loc}_{6_i}, 5}}$$

$$s_{psd6_i} := \text{SMPA}_{\text{data}_{\text{loc}_{6_i}, 6}}$$

$$\text{loc}_{7_i} := \left[\text{ceil} \left(\text{linterp} \left(z, z_k, T_{kTl_i} \right) \right) \cdot (nx + 1) \cdot (ny + 1) \right] + \text{ceil} \left(\text{linterp} \left(y, y_j, T_{1\alpha_i} \right) \right) \cdot (nx + 1) \dots \\ + \text{ceil} \left(\text{linterp} \left(x, x_i, q_{pff_i} \right) \right)$$

$$s_{ms7_i} := \text{SMPA}_{\text{data}_{\text{loc}_{7_i}, 3}}$$

$$s_{msd7_i} := \text{SMPA}_{\text{data}_{\text{loc}_{7_i}, 4}}$$

$$s_{pms7_i} := \text{SMPA}_{\text{data}_{\text{loc}_{7_i}, 5}}$$

$$s_{psd7_i} := \text{SMPA}_{\text{data}_{\text{loc}_{7_i}, 6}}$$

$$\text{loc}_{8_i} := \text{ceil} \left(\text{linterp} \left(z, z_k, T_{kTl_i} \right) \right) \cdot (nx + 1) \cdot (ny + 1) + \text{ceil} \left(\text{linterp} \left(y, y_j, T_{1\alpha_i} \right) \right) \cdot (nx + 1) \dots \\ + \text{floor} \left(\text{linterp} \left(x, x_i, q_{pff_i} \right) \right)$$

$$s_{ms8_i} := \text{SMPA}_{\text{data}_{\text{loc}_{8_i}, 3}}$$

$$s_{msd8_i} := \text{SMPA}_{\text{data}_{\text{loc}_{8_i}, 4}}$$

$$s_{pms8_i} := \text{SMPA}_{\text{data}_{\text{loc}_{8_i}, 5}}$$

$$s_{psd8_i} := \text{SMPA}_{\text{data}_{\text{loc}_{8_i}, 6}}$$

Develop the upper and lower bound of the randomly generated $1/\alpha$, k, and adjusted percolation flux.

Develop the upper and lower bound for permeability (k) for Tptpl Unit

$$qq_i := -1 \cdot T_{kTI_i}$$

$$\text{mantissa}(x) := x - \text{floor}(qq)$$

$$tt_i := \text{floor}(qq_i)$$

$$rr := \text{round}(\text{mantissa}(qq), 2)$$

$$yy1_i := \text{if}(rr_i \leq 0.25, 0, \text{if}(0.25 < rr_i \leq 0.5, 0.25, rr_i))$$

$$zz1_i := \text{if}(yy1_i \leq 0.5, yy1_i, \text{if}(0.5 < yy1_i \leq 0.75, 0.5, 0.75))$$

$$T_{kTI2_i} := -1 \cdot (tt_i + zz1_i)$$

$$yy2_i := \text{if}(rr_i \leq 0.25, 0.25, \text{if}(0.25 < rr_i \leq 0.5, 0.5, rr_i))$$

$$zz2_i := \text{if}(yy2_i \leq 0.5, yy2_i, \text{if}(0.5 < yy2_i \leq 0.75, 0.75, 1))$$

$$T_{kTI1_i} := -1 \cdot (tt_i + zz2_i)$$

Develop the upper and lower bound for capillary strength ($1/\alpha$)

$$hh1_i := \text{floor}\left(\frac{T_{1\alpha_i}}{100}\right)$$

$$T_{1\alpha1_i} := (hh1_i \cdot 100)$$

$$hh2_i := \text{ceil}\left(\frac{T_{1\alpha_i}}{100}\right)$$

$$T_{1\alpha2_i} := (hh2_i \cdot 100)$$

Lower Bound value adjusted percolation flux (q_{pff})

$$aaa1_i := \text{if}(q_{pff_i} \leq 1, 1, \text{if}(1 < q_{pff_i} \leq 5, 1, q_{pff_i}))$$

$$bbb1_i := \text{if}(aaa1_i \leq 5, aaa1_i, \text{if}(5 < aaa1_i \leq 10, 5, aaa1_i))$$

$$ccc1_i := \text{if}(bbb1_i \leq 10, bbb1_i, \text{if}(10 < bbb1_i \leq 20, 10, bbb1_i))$$

$$ddd1_i := \text{if}(ccc1_i \leq 20, ccc1_i, \text{if}(20 < ccc1_i \leq 50, 20, ccc1_i))$$

$$eee1_i := \text{if}(ddd1_i \leq 50, ddd1_i, \text{if}(50 < ddd1_i \leq 100, 50, ddd1_i))$$

$$fff1_i := \text{if}(eee1_i \leq 100, eee1_i, \text{if}(100 < eee1_i \leq 200, 100, eee1_i))$$

$$\begin{aligned} ggg1_i &:= \text{if}(fff1_i \leq 200, fff1_i, \text{if}(200 < fff1_i \leq 300, 200, fff1_i)) \\ hhh1_i &:= \text{if}(ggg1_i \leq 300, ggg1_i, \text{if}(300 < ggg1_i \leq 400, 300, ggg1_i)) \\ iii1_i &:= \text{if}(hhh1_i \leq 400, hhh1_i, \text{if}(400 < hhh1_i \leq 500, 400, hhh1_i)) \\ jjj1_i &:= \text{if}(iii1_i \leq 500, iii1_i, \text{if}(500 < iii1_i \leq 600, 500, iii1_i)) \\ kkk1_i &:= \text{if}(jjj1_i \leq 600, jjj1_i, \text{if}(600 < jjj1_i \leq 700, 600, jjj1_i)) \\ mmm1_i &:= \text{if}(kkk1_i \leq 700, kkk1_i, \text{if}(700 < kkk1_i \leq 800, 700, kkk1_i)) \\ q_{pff1}_i &:= \text{if}(mmm1_i \leq 800, mmm1_i, \text{if}(800 < mmm1_i \leq 900, 800, 900)) \end{aligned}$$

Upper Bound value adjusted percolation flux (q_{pff}).

$$\begin{aligned} aaa2_i &:= \text{if}(q_{pff}_i \leq 1, 5, \text{if}(1 < q_{pff}_i \leq 5, 5, q_{pff}_i)) \\ bbb2_i &:= \text{if}(aaa2_i \leq 5, aaa2_i, \text{if}(5 < aaa2_i \leq 10, 10, aaa2_i)) \\ ccc2_i &:= \text{if}(bbb2_i \leq 10, bbb2_i, \text{if}(10 < bbb2_i \leq 20, 20, bbb2_i)) \\ ddd2_i &:= \text{if}(ccc2_i \leq 20, ccc2_i, \text{if}(20 < ccc2_i \leq 50, 50, ccc2_i)) \\ eee2_i &:= \text{if}(ddd2_i \leq 50, ddd2_i, \text{if}(50 < ddd2_i \leq 100, 100, ddd2_i)) \\ fff2_i &:= \text{if}(eee2_i \leq 100, eee2_i, \text{if}(100 < eee2_i \leq 200, 200, eee2_i)) \\ ggg2_i &:= \text{if}(fff2_i \leq 200, fff2_i, \text{if}(200 < fff2_i \leq 300, 300, fff2_i)) \\ hhh2_i &:= \text{if}(ggg2_i \leq 300, ggg2_i, \text{if}(300 < ggg2_i \leq 400, 400, ggg2_i)) \\ iii2_i &:= \text{if}(hhh2_i \leq 400, hhh2_i, \text{if}(400 < hhh2_i \leq 500, 500, hhh2_i)) \\ jjj2_i &:= \text{if}(iii2_i \leq 500, iii2_i, \text{if}(500 < iii2_i \leq 600, 600, iii2_i)) \\ kkk2_i &:= \text{if}(jjj2_i \leq 600, jjj2_i, \text{if}(600 < jjj2_i \leq 700, 700, jjj2_i)) \\ mmm2_i &:= \text{if}(kkk2_i \leq 700, kkk2_i, \text{if}(700 < kkk2_i \leq 800, 800, kkk2_i)) \\ q_{pff2}_i &:= \text{if}(mmm2_i \leq 800, mmm2_i, \text{if}(800 < mmm2_i \leq 900, 900, 1000)) \end{aligned}$$

Interpolate (Solve) for seepage rate (Tptpl Unit)

$$t_{q_{pff}_i} := \frac{q_{pff}_i - q_{pff1}_i}{q_{pff2}_i - q_{pff1}_i} \quad u_{T1\alpha_i} := \frac{T_{1\alpha_i} - T_{1\alpha1}_i}{T_{1\alpha2}_i - T_{1\alpha1}_i} \quad v_{TKT1_i} := \frac{T_{kT1}_i - T_{kT11}_i}{T_{kT12}_i - T_{kT11}_i}$$

$$\begin{aligned}
 \text{spflux}_{T1m_i} := & (1 - t_{\text{qpf}f_i}) \cdot (1 - u_{T1\alpha_i}) \cdot (1 - v_{TkTl_i}) \cdot s_{ms1_i} \dots \\
 & + (t_{\text{qpf}f_i}) \cdot (1 - u_{T1\alpha_i}) \cdot (1 - v_{TkTl_i}) \cdot s_{ms2_i} \dots \\
 & + (t_{\text{qpf}f_i}) \cdot (u_{T1\alpha_i}) \cdot (1 - v_{TkTl_i}) \cdot s_{ms3_i} \dots \\
 & + (1 - t_{\text{qpf}f_i}) \cdot (u_{T1\alpha_i}) \cdot (1 - v_{TkTl_i}) \cdot s_{ms4_i} \dots \\
 & + (1 - t_{\text{qpf}f_i}) \cdot (1 - u_{T1\alpha_i}) \cdot (v_{TkTl_i}) \cdot s_{ms5_i} \dots \\
 & + (t_{\text{qpf}f_i}) \cdot (1 - u_{T1\alpha_i}) \cdot (v_{TkTl_i}) \cdot s_{ms6_i} \dots \\
 & + (t_{\text{qpf}f_i}) \cdot (u_{T1\alpha_i}) \cdot (v_{TkTl_i}) \cdot s_{ms7_i} \dots \\
 & + (1 - t_{\text{qpf}f_i}) \cdot (u_{T1\alpha_i}) \cdot (v_{TkTl_i}) \cdot s_{ms8_i}
 \end{aligned}$$

$$\begin{aligned}
 \text{spflux}_{T1sd_i} := & (1 - t_{\text{qpf}f_i}) \cdot (1 - u_{T1\alpha_i}) \cdot (1 - v_{TkTl_i}) \cdot s_{msd1_i} \dots \\
 & + (t_{\text{qpf}f_i}) \cdot (1 - u_{T1\alpha_i}) \cdot (1 - v_{TkTl_i}) \cdot s_{msd2_i} \dots \\
 & + (t_{\text{qpf}f_i}) \cdot (u_{T1\alpha_i}) \cdot (1 - v_{TkTl_i}) \cdot s_{msd3_i} \dots \\
 & + (1 - t_{\text{qpf}f_i}) \cdot (u_{T1\alpha_i}) \cdot (1 - v_{TkTl_i}) \cdot s_{msd4_i} \dots \\
 & + (1 - t_{\text{qpf}f_i}) \cdot (1 - u_{T1\alpha_i}) \cdot (v_{TkTl_i}) \cdot s_{msd5_i} \dots \\
 & + (t_{\text{qpf}f_i}) \cdot (1 - u_{T1\alpha_i}) \cdot (v_{TkTl_i}) \cdot s_{msd6_i} \dots \\
 & + (t_{\text{qpf}f_i}) \cdot (u_{T1\alpha_i}) \cdot (v_{TkTl_i}) \cdot s_{msd7_i} \dots \\
 & + (1 - t_{\text{qpf}f_i}) \cdot (u_{T1\alpha_i}) \cdot (v_{TkTl_i}) \cdot s_{msd8_i}
 \end{aligned}$$

Calculate mean seepage for Tptpl Unit

$$QT11_{stdl_i} := -1.7321 \cdot \text{spflux}_{T1sd_i}$$

$$QT11_{stdu_i} := 1.7321 \cdot \text{spflux}_{T1sd_i}$$

$$QT1_{stdl_i} := \text{if}(QT11_{stdl_i} = 0, -0.00001, QT11_{stdl_i})$$

$$QT1_{std_i} := \text{qunif}(X_{i,10}, QT1_{stdl_i}, QT1_{stdu_i})$$

$$QT11_{spm_i} := \text{spflux}_{T1m_i} + QT1_{std_i}$$

$$QT12_{spm_i} := \text{if}(QT11_{spm_i} \leq 0.1, 0, QT11_{spm_i})$$

$$QT2_{perc_i} := \frac{QT12_{spm_i} \cdot 100}{q_{\text{pff}f_i} \cdot 28.052}$$

Equation to calculate seepage percent is based on seepage rate (see SMPA data table) (from DTN: LB0310AMRU0120.002 [DIRS 166116])

$$QT3_{perc_i} := \text{if}(QT2_{perc_i} \leq 0, 0, \text{if}(QT2_{perc_i} \geq 100, 100, QT2_{perc_i}))$$

Check seepage percent; if above 100 percent, then recalculate seepage back to 100 percent.

$$QTl_{spr_i} := QT3_{perc_i} \cdot q_{pff_i} \cdot \frac{2 \cdot 28.05}{100} \quad \text{Mean Seepage Rate (kg/yr per WP)}$$

$$\text{mean}(QTl_{spr}) = 3.754$$

Determine the seepage fraction for Tptpl Unit within the repository and then fit the output data to distribution.

Seepage fraction represents the non-zero seepage rates based on the LHS sampling of all of the parameters.

$$\text{sort}(QTl_{spr}) =$$

	0
16122	0
16123	0
16124	0.101
16125	0.101
16126	0.101

$$n_{Tl} := 16123$$

$$\text{spfr}_{Tl} := \frac{(n - 1) - n_{Tl}}{n} \quad \text{spfr}_{Tl} = 0.194 \quad \text{Seepage fraction (i.e., waste package locations that see seepage)}$$

$$n1_{Tl} := (n - 1) - (n_{Tl} + 1)$$

$$Q1_{Tl} := \text{sort}(QTl_{spr})$$

$$Q1_{Tl} := \text{reverse}(Q1_{Tl})$$

$$ab := 0..n1_{Tl}$$

$$Q2_{Tl_{ab}} := \left(\frac{1}{998} \cdot Q1_{Tl_{ab}} \right)$$

$$Q_{Tl} := \text{sort}(Q2_{Tl})$$

$$\text{CDF}_{Tl_{ab}} := \frac{(ab + 1) - 0.375}{(n1_{Tl} + 1) - 0.25}$$

Fit the seepage rates to a Weibull distribution.

The following equations are from *What Every Engineer Should Know About Reliability and Risk Analysis* (Modarres 1993 [DIRS 104667], p. 109)

$$n1_{Tl} = 3.875 \times 10^3$$

$$\beta := \text{root} \left[\left[\frac{\sum_{i=0}^{n1_{T1}} (Q_{T1_i})^r \cdot \ln(Q_{T1_i})}{\sum_{i=0}^{n1_{T1}} (Q_{T1_i})^r} - \left(\frac{1}{r}\right) - \left[\left(\frac{1}{n1_{T1}}\right) \cdot \sum_{i=0}^{n1_{T1}} \ln(Q_{T1_i})\right] \right], r, 0.1, 4 \right] \quad \beta = 0.52$$

$$\alpha := \left[\frac{\sum_{i=0}^{n1_{T1}} (Q_{T1_i})^\beta}{n1_{T1}} \right]^{\frac{1}{\beta}} \quad \alpha = 8.869 \times 10^{-3}$$

Plot of raw data versus Weibull distribution

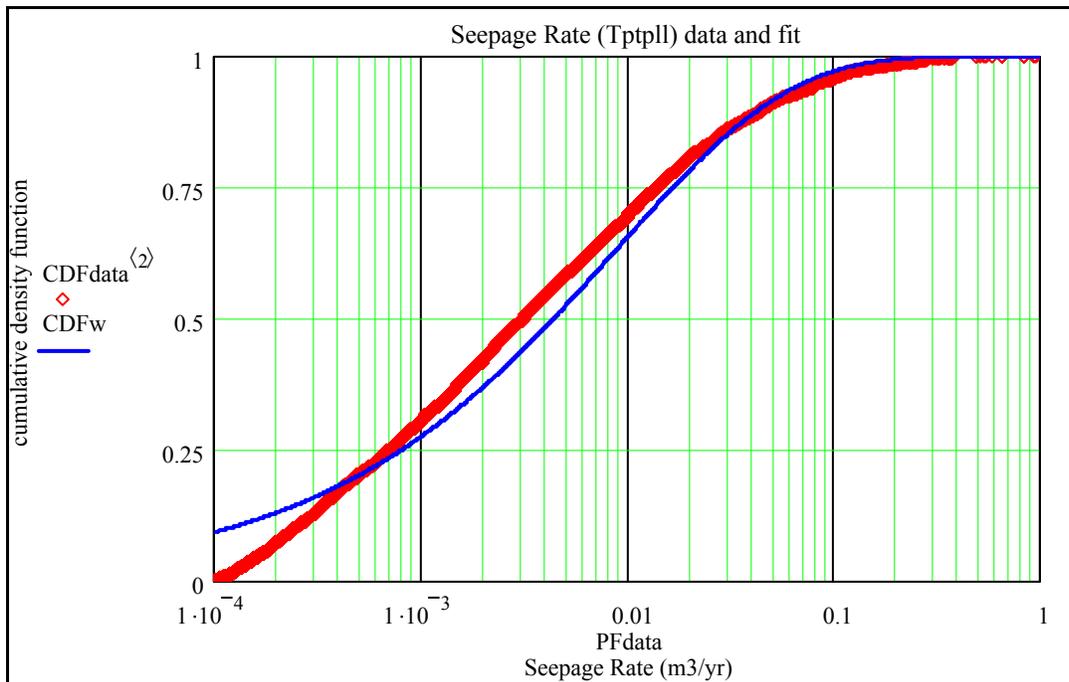
ji := 0..n1_T1

PFdata_ji := Q_T1_ji

CDFdata_ji,2 := CDF_T1_ji

CDFw1_ji := 1 - exp $\left[- \left(\frac{\text{PFdata}_j_i}{\alpha} \right)^\beta \right]$

CDFw_ji,0 := CDFw1_ji



IV.2 SEEPAGE ANALYSIS FOR MEAN INFILTRATION RATE IN THE LITHOPHYSAL ZONE

The following section presents the Mathcad analysis for the mean seepage infiltration rate of the glacial transition climate in the lithophysal zone. The seepage information used in this analysis was obtained from *Abstraction of Drift Seepage* (BSC 2003 [DIRS 165564]). The information contained in the section has been abstracted from the “seepage glac mean Tptpl driftcollapse report.mcd” Mathcad file of Attachment VII.

Seepage rate and seepage fraction calculation followed *Abstraction of Drift Seepage* (BSC 2003 [DIRS 165564], Section 6.7).

Latin Hypercube Sampling Routine to Generate Random Numbers

Sample Size: n := 20000

i := 1..n

RD_{i-1,0} := i RD_{i-1,3} := rnd(1.0) RD_{i-1,6} := rnd(1.0) RD_{i-1,9} := rnd(1.0) RD_{i-1,12} := rnd(1.0)
 RD_{i-1,1} := rnd(1.0) RD_{i-1,4} := rnd(1.0) RD_{i-1,7} := rnd(1.0) RD_{i-1,10} := rnd(1.0)
 RD_{i-1,2} := rnd(1.0) RD_{i-1,5} := rnd(1.0) RD_{i-1,8} := rnd(1.0) RD_{i-1,11} := rnd(1.0)

RKs are matrixes in which the first column contain a permutation on the integers on the interval [1,n].

RK1 := csort(RD, 1) RK4 := csort(RD, 4) RK7 := csort(RD, 7) RK10 := csort(RD, 10)
 RK2 := csort(RD, 2) RK5 := csort(RD, 5) RK8 := csort(RD, 8) RK11 := csort(RD, 11)
 RK3 := csort(RD, 3) RK6 := csort(RD, 6) RK9 := csort(RD, 9) RK12 := csort(RD, 12)

Define sets of random values. Each random value is selected within one of the equiprobable n intervals that partition [0,1], one set for each random variable.

$$X^{(0)} := \frac{RK1^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} \quad X^{(3)} := \frac{RK4^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} \quad X^{(6)} := \frac{RK7^{(0)} - 1 + \text{runif}(n, 0, 1)}{n}$$

$$X^{(1)} := \frac{RK2^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} \quad X^{(4)} := \frac{RK5^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} \quad X^{(7)} := \frac{RK8^{(0)} - 1 + \text{runif}(n, 0, 1)}{n}$$

$$X^{(2)} := \frac{RK3^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} \quad X^{(5)} := \frac{RK6^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} \quad X^{(8)} := \frac{RK9^{(0)} - 1 + \text{runif}(n, 0, 1)}{n}$$

$$X^{(9)} := \frac{RK10^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} \quad X^{(10)} := \frac{RK11^{(0)} - 1 + \text{runif}(n, 0, 1)}{n}$$

$$X^{(11)} := \frac{RK12^{(0)} - 1 + \text{runif}(n, 0, 1)}{n}$$

i := 0..n - 1

Capillary Strength $1/\alpha$ in (Pa)

$\alpha_{1lb} := 402$ $\alpha_{1ub} := 780$ $\alpha_{1\mu} := 591$ **Spatial variability follows a uniform distribution**

$\Delta\alpha_{1l} := -105$ $\Delta\alpha_{1\mu} := 0$ $\Delta\alpha_{1u} := 105$ **Uncertainty follows a triangular distribution**

Sampling from spatial variability to obtain the $1/\alpha$ value

$\alpha_{1i} := \text{qunif}(X_{i,0}, \alpha_{1lb}, \alpha_{1ub})$ **$1/\alpha$ value**

Sample from uncertainty triangular distribution to obtain $\Delta 1/\alpha$

Determine which equation to use:

if Random Number $< \text{RN}_{\Delta\alpha 1}$ then use Equation 1 ($\Delta\alpha 1eq1$).

if Random Number $> \text{RN}_{\Delta\alpha 1}$ then use Equation 2 ($\Delta\alpha 1eq2$).

$$\text{RN}_{\Delta\alpha 1} := \frac{(\Delta\alpha_{1\mu} - \Delta\alpha_{1l})^2}{(\Delta\alpha_{1u} - \Delta\alpha_{1l}) \cdot (\Delta\alpha_{1\mu} - \Delta\alpha_{1l})}$$

$$\Delta\alpha_{1eq1i} := \Delta\alpha_{1l} + \sqrt{X_{i,1} \cdot (\Delta\alpha_{1u} - \Delta\alpha_{1l}) \cdot (\Delta\alpha_{1\mu} - \Delta\alpha_{1l})}$$

$$\Delta\alpha_{1eq2i} := \Delta\alpha_{1u} - \sqrt{(1 - X_{i,1}) \cdot (\Delta\alpha_{1u} - \Delta\alpha_{1l}) \cdot (\Delta\alpha_{1u} - \Delta\alpha_{1\mu})}$$

$$\Delta\alpha_{1i} := \text{if} \left[\left(X_{i,1} \leq \text{RN}_{\Delta\alpha 1} \right), \Delta\alpha_{1eq1i}, \Delta\alpha_{1eq2i} \right] \quad \mathbf{\Delta 1/\alpha \text{ value}}$$

Overall Capillary Strength $1/\alpha + \Delta 1/\alpha$

$$T_{1\alpha_i} := \alpha_{1i} + \Delta\alpha_{1i} \quad \mathbf{1/\alpha \text{ value}}$$

Permeability k in Tptpl Unit (in log 10)

$\mu_{kTl} := -11.5$ **Mean of lognormal distribution**

$\sigma_{kTl} := 0.47$ **Standard deviation of lognormal distribution**

$$k_{Tli} := \ln \left(\text{qlnorm} \left(X_{i,2}, \mu_{kTl}, \sigma_{kTl} \right) \right)$$

$$\text{mean}(k_{Tl}) = -11.5$$

$$\text{Stdev}(k_{Tl}) = 0.47$$

Permeability Δk in Tptpl Unit (in log 10)

$\Delta k_{Tll} := -0.92$ $\Delta k_{Tl\mu} := 0$ $\Delta k_{Tlu} := 0.92$ **Uncertainty follows a triangular distribution**

Sample from uncertainty triangular distribution to obtain Δk

Determine which equation to use:

if Random Number < $RN_{\Delta k_{TI}}$ then use Equation 1 (Δk_{TIeq1}).

if Random Number > $RN_{\Delta k_{TI}}$ then use Equation 2 (Δk_{TIeq2}).

$$RN_{\Delta k_{TI}} := \frac{(\Delta k_{TI\mu} - \Delta k_{TII})^2}{(\Delta k_{TII} - \Delta k_{TII}) \cdot (\Delta k_{TII} - \Delta k_{TII})}$$

$$\Delta k_{TIeq1_i} := \Delta k_{TII} + \sqrt{X_{i,3} \cdot (\Delta k_{TII} - \Delta k_{TII}) \cdot (\Delta k_{TII} - \Delta k_{TII})}$$

$$\Delta k_{TIeq2_i} := \Delta k_{TII} - \sqrt{(1 - X_{i,3}) \cdot (\Delta k_{TII} - \Delta k_{TII}) \cdot (\Delta k_{TII} - \Delta k_{TII})}$$

$$\Delta k_{TI_i} := \text{if} \left[\left(X_{i,3} \leq RN_{\Delta k_{TI}} \right), \Delta k_{TIeq1_i}, \Delta k_{TIeq2_i} \right] \quad \Delta k \text{ value}$$

Overall Permeability $k + \Delta k$

$$T1_{k_{TI}_i} := k_{TI_i} + \Delta k_{TI_i}$$

Permeability must lie between -14 and -10 (bounds of SMPA simulations)

$$T_{k_{TI}_i} := \text{if} \left(T1_{k_{TI}_i} \geq -10, -10, \text{if} \left(T1_{k_{TI}_i} \leq -14, -14, T1_{k_{TI}_i} \right) \right) \quad k \text{ value}$$

Flow Focusing Factor (DTN: LB0104AMRU0185.012 [DIRS 163906])

$$f(x) := -0.3137x^4 + 5.4998x^3 - 35.66x^2 + 102.3x - 11.434$$

$$ff_i := \text{root} \left[f(x) - (X_{i,5} \cdot 100), x, 0, 6 \right]$$

Percolation Flux (mm/yr)

The percolation flux used here is for the glacial transition period only. The percolation flux is based on sampling from the mean bound TSPA repository location only (DTN: LB0310AMRU0120.002 [DIRS 166116])

$$nnn := 0..468$$

Mean Bound Percolation Flux

PF1_m :=

	0
0	15.97
1	19.87
2	14.2
3	7.59
4	16.94
5	17.76
6	10.45
7	27.77
8	8.95
9	16.02

$$PFt_{m_{nnn}} := PF1_{m_{nnn},0}$$

$$Z^{(0)} := \text{round}(\text{runif}(n, 0, 468))$$

$$PF_i := PFt_m(Z_i, 0)$$

Adjusted Percolation Flux

Multiply the flow-focusing factor by to the percolation flux, which will be used to obtain the seepage rate, seepage fraction, and seepage percentage

$$q1_{pff_i} := PF_i \cdot ff_i$$

Percolation Flux must lie between 1 and 1000 mm/yr (bounds of SMPA simulations)

$$q_{pff_i} := \text{if}(q1_{pff_i} \leq 1, 1, \text{if}(q1_{pff_i} \geq 1000, 1000, q1_{pff_i}))$$

**Seepage Information from SMPA analysis
(DTN: LB0307SEEPDRCL.002 [DIRS 164337])**

m := 2549 **Data points**

SMPA_{data}^{<0>} is permeability value log(k [m²])

SMPA_{data}^{<1>} is capillary strength 1/alpha [Pa]

SMPA_{data}^{<2>} is local percolation flux (mm/yr)

SMPA_{data}^{<3>} is Mean Seepage [kg/yr/WP]

SMPA_{data}^{<4>} is Std. Dev. Seepage [kg/yr/WP]

SMPA_{data}^{<5>} is Mean Seepage [%]

SMPA_{data}^{<6>} is Std. Dev. Seepage [%]

SMPA_{data} :=

	0	1	2	3	4	5	6
0	-14	100	1	56.44	5.47	100.6	9.75
1	-14	100	5	282.63	27.5	100.76	9.8
2	-14	100	10	566.16	55.13	100.92	9.83
3	-14	100	20	1135.12	109.85	101.17	9.79
4	-14	100	50	2849.95	272.25	101.6	9.71
5	-14	100	100	5726.78	535.98	102.08	9.55
6	-14	100	200	11523.63	1064.22	102.71	9.49
7	-14	100	300	17369.22	1583.08	103.2	9.41
8	-14	100	400	23241.94	2086.65	103.57	9.3
9	-14	100	500	29154.54	2552.38	103.94	9.1
10	-14	100	600	35097.8	2992.46	104.27	8.89
11	-14	100	700	41099.26	3411.36	104.66	8.69
12	-14	100	800	47084.03	3860.77	104.91	8.6
13	-14	100	900	53190.45	4145.2	105.35	8.21
14	-14	100	1000	59206.88	4520.61	105.54	8.06
15	-14	200	1	55.25	5.44	98.48	9.69

Develop routine to select correct mean seepage, seepage standard deviation, seepage percent, and seepage percent standard deviation based on sampled value of 1/ α , k, percolation flux.

nx := 14 ny := 9 nz := 16

ii := 0..nx

x_{ii} := SMPA_{data}_{ii,2} x_{ii}ⁱ := ii

jj := 0..ny

y_{jj} := 100*jj + 100 y_{jj}^j := jj

kk := 0..nz

z_{kk} := -14 + kk*0.25 z_{kk}^k := kk

loc represents the location within the matrix of which value to pick for the interpolation process

$$\text{loc}_{1_i} := \text{floor}\left(\text{linterp}\left(z, z_k, T_{kT1_i}\right)\right) \cdot (nx + 1) \cdot (ny + 1) + \text{floor}\left(\text{linterp}\left(y, y_j, T_{1\alpha_i}\right)\right) \cdot (nx + 1) \dots \\ + \text{floor}\left(\text{linterp}\left(x, x_i, q_{pff_i}\right)\right)$$

$$s_{ms1_i} := \text{SMPA}_{\text{data loc}_{1_i}, 3}$$

$$s_{msd1_i} := \text{SMPA}_{\text{data loc}_{1_i}, 4}$$

$$s_{pms1_i} := \text{SMPA}_{\text{data loc}_{1_i}, 5}$$

$$s_{psd1_i} := \text{SMPA}_{\text{data loc}_{1_i}, 6}$$

$$\text{loc}_{2_i} := \left[\text{floor}\left(\text{linterp}\left(z, z_k, T_{kT1_i}\right)\right) \cdot (nx + 1) \cdot (ny + 1) \right] + \text{floor}\left(\text{linterp}\left(y, y_j, T_{1\alpha_i}\right)\right) \cdot (nx + 1) \dots \\ + \text{ceil}\left(\text{linterp}\left(x, x_i, q_{pff_i}\right)\right)$$

$$s_{ms2_i} := \text{SMPA}_{\text{data loc}_{2_i}, 3}$$

$$s_{msd2_i} := \text{SMPA}_{\text{data loc}_{2_i}, 4}$$

$$s_{pms2_i} := \text{SMPA}_{\text{data loc}_{2_i}, 5}$$

$$s_{psd2_i} := \text{SMPA}_{\text{data loc}_{2_i}, 6}$$

$$\text{loc}_{3_i} := \text{floor}\left(\text{linterp}\left(z, z_k, T_{kT1_i}\right)\right) \cdot (nx + 1) \cdot (ny + 1) + \text{ceil}\left(\text{linterp}\left(y, y_j, T_{1\alpha_i}\right)\right) \cdot (nx + 1) \dots \\ + \text{ceil}\left(\text{linterp}\left(x, x_i, q_{pff_i}\right)\right)$$

$$s_{ms3_i} := \text{SMPA}_{\text{data loc}_{3_i}, 3}$$

$$s_{msd3_i} := \text{SMPA}_{\text{data loc}_{3_i}, 4}$$

$$s_{pms3_i} := \text{SMPA}_{\text{data loc}_{3_i}, 5}$$

$$s_{psd3_i} := \text{SMPA}_{\text{data loc}_{3_i}, 6}$$

$$\text{loc}_{4_i} := \text{floor}\left(\text{linterp}\left(z, z_k, T_{kT1_i}\right)\right) \cdot (nx + 1) \cdot (ny + 1) + \text{ceil}\left(\text{linterp}\left(y, y_j, T_{1\alpha_i}\right)\right) \cdot (nx + 1) \dots \\ + \text{floor}\left(\text{linterp}\left(x, x_i, q_{pff_i}\right)\right)$$

$$s_{ms4_i} := \text{SMPA}_{\text{data loc}_{4_i}, 3}$$

$$s_{msd4_i} := \text{SMPA}_{\text{data loc}_{4_i}, 4}$$

$$s_{pms4_i} := \text{SMPA}_{\text{data loc}_{4_i}, 5}$$

$$s_{psd4_i} := \text{SMPA}_{\text{data loc}_{4_i}, 6}$$

$$\text{loc}_{5_i} := \left[\text{ceil} \left(\text{linterp} \left(z, z_k, T_{kTl_i} \right) \right) \cdot (nx + 1) \cdot (ny + 1) \right] + \text{floor} \left(\text{linterp} \left(y, y_j, T_{1\alpha_i} \right) \right) \cdot (nx + 1) \dots \\ + \text{floor} \left(\text{linterp} \left(x, x_i, q_{pff_i} \right) \right)$$

$$s_{ms5_i} := \text{SMPA}_{\text{data loc}_{5_i}, 3}$$

$$s_{msd5_i} := \text{SMPA}_{\text{data loc}_{5_i}, 4}$$

$$s_{pms5_i} := \text{SMPA}_{\text{data loc}_{5_i}, 5}$$

$$s_{psd5_i} := \text{SMPA}_{\text{data loc}_{5_i}, 6}$$

$$\text{loc}_{6_i} := \text{ceil} \left(\text{linterp} \left(z, z_k, T_{kTl_i} \right) \right) \cdot (nx + 1) \cdot (ny + 1) + \text{floor} \left(\text{linterp} \left(y, y_j, T_{1\alpha_i} \right) \right) \cdot (nx + 1) \dots \\ + \text{ceil} \left(\text{linterp} \left(x, x_i, q_{pff_i} \right) \right)$$

$$s_{ms6_i} := \text{SMPA}_{\text{data loc}_{6_i}, 3}$$

$$s_{msd6_i} := \text{SMPA}_{\text{data loc}_{6_i}, 4}$$

$$s_{pms6_i} := \text{SMPA}_{\text{data loc}_{6_i}, 5}$$

$$s_{psd6_i} := \text{SMPA}_{\text{data loc}_{6_i}, 6}$$

$$\text{loc}_{7_i} := \left[\text{ceil} \left(\text{linterp} \left(z, z_k, T_{kTl_i} \right) \right) \cdot (nx + 1) \cdot (ny + 1) \right] + \text{ceil} \left(\text{linterp} \left(y, y_j, T_{1\alpha_i} \right) \right) \cdot (nx + 1) \dots \\ + \text{ceil} \left(\text{linterp} \left(x, x_i, q_{pff_i} \right) \right)$$

$$s_{ms7_i} := \text{SMPA}_{\text{data loc}_{7_i}, 3}$$

$$s_{msd7_i} := \text{SMPA}_{\text{data loc}_{7_i}, 4}$$

$$s_{pms7_i} := \text{SMPA}_{\text{data loc}_{7_i}, 5}$$

$$s_{psd7_i} := \text{SMPA}_{\text{data loc}_{7_i}, 6}$$

$$\text{loc}_{8_i} := \text{ceil} \left(\text{linterp} \left(z, z_k, T_{kTl_i} \right) \right) \cdot (nx + 1) \cdot (ny + 1) + \text{ceil} \left(\text{linterp} \left(y, y_j, T_{1\alpha_i} \right) \right) \cdot (nx + 1) \dots \\ + \text{floor} \left(\text{linterp} \left(x, x_i, q_{pff_i} \right) \right)$$

$$s_{ms8_i} := \text{SMPA}_{\text{data loc}_{8_i}, 3}$$

$$s_{msd8_i} := \text{SMPA}_{\text{data loc}_{8_i}, 4}$$

$$s_{pms8_i} := \text{SMPA}_{\text{data loc}_{8_i}, 5}$$

$$s_{psd8_i} := \text{SMPA}_{\text{data loc}_{8_i}, 6}$$

Develop the upper and lower bound of the randomly generated $1/\alpha$, k, and adjusted percolation flux

Develop the upper and lower bound for permeability (k) for Tptpl Unit

$$\begin{aligned}
 qq_i &:= -1 \cdot T_{kT1}_i \\
 \text{mantissa}(x) &:= x - \text{floor}(qq) \\
 tt_i &:= \text{floor}(qq_i) \\
 rr &:= \text{round}(\text{mantissa}(qq), 2) \\
 yy1_i &:= \text{if}(rr_i \leq 0.25, 0, \text{if}(0.25 < rr_i \leq 0.5, 0.25, rr_i)) \\
 zz1_i &:= \text{if}(yy1_i \leq 0.5, yy1_i, \text{if}(0.5 < yy1_i \leq 0.75, 0.5, 0.75)) \\
 T_{kT12}_i &:= -1 \cdot (tt_i + zz1_i) \\
 yy2_i &:= \text{if}(rr_i \leq 0.25, 0.25, \text{if}(0.25 < rr_i \leq 0.5, 0.5, rr_i)) \\
 zz2_i &:= \text{if}(yy2_i \leq 0.5, yy2_i, \text{if}(0.5 < yy2_i \leq 0.75, 0.75, 1)) \\
 T_{kT11}_i &:= -1 \cdot (tt_i + zz2_i)
 \end{aligned}$$

Develop the upper and lower bound for capillary strength ($1/\alpha$)

$$\begin{aligned}
 hh1_i &:= \text{floor}\left(\frac{T_{1\alpha}_i}{100}\right) \\
 T_{1\alpha1}_i &:= (hh1_i \cdot 100) \\
 hh2_i &:= \text{ceil}\left(\frac{T_{1\alpha}_i}{100}\right) \\
 T_{1\alpha2}_i &:= (hh2_i \cdot 100)
 \end{aligned}$$

Lower Bound value adjusted percolation flux (q_{pff})

$$\begin{aligned}
 aaa1_i &:= \text{if}(q_{pff}_i \leq 1, 1, \text{if}(1 < q_{pff}_i \leq 5, 1, q_{pff}_i)) \\
 bbb1_i &:= \text{if}(aaa1_i \leq 5, aaa1_i, \text{if}(5 < aaa1_i \leq 10, 5, aaa1_i)) \\
 ccc1_i &:= \text{if}(bbb1_i \leq 10, bbb1_i, \text{if}(10 < bbb1_i \leq 20, 10, bbb1_i)) \\
 ddd1_i &:= \text{if}(ccc1_i \leq 20, ccc1_i, \text{if}(20 < ccc1_i \leq 50, 20, ccc1_i)) \\
 eee1_i &:= \text{if}(ddd1_i \leq 50, ddd1_i, \text{if}(50 < ddd1_i \leq 100, 50, ddd1_i)) \\
 fff1_i &:= \text{if}(eee1_i \leq 100, eee1_i, \text{if}(100 < eee1_i \leq 200, 100, eee1_i))
 \end{aligned}$$

$$\begin{aligned}
 ggg1_i &:= \text{if}(fff1_i \leq 200, fff1_i, \text{if}(200 < fff1_i \leq 300, 200, fff1_i)) \\
 hhh1_i &:= \text{if}(ggg1_i \leq 300, ggg1_i, \text{if}(300 < ggg1_i \leq 400, 300, ggg1_i)) \\
 iii1_i &:= \text{if}(hhh1_i \leq 400, hhh1_i, \text{if}(400 < hhh1_i \leq 500, 400, hhh1_i)) \\
 jjj1_i &:= \text{if}(iii1_i \leq 500, iii1_i, \text{if}(500 < iii1_i \leq 600, 500, iii1_i)) \\
 kkk1_i &:= \text{if}(jjj1_i \leq 600, jjj1_i, \text{if}(600 < jjj1_i \leq 700, 600, jjj1_i)) \\
 mmm1_i &:= \text{if}(kkk1_i \leq 700, kkk1_i, \text{if}(700 < kkk1_i \leq 800, 700, kkk1_i)) \\
 q_{pff1_i} &:= \text{if}(mmm1_i \leq 800, mmm1_i, \text{if}(800 < mmm1_i \leq 900, 800, 900))
 \end{aligned}$$

Upper Bound value adjusted percolation flux (q_{pff})

$$\begin{aligned}
 aaa2_i &:= \text{if}(q_{pff1_i} \leq 1, 5, \text{if}(1 < q_{pff1_i} \leq 5, 5, q_{pff1_i})) \\
 bbb2_i &:= \text{if}(aaa2_i \leq 5, aaa2_i, \text{if}(5 < aaa2_i \leq 10, 10, aaa2_i)) \\
 ccc2_i &:= \text{if}(bbb2_i \leq 10, bbb2_i, \text{if}(10 < bbb2_i \leq 20, 20, bbb2_i)) \\
 ddd2_i &:= \text{if}(ccc2_i \leq 20, ccc2_i, \text{if}(20 < ccc2_i \leq 50, 50, ccc2_i)) \\
 eee2_i &:= \text{if}(ddd2_i \leq 50, ddd2_i, \text{if}(50 < ddd2_i \leq 100, 100, ddd2_i)) \\
 fff2_i &:= \text{if}(eee2_i \leq 100, eee2_i, \text{if}(100 < eee2_i \leq 200, 200, eee2_i)) \\
 ggg2_i &:= \text{if}(fff2_i \leq 200, fff2_i, \text{if}(200 < fff2_i \leq 300, 300, fff2_i)) \\
 hhh2_i &:= \text{if}(ggg2_i \leq 300, ggg2_i, \text{if}(300 < ggg2_i \leq 400, 400, ggg2_i)) \\
 iii2_i &:= \text{if}(hhh2_i \leq 400, hhh2_i, \text{if}(400 < hhh2_i \leq 500, 500, hhh2_i)) \\
 jjj2_i &:= \text{if}(iii2_i \leq 500, iii2_i, \text{if}(500 < iii2_i \leq 600, 600, iii2_i)) \\
 kkk2_i &:= \text{if}(jjj2_i \leq 600, jjj2_i, \text{if}(600 < jjj2_i \leq 700, 700, jjj2_i)) \\
 mmm2_i &:= \text{if}(kkk2_i \leq 700, kkk2_i, \text{if}(700 < kkk2_i \leq 800, 800, kkk2_i)) \\
 q_{pff2_i} &:= \text{if}(mmm2_i \leq 800, mmm2_i, \text{if}(800 < mmm2_i \leq 900, 900, 1000))
 \end{aligned}$$

Solve for seepage rate (Tptpl Unit)

$$t_{q_{pff1_i}} := \frac{q_{pff1_i} - q_{pff2_i}}{q_{pff2_i} - q_{pff1_i}} \quad u_{T1\alpha_i} := \frac{T_{1\alpha_i} - T_{1\alpha1_i}}{T_{1\alpha2_i} - T_{1\alpha1_i}} \quad v_{TKT1_i} := \frac{T_{kT1_i} - T_{kT11_i}}{T_{kT12_i} - T_{kT11_i}}$$

$$\begin{aligned}
 \text{spflux}_{T1m_i} := & (1 - t_{\text{qpf}i}) \cdot (1 - u_{T1\alpha_i}) \cdot (1 - v_{TkTl_i}) \cdot s_{ms1_i} \dots \\
 & + (t_{\text{qpf}i}) \cdot (1 - u_{T1\alpha_i}) \cdot (1 - v_{TkTl_i}) \cdot s_{ms2_i} \dots \\
 & + (t_{\text{qpf}i}) \cdot (u_{T1\alpha_i}) \cdot (1 - v_{TkTl_i}) \cdot s_{ms3_i} \dots \\
 & + (1 - t_{\text{qpf}i}) \cdot (u_{T1\alpha_i}) \cdot (1 - v_{TkTl_i}) \cdot s_{ms4_i} \dots \\
 & + (1 - t_{\text{qpf}i}) \cdot (1 - u_{T1\alpha_i}) \cdot (v_{TkTl_i}) \cdot s_{ms5_i} \dots \\
 & + (t_{\text{qpf}i}) \cdot (1 - u_{T1\alpha_i}) \cdot (v_{TkTl_i}) \cdot s_{ms6_i} \dots \\
 & + (t_{\text{qpf}i}) \cdot (u_{T1\alpha_i}) \cdot (v_{TkTl_i}) \cdot s_{ms7_i} \dots \\
 & + (1 - t_{\text{qpf}i}) \cdot (u_{T1\alpha_i}) \cdot (v_{TkTl_i}) \cdot s_{ms8_i}
 \end{aligned}$$

$$\begin{aligned}
 \text{spflux}_{T1sd_i} := & (1 - t_{\text{qpf}i}) \cdot (1 - u_{T1\alpha_i}) \cdot (1 - v_{TkTl_i}) \cdot s_{msd1_i} \dots \\
 & + (t_{\text{qpf}i}) \cdot (1 - u_{T1\alpha_i}) \cdot (1 - v_{TkTl_i}) \cdot s_{msd2_i} \dots \\
 & + (t_{\text{qpf}i}) \cdot (u_{T1\alpha_i}) \cdot (1 - v_{TkTl_i}) \cdot s_{msd3_i} \dots \\
 & + (1 - t_{\text{qpf}i}) \cdot (u_{T1\alpha_i}) \cdot (1 - v_{TkTl_i}) \cdot s_{msd4_i} \dots \\
 & + (1 - t_{\text{qpf}i}) \cdot (1 - u_{T1\alpha_i}) \cdot (v_{TkTl_i}) \cdot s_{msd5_i} \dots \\
 & + (t_{\text{qpf}i}) \cdot (1 - u_{T1\alpha_i}) \cdot (v_{TkTl_i}) \cdot s_{msd6_i} \dots \\
 & + (t_{\text{qpf}i}) \cdot (u_{T1\alpha_i}) \cdot (v_{TkTl_i}) \cdot s_{msd7_i} \dots \\
 & + (1 - t_{\text{qpf}i}) \cdot (u_{T1\alpha_i}) \cdot (v_{TkTl_i}) \cdot s_{msd8_i}
 \end{aligned}$$

Calculate mean seepage for Tptpl Unit

$$QT11_{stdl_i} := -1.7321 \cdot \text{spflux}_{T1sd_i}$$

$$QT11_{stdu_i} := 1.7321 \cdot \text{spflux}_{T1sd_i}$$

$$QT1_{stdl_i} := \text{if}(QT11_{stdl_i} = 0, -0.00001, QT11_{stdl_i})$$

$$QT1_{std_i} := \text{qunif}(X_{i,10}, QT1_{stdl_i}, QT11_{stdu_i})$$

$$QT11_{spm_i} := \text{spflux}_{T1m_i} + QT1_{std_i}$$

$$QT12_{spm_i} := \text{if}(QT11_{spm_i} \leq 0.1, 0, QT11_{spm_i})$$

$$QT2_{perc_i} := \frac{QT12_{spm_i} \cdot 100}{q_{pff_i} \cdot 28.052}$$

Equation to calculate seepage percent based on seepage rate (see SMPA data table) from DTN: LB0310AMRU0120.002 [DIRS 166116]

$$QT3_{perc_i} := \text{if}(QT2_{perc_i} \leq 0, 0, \text{if}(QT2_{perc_i} \geq 100, 100, QT2_{perc_i}))$$

Check seepage percent; if above 100 percent, then recalculate seepage back to 100 percent.

$$QT_{spr_i} := QT3_{perc_i} \cdot q_{pff_i} \cdot \frac{2 \cdot 28.05}{100} \quad \text{Mean Seepage Rate (kg/yr per WP)}$$

$$\text{mean}(QT_{spr}) = 175.204$$

Determine the seepage fraction for Tptpl Unit within the repository and then fit the output data to distribution

Seepage fraction represents the non-zero seepage rates based on the LHS sampling of all of the parameters

$$\text{sort}(QT_{spr}) =$$

	0
9713	0
9714	0
9715	0.1
9716	0.1
9717	0.1

$$n_{T1} := 9714$$

$$\text{spfr}_{T1} := \frac{(n - 1) - n_{T1}}{n} \quad \text{spfr}_{T1} = 0.514 \quad \text{Seepage fraction (i.e., waste package locations that see seepage)}$$

$$n1_{T1} := (n - 1) - (n_{T1} + 1)$$

$$Q11_{T1} := \text{sort}(QT_{spr})$$

$$Q1_{T1} := \text{reverse}(Q11_{T1})$$

$$ab := 0..n1_{T1}$$

$$Q2_{T1_{ab}} := \left(\frac{1}{998} \cdot Q1_{T1_{ab}} \right)$$

$$Q_{T1} := \text{sort}(Q2_{T1})$$

$$\text{mean}(Q_{T1} \cdot 998) = 340.699$$

$$CDF_{T1_{ab}} := \frac{(ab + 1) - 0.375}{(n1_{T1} + 1) - 0.25}$$

Fit the seepage rates to a Weibull distribution.

The following equations are from *What Every Engineer Should Know About Reliability and Risk Analysis* (Modarres 1993 [DIRS 104667], p. 109).

$$n1_{T1} = 1.028 \times 10^4$$

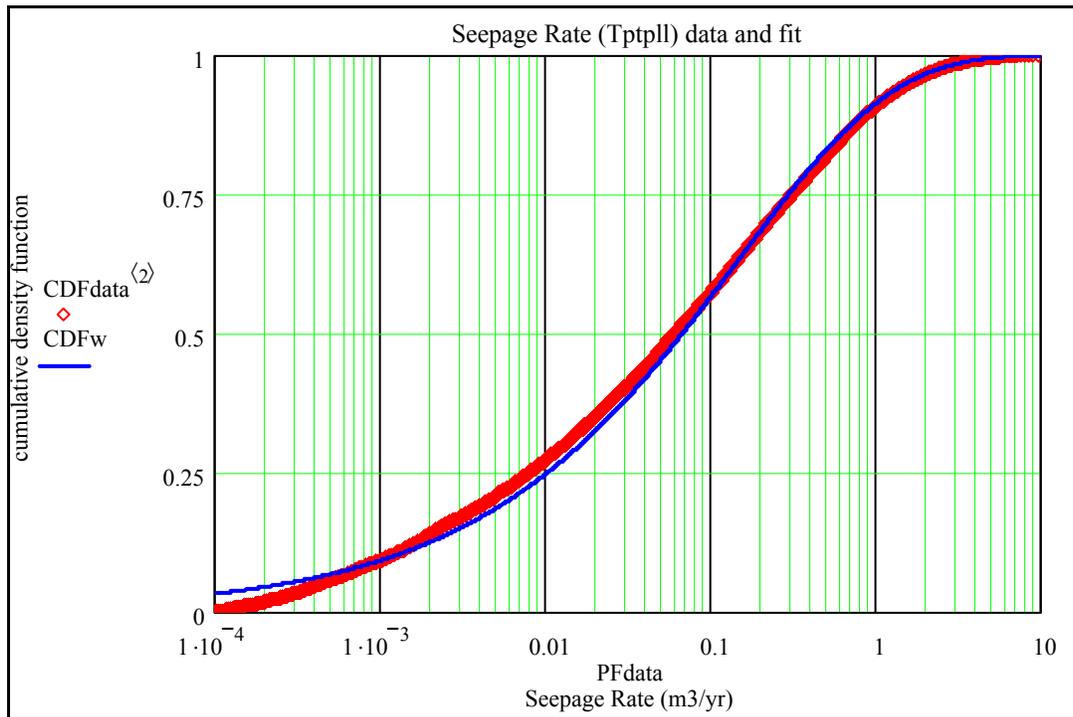
$$\beta := \text{root} \left[\left[\frac{\sum_{i=0}^{n1_{T1}} (Q_{T1_i})^r \cdot \ln(Q_{T1_i})}{\sum_{i=0}^{n1_{T1}} (Q_{T1_i})^r} - \left(\frac{1}{r}\right) - \left[\left(\frac{1}{n1_{T1}}\right) \cdot \sum_{i=0}^{n1_{T1}} \ln(Q_{T1_i})\right] \right], r, 0.1, 4 \right] \quad \beta = 0.468$$

$$\alpha := \left[\frac{\sum_{i=0}^{n1_{T1}} (Q_{T1_i})^\beta}{n1_{T1}} \right]^{\frac{1}{\beta}} \quad \alpha = 1.464 \times 10^{-1}$$

Plot of raw data versus Weibull distribution

```

ji := 0.. n1_T1
PFdata_ji := Q_T1_ji
CDFdata_ji,2 := CDF_T1_ji
CDFw1_ji := 1 - exp[-(PFdata_ji)^beta / alpha]
CDFw_ji,0 := CDFw1_ji
    
```



IV.3 SEEPAGE ANALYSIS FOR UPPER INFILTRATION RATE IN THE LITHOPHYSAL ZONE

The following section presents the Mathcad analysis for the upper seepage infiltration rate of the glacial transition climate in the lithophysal zone. The seepage information used in this analysis was obtained from *Abstraction of Drift Seepage* (BSC 2003 [DIRS 165564]). The information contained in the section has been abstracted from the “seepage glac upper Tptpl driftcollapse report.mcd” Mathcad file of Attachment VII.

Seepage rate and seepage fraction calculation followed *Abstraction of Drift Seepage* (BSC 2003 [DIRS 165564], Section 6.7).

Latin Hypercube Sampling Routine to Generate Random Numbers

Sample Size: n := 20000

i := 1..n

RD_{i-1,0} := i RD_{i-1,3} := rnd(1.0) RD_{i-1,6} := rnd(1.0) RD_{i-1,9} := rnd(1.0) RD_{i-1,12} := rnd(1.0)
 RD_{i-1,1} := rnd(1.0) RD_{i-1,4} := rnd(1.0) RD_{i-1,7} := rnd(1.0) RD_{i-1,10} := rnd(1.0)
 RD_{i-1,2} := rnd(1.0) RD_{i-1,5} := rnd(1.0) RD_{i-1,8} := rnd(1.0) RD_{i-1,11} := rnd(1.0)

RKs are matrixes in which the first column contain a permutation on the integers on the interval [1,n].

RK1 := csort(RD, 1) RK4 := csort(RD, 4) RK7 := csort(RD, 7) RK10 := csort(RD, 10)
 RK2 := csort(RD, 2) RK5 := csort(RD, 5) RK8 := csort(RD, 8) RK11 := csort(RD, 11)
 RK3 := csort(RD, 3) RK6 := csort(RD, 6) RK9 := csort(RD, 9) RK12 := csort(RD, 12)

Define sets of random values. Each random value is selected within one of the equiprobable n intervals that partition [0,1], one set for each random variable.

$$X^{(0)} := \frac{RK1^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} \quad X^{(3)} := \frac{RK4^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} \quad X^{(6)} := \frac{RK7^{(0)} - 1 + \text{runif}(n, 0, 1)}{n}$$

$$X^{(1)} := \frac{RK2^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} \quad X^{(4)} := \frac{RK5^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} \quad X^{(7)} := \frac{RK8^{(0)} - 1 + \text{runif}(n, 0, 1)}{n}$$

$$X^{(2)} := \frac{RK3^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} \quad X^{(5)} := \frac{RK6^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} \quad X^{(8)} := \frac{RK9^{(0)} - 1 + \text{runif}(n, 0, 1)}{n}$$

$$X^{(9)} := \frac{RK10^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} \quad X^{(10)} := \frac{RK11^{(0)} - 1 + \text{runif}(n, 0, 1)}{n}$$

$$X^{(11)} := \frac{RK12^{(0)} - 1 + \text{runif}(n, 0, 1)}{n}$$

i := 0..n - 1

Capillary Strength $1/\alpha$ in (Pa)

$\alpha_{1lb} := 402$ $\alpha_{1ub} := 780$ $\alpha_{1\mu} := 591$ **Spatial variability follows a uniform distribution**

$\Delta\alpha_{1l} := -105$ $\Delta\alpha_{1\mu} := 0$ $\Delta\alpha_{1u} := 105$ **Uncertainty follows a triangular distribution**

Sampling from spatial variability to obtain the $1/\alpha$ value

$\alpha_{1i} := \text{qunif}(X_{i,0}, \alpha_{1lb}, \alpha_{1ub})$ **$1/\alpha$ value**

Sample from uncertainty triangular distribution to obtain $\Delta 1/\alpha$

Determine which equation to use:

if Random Number $< \text{RN}_{\Delta\alpha 1}$ then use Equation 1 ($\Delta\alpha 1_{eq1}$).

if Random Number $> \text{RN}_{\Delta\alpha 1}$ then use Equation 2 ($\Delta\alpha 1_{eq2}$).

$$\text{RN}_{\Delta\alpha 1} := \frac{(\Delta\alpha_{1\mu} - \Delta\alpha_{1l})^2}{(\Delta\alpha_{1u} - \Delta\alpha_{1l}) \cdot (\Delta\alpha_{1\mu} - \Delta\alpha_{1l})}$$

$$\Delta\alpha_{1_{eq1}} := \Delta\alpha_{1l} + \sqrt{X_{i,1} \cdot (\Delta\alpha_{1u} - \Delta\alpha_{1l}) \cdot (\Delta\alpha_{1\mu} - \Delta\alpha_{1l})}$$

$$\Delta\alpha_{1_{eq2}} := \Delta\alpha_{1u} - \sqrt{(1 - X_{i,1}) \cdot (\Delta\alpha_{1u} - \Delta\alpha_{1l}) \cdot (\Delta\alpha_{1u} - \Delta\alpha_{1\mu})}$$

$\Delta\alpha_{1i} := \text{if} \left[\left(X_{i,1} \leq \text{RN}_{\Delta\alpha 1} \right), \Delta\alpha_{1_{eq1}}, \Delta\alpha_{1_{eq2}} \right]$ **$\Delta 1/\alpha$ value**

Overall Capillary Strength $1/\alpha + \Delta 1/\alpha$

$T_{1\alpha_i} := \alpha_{1i} + \Delta\alpha_{1i}$ **$1/\alpha$ value**

Permeability k in Tptpl Unit (in log 10)

$\mu_{k_{Tl}} := -11.5$ **Mean of lognormal distribution**

$\sigma_{k_{Tl}} := 0.47$ **Standard deviation of lognormal distribution**

$$k_{Tl_i} := \ln(\text{qlnorm}(X_{i,2}, \mu_{k_{Tl}}, \sigma_{k_{Tl}}))$$

$$\text{mean}(k_{Tl}) = -11.5$$

$$\text{Stdev}(k_{Tl}) = 0.47$$

Permeability Δk in Tptpl Unit (in log 10)

$\Delta k_{Tlu} := -0.92$ $\Delta k_{Tl\mu} := 0$ $\Delta k_{Tlu} := 0.92$ **Uncertainty follows a triangular distribution**

Sample from uncertainty triangular distribution to obtain Δk

Determine which equation to use:

if Random Number < $RN_{\Delta k_{TI}}$ then use Equation 1 (Δk_{Tleq1}).

if Random Number > $RN_{\Delta k_{TI}}$ then use Equation 2 (Δk_{Tleq2}).

$$RN_{\Delta k_{TI}} := \frac{(\Delta k_{Tl\mu} - \Delta k_{Tll})^2}{(\Delta k_{Tlu} - \Delta k_{Tll}) \cdot (\Delta k_{Tl\mu} - \Delta k_{Tll})}$$

$$\Delta k_{Tleq1_i} := \Delta k_{Tll} + \sqrt{X_{i,3} \cdot (\Delta k_{Tlu} - \Delta k_{Tll}) \cdot (\Delta k_{Tl\mu} - \Delta k_{Tll})}$$

$$\Delta k_{Tleq2_i} := \Delta k_{Tlu} - \sqrt{(1 - X_{i,3}) \cdot (\Delta k_{Tlu} - \Delta k_{Tll}) \cdot (\Delta k_{Tlu} - \Delta k_{Tl\mu})}$$

$$\Delta k_{Tl_i} := \text{if} \left[\left(X_{i,3} \leq RN_{\Delta k_{TI}} \right), \Delta k_{Tleq1_i}, \Delta k_{Tleq2_i} \right] \quad \Delta k \text{ value}$$

Overall Permeability $k + \Delta k$

$$Tl_{k_{TI}_i} := k_{Tl_i} + \Delta k_{Tl_i}$$

Permeability must lie between -14 and -10 (bounds of SMPA simulations)

$$T_{k_{TI}_i} := \text{if} \left(Tl_{k_{TI}_i} \geq -10, -10, \text{if} \left(Tl_{k_{TI}_i} \leq -14, -14, Tl_{k_{TI}_i} \right) \right) \quad k \text{ value}$$

Flow Focusing Factor (DTN: LB0104AMRU0185.012 [DIRS 163906])

$$f(x) := -0.3137x^4 + 5.4998x^3 - 35.66x^2 + 102.3x - 11.434$$

$$ff_i := \text{root} \left[f(x) - \left(X_{i,5} \cdot 100 \right), x, 0, 6 \right]$$

Percolation Flux (mm/yr)

The percolation flux used here is for the glacial transition period only. The percolation flux is based on sampling from the upper bound TSPA repository location only (DTN: LB0310AMRU0120.002 [DIRS 166116])

$$nnn := 0..468$$

Upper Bound Percolation Flux

$$PF1_u :=$$

	0
0	40
1	36.19
2	35.73
3	27.83
4	30.74
5	40.03
6	31.86
7	57.08
8	18.33
9	27.91

$$PFt_{u_{nnn}} := PF1_u_{nnn,0}$$

$$Z^{(0)} := \text{round}(\text{runif}(n, 0, 468))$$

$$PF_i := PFt_u(Z_i, 0)$$

Adjusted Percolation Flux

Multiply the flow-focusing factor by the percolation flux, which will be used to obtain the seepage rate, seepage fraction, and seepage percentage

$$q1_{pff_i} := PF_i \cdot ff_i$$

Percolation Flux must lie between 1 and 1000 mm/yr (bounds of SMPA simulations)

$$q_{pff_i} := \text{if}(q1_{pff_i} \leq 1, 1, \text{if}(q1_{pff_i} \geq 1000, 1000, q1_{pff_i}))$$

**Seepage Information from SMPA analysis
(DTN: LB0307SEEPDRCL.002 [DIRS 164337])**

m := 2549 **Data points**

SMPA_{data}^{<0>} is permeability value log(k [m²])

SMPA_{data}^{<1>} is capillary strength 1/alpha [Pa]

SMPA_{data}^{<2>} is local percolation flux (mm/yr)

SMPA_{data}^{<3>} is Mean Seepage [kg/yr/WP]

SMPA_{data}^{<4>} is Std. Dev. Seepage [kg/yr/WP]

SMPA_{data}^{<5>} is Mean Seepage [%]

SMPA_{data}^{<6>} is Std. Dev. Seepage [%]

SMPA_{data} :=

	0	1	2	3	4	5	6
0	-14	100	1	56.44	5.47	100.6	9.75
1	-14	100	5	282.63	27.5	100.76	9.8
2	-14	100	10	566.16	55.13	100.92	9.83
3	-14	100	20	1135.12	109.85	101.17	9.79
4	-14	100	50	2849.95	272.25	101.6	9.71
5	-14	100	100	5726.78	535.98	102.08	9.55
6	-14	100	200	11523.63	1064.22	102.71	9.49
7	-14	100	300	17369.22	1583.08	103.2	9.41
8	-14	100	400	23241.94	2086.65	103.57	9.3
9	-14	100	500	29154.54	2552.38	103.94	9.1
10	-14	100	600	35097.8	2992.46	104.27	8.89
11	-14	100	700	41099.26	3411.36	104.66	8.69
12	-14	100	800	47084.03	3860.77	104.91	8.6
13	-14	100	900	53190.45	4145.2	105.35	8.21
14	-14	100	1000	59206.88	4520.61	105.54	8.06
15	-14	200	1	55.25	5.44	98.48	9.69

Develop routine to select correct mean seepage, seepage standard deviation, seepage percent, and seepage percent standard deviation based on sampled value of 1/ α , k, percolation flux

nx := 14 ny := 9 nz := 16

ii := 0..nx

x_{ii} := SMPA_{data}_{ii,2} xi_{ii} := ii

jj := 0..ny

y_{jj} := 100·jj + 100 yj_{jj} := jj

kk := 0..nz

z_{kk} := -14 + kk·0.25 zk_{kk} := kk

loc represents the location within the matrix of which value to pick for the interpolation process

$$\text{loc}_{1_i} := \text{floor}\left(\text{linterp}\left(z, z_k, T_{kT1_i}\right)\right) \cdot (n_x + 1) \cdot (n_y + 1) + \text{floor}\left(\text{linterp}\left(y, y_j, T_{1\alpha_i}\right)\right) \cdot (n_x + 1) \dots \\ + \text{floor}\left(\text{linterp}\left(x, x_i, q_{\text{pff}_i}\right)\right)$$

$$s_{\text{ms}1_i} := \text{SMPA}_{\text{data}_{\text{loc}_{1_i}, 3}}$$

$$s_{\text{msd}1_i} := \text{SMPA}_{\text{data}_{\text{loc}_{1_i}, 4}}$$

$$s_{\text{pms}1_i} := \text{SMPA}_{\text{data}_{\text{loc}_{1_i}, 5}}$$

$$s_{\text{psd}1_i} := \text{SMPA}_{\text{data}_{\text{loc}_{1_i}, 6}}$$

$$\text{loc}_{2_i} := \left[\text{floor}\left(\text{linterp}\left(z, z_k, T_{kT1_i}\right)\right) \cdot (n_x + 1) \cdot (n_y + 1) \right] + \text{floor}\left(\text{linterp}\left(y, y_j, T_{1\alpha_i}\right)\right) \cdot (n_x + 1) \dots \\ + \text{ceil}\left(\text{linterp}\left(x, x_i, q_{\text{pff}_i}\right)\right)$$

$$s_{\text{ms}2_i} := \text{SMPA}_{\text{data}_{\text{loc}_{2_i}, 3}}$$

$$s_{\text{msd}2_i} := \text{SMPA}_{\text{data}_{\text{loc}_{2_i}, 4}}$$

$$s_{\text{pms}2_i} := \text{SMPA}_{\text{data}_{\text{loc}_{2_i}, 5}}$$

$$s_{\text{psd}2_i} := \text{SMPA}_{\text{data}_{\text{loc}_{2_i}, 6}}$$

$$\text{loc}_{3_i} := \text{floor}\left(\text{linterp}\left(z, z_k, T_{kT1_i}\right)\right) \cdot (n_x + 1) \cdot (n_y + 1) + \text{ceil}\left(\text{linterp}\left(y, y_j, T_{1\alpha_i}\right)\right) \cdot (n_x + 1) \dots \\ + \text{ceil}\left(\text{linterp}\left(x, x_i, q_{\text{pff}_i}\right)\right)$$

$$s_{\text{ms}3_i} := \text{SMPA}_{\text{data}_{\text{loc}_{3_i}, 3}}$$

$$s_{\text{msd}3_i} := \text{SMPA}_{\text{data}_{\text{loc}_{3_i}, 4}}$$

$$s_{\text{pms}3_i} := \text{SMPA}_{\text{data}_{\text{loc}_{3_i}, 5}}$$

$$s_{\text{psd}3_i} := \text{SMPA}_{\text{data}_{\text{loc}_{3_i}, 6}}$$

$$\text{loc}_{4_i} := \text{floor}\left(\text{linterp}\left(z, z_k, T_{kT1_i}\right)\right) \cdot (n_x + 1) \cdot (n_y + 1) + \text{ceil}\left(\text{linterp}\left(y, y_j, T_{1\alpha_i}\right)\right) \cdot (n_x + 1) \dots \\ + \text{floor}\left(\text{linterp}\left(x, x_i, q_{\text{pff}_i}\right)\right)$$

$$s_{\text{ms}4_i} := \text{SMPA}_{\text{data}_{\text{loc}_{4_i}, 3}}$$

$$s_{\text{msd}4_i} := \text{SMPA}_{\text{data}_{\text{loc}_{4_i}, 4}}$$

$$s_{\text{pms}4_i} := \text{SMPA}_{\text{data}_{\text{loc}_{4_i}, 5}}$$

$$s_{\text{psd}4_i} := \text{SMPA}_{\text{data}_{\text{loc}_{4_i}, 6}}$$

$$\text{loc}_{5_i} := \left[\text{ceil} \left(\text{linterp} \left(z, z_k, T_{kTl_i} \right) \right) \cdot (nx + 1) \cdot (ny + 1) \right] + \text{floor} \left(\text{linterp} \left(y, y_j, T_{1\alpha_i} \right) \right) \cdot (nx + 1) \dots \\ + \text{floor} \left(\text{linterp} \left(x, x_i, q_{pff_i} \right) \right)$$

$$s_{ms5_i} := \text{SMPA}_{\text{data loc}_{5_i}, 3}$$

$$s_{msd5_i} := \text{SMPA}_{\text{data loc}_{5_i}, 4}$$

$$s_{pms5_i} := \text{SMPA}_{\text{data loc}_{5_i}, 5}$$

$$s_{psd5_i} := \text{SMPA}_{\text{data loc}_{5_i}, 6}$$

$$\text{loc}_{6_i} := \text{ceil} \left(\text{linterp} \left(z, z_k, T_{kTl_i} \right) \right) \cdot (nx + 1) \cdot (ny + 1) + \text{floor} \left(\text{linterp} \left(y, y_j, T_{1\alpha_i} \right) \right) \cdot (nx + 1) \dots \\ + \text{ceil} \left(\text{linterp} \left(x, x_i, q_{pff_i} \right) \right)$$

$$s_{ms6_i} := \text{SMPA}_{\text{data loc}_{6_i}, 3}$$

$$s_{msd6_i} := \text{SMPA}_{\text{data loc}_{6_i}, 4}$$

$$s_{pms6_i} := \text{SMPA}_{\text{data loc}_{6_i}, 5}$$

$$s_{psd6_i} := \text{SMPA}_{\text{data loc}_{6_i}, 6}$$

$$\text{loc}_{7_i} := \left[\text{ceil} \left(\text{linterp} \left(z, z_k, T_{kTl_i} \right) \right) \cdot (nx + 1) \cdot (ny + 1) \right] + \text{ceil} \left(\text{linterp} \left(y, y_j, T_{1\alpha_i} \right) \right) \cdot (nx + 1) \dots \\ + \text{ceil} \left(\text{linterp} \left(x, x_i, q_{pff_i} \right) \right)$$

$$s_{ms7_i} := \text{SMPA}_{\text{data loc}_{7_i}, 3}$$

$$s_{msd7_i} := \text{SMPA}_{\text{data loc}_{7_i}, 4}$$

$$s_{pms7_i} := \text{SMPA}_{\text{data loc}_{7_i}, 5}$$

$$s_{psd7_i} := \text{SMPA}_{\text{data loc}_{7_i}, 6}$$

$$\text{loc}_{8_i} := \text{ceil} \left(\text{linterp} \left(z, z_k, T_{kTl_i} \right) \right) \cdot (nx + 1) \cdot (ny + 1) + \text{ceil} \left(\text{linterp} \left(y, y_j, T_{1\alpha_i} \right) \right) \cdot (nx + 1) \dots \\ + \text{floor} \left(\text{linterp} \left(x, x_i, q_{pff_i} \right) \right)$$

$$s_{ms8_i} := \text{SMPA}_{\text{data loc}_{8_i}, 3}$$

$$s_{msd8_i} := \text{SMPA}_{\text{data loc}_{8_i}, 4}$$

$$s_{pms8_i} := \text{SMPA}_{\text{data loc}_{8_i}, 5}$$

$$s_{psd8_i} := \text{SMPA}_{\text{data loc}_{8_i}, 6}$$

Develop the upper and lower bound of the randomly generated $1/\alpha$, k, and adjusted percolation flux

Develop the upper and lower bound for permeability (k) for Tptpl Unit

$$\begin{aligned}
 qq_i &:= -1 \cdot T_{kT1}_i \\
 \text{mantissa}(x) &:= x - \text{floor}(qq) \\
 tt_i &:= \text{floor}(qq_i) \\
 rr &:= \text{round}(\text{mantissa}(qq), 2) \\
 yy1_i &:= \text{if}(rr_i \leq 0.25, 0, \text{if}(0.25 < rr_i \leq 0.5, 0.25, rr_i)) \\
 zz1_i &:= \text{if}(yy1_i \leq 0.5, yy1_i, \text{if}(0.5 < yy1_i \leq 0.75, 0.5, 0.75)) \\
 T_{kT2}_i &:= -1 \cdot (tt_i + zz1_i) \\
 yy2_i &:= \text{if}(rr_i \leq 0.25, 0.25, \text{if}(0.25 < rr_i \leq 0.5, 0.5, rr_i)) \\
 zz2_i &:= \text{if}(yy2_i \leq 0.5, yy2_i, \text{if}(0.5 < yy2_i \leq 0.75, 0.75, 1)) \\
 T_{kT1}_i &:= -1 \cdot (tt_i + zz2_i)
 \end{aligned}$$

Develop the upper and lower bound for capillary strength ($1/\alpha$).

$$\begin{aligned}
 hh1_i &:= \text{floor}\left(\frac{T_{1\alpha}_i}{100}\right) \\
 T_{1\alpha1}_i &:= (hh1_i \cdot 100) \\
 hh2_i &:= \text{ceil}\left(\frac{T_{1\alpha}_i}{100}\right) \\
 T_{1\alpha2}_i &:= (hh2_i \cdot 100)
 \end{aligned}$$

Lower Bound value adjusted percolation flux (q_{pff})

$$\begin{aligned}
 aaa1_i &:= \text{if}(q_{pff}_i \leq 1, 1, \text{if}(1 < q_{pff}_i \leq 5, 1, q_{pff}_i)) \\
 bbb1_i &:= \text{if}(aaa1_i \leq 5, aaa1_i, \text{if}(5 < aaa1_i \leq 10, 5, aaa1_i)) \\
 ccc1_i &:= \text{if}(bbb1_i \leq 10, bbb1_i, \text{if}(10 < bbb1_i \leq 20, 10, bbb1_i)) \\
 ddd1_i &:= \text{if}(ccc1_i \leq 20, ccc1_i, \text{if}(20 < ccc1_i \leq 50, 20, ccc1_i)) \\
 eee1_i &:= \text{if}(ddd1_i \leq 50, ddd1_i, \text{if}(50 < ddd1_i \leq 100, 50, ddd1_i)) \\
 fff1_i &:= \text{if}(eee1_i \leq 100, eee1_i, \text{if}(100 < eee1_i \leq 200, 100, eee1_i))
 \end{aligned}$$

$$\begin{aligned} \text{ggg1}_i &:= \text{if}(\text{fff1}_i \leq 200, \text{fff1}_i, \text{if}(200 < \text{fff1}_i \leq 300, 200, \text{fff1}_i)) \\ \text{hhh1}_i &:= \text{if}(\text{ggg1}_i \leq 300, \text{ggg1}_i, \text{if}(300 < \text{ggg1}_i \leq 400, 300, \text{ggg1}_i)) \\ \text{iii1}_i &:= \text{if}(\text{hhh1}_i \leq 400, \text{hhh1}_i, \text{if}(400 < \text{hhh1}_i \leq 500, 400, \text{hhh1}_i)) \\ \text{jjj1}_i &:= \text{if}(\text{iii1}_i \leq 500, \text{iii1}_i, \text{if}(500 < \text{iii1}_i \leq 600, 500, \text{iii1}_i)) \\ \text{kkk1}_i &:= \text{if}(\text{jjj1}_i \leq 600, \text{jjj1}_i, \text{if}(600 < \text{jjj1}_i \leq 700, 600, \text{jjj1}_i)) \\ \text{mmm1}_i &:= \text{if}(\text{kkk1}_i \leq 700, \text{kkk1}_i, \text{if}(700 < \text{kkk1}_i \leq 800, 700, \text{kkk1}_i)) \\ \text{q}_{\text{pff1}_i} &:= \text{if}(\text{mmm1}_i \leq 800, \text{mmm1}_i, \text{if}(800 < \text{mmm1}_i \leq 900, 800, 900)) \end{aligned}$$

Upper Bound value adjusted percolation flux (q_{pff})

$$\begin{aligned} \text{aaa2}_i &:= \text{if}(q_{\text{pff}_i} \leq 1, 5, \text{if}(1 < q_{\text{pff}_i} \leq 5, 5, q_{\text{pff}_i})) \\ \text{bbb2}_i &:= \text{if}(\text{aaa2}_i \leq 5, \text{aaa2}_i, \text{if}(5 < \text{aaa2}_i \leq 10, 10, \text{aaa2}_i)) \\ \text{ccc2}_i &:= \text{if}(\text{bbb2}_i \leq 10, \text{bbb2}_i, \text{if}(10 < \text{bbb2}_i \leq 20, 20, \text{bbb2}_i)) \\ \text{ddd2}_i &:= \text{if}(\text{ccc2}_i \leq 20, \text{ccc2}_i, \text{if}(20 < \text{ccc2}_i \leq 50, 50, \text{ccc2}_i)) \\ \text{eee2}_i &:= \text{if}(\text{ddd2}_i \leq 50, \text{ddd2}_i, \text{if}(50 < \text{ddd2}_i \leq 100, 100, \text{ddd2}_i)) \\ \text{fff2}_i &:= \text{if}(\text{eee2}_i \leq 100, \text{eee2}_i, \text{if}(100 < \text{eee2}_i \leq 200, 200, \text{eee2}_i)) \\ \text{ggg2}_i &:= \text{if}(\text{fff2}_i \leq 200, \text{fff2}_i, \text{if}(200 < \text{fff2}_i \leq 300, 300, \text{fff2}_i)) \\ \text{hhh2}_i &:= \text{if}(\text{ggg2}_i \leq 300, \text{ggg2}_i, \text{if}(300 < \text{ggg2}_i \leq 400, 400, \text{ggg2}_i)) \\ \text{iii2}_i &:= \text{if}(\text{hhh2}_i \leq 400, \text{hhh2}_i, \text{if}(400 < \text{hhh2}_i \leq 500, 500, \text{hhh2}_i)) \\ \text{jjj2}_i &:= \text{if}(\text{iii2}_i \leq 500, \text{iii2}_i, \text{if}(500 < \text{iii2}_i \leq 600, 600, \text{iii2}_i)) \\ \text{kkk2}_i &:= \text{if}(\text{jjj2}_i \leq 600, \text{jjj2}_i, \text{if}(600 < \text{jjj2}_i \leq 700, 700, \text{jjj2}_i)) \\ \text{mmm2}_i &:= \text{if}(\text{kkk2}_i \leq 700, \text{kkk2}_i, \text{if}(700 < \text{kkk2}_i \leq 800, 800, \text{kkk2}_i)) \\ \text{q}_{\text{pff2}_i} &:= \text{if}(\text{mmm2}_i \leq 800, \text{mmm2}_i, \text{if}(800 < \text{mmm2}_i \leq 900, 900, 1000)) \end{aligned}$$

Solve for seepage rate (Tptpl Unit)

$$t_{\text{qpff}_i} := \frac{q_{\text{pff}_i} - q_{\text{pff1}_i}}{q_{\text{pff2}_i} - q_{\text{pff1}_i}} \quad u_{T1\alpha_i} := \frac{T_{1\alpha_i} - T_{1\alpha1_i}}{T_{1\alpha2_i} - T_{1\alpha1_i}} \quad v_{\text{TKTl}_i} := \frac{T_{\text{kTl}_i} - T_{\text{kTl1}_i}}{T_{\text{kTl2}_i} - T_{\text{kTl1}_i}}$$

$$\begin{aligned}
 \text{spflux}_{Tl m_i} := & (1 - t_{\text{qpf}f_i}) \cdot (1 - u_{T1\alpha_i}) \cdot (1 - v_{TkTl_i}) \cdot s_{\text{ms}1_i} \dots \\
 & + (t_{\text{qpf}f_i}) \cdot (1 - u_{T1\alpha_i}) \cdot (1 - v_{TkTl_i}) \cdot s_{\text{ms}2_i} \dots \\
 & + (t_{\text{qpf}f_i}) \cdot (u_{T1\alpha_i}) \cdot (1 - v_{TkTl_i}) \cdot s_{\text{ms}3_i} \dots \\
 & + (1 - t_{\text{qpf}f_i}) \cdot (u_{T1\alpha_i}) \cdot (1 - v_{TkTl_i}) \cdot s_{\text{ms}4_i} \dots \\
 & + (1 - t_{\text{qpf}f_i}) \cdot (1 - u_{T1\alpha_i}) \cdot (v_{TkTl_i}) \cdot s_{\text{ms}5_i} \dots \\
 & + (t_{\text{qpf}f_i}) \cdot (1 - u_{T1\alpha_i}) \cdot (v_{TkTl_i}) \cdot s_{\text{ms}6_i} \dots \\
 & + (t_{\text{qpf}f_i}) \cdot (u_{T1\alpha_i}) \cdot (v_{TkTl_i}) \cdot s_{\text{ms}7_i} \dots \\
 & + (1 - t_{\text{qpf}f_i}) \cdot (u_{T1\alpha_i}) \cdot (v_{TkTl_i}) \cdot s_{\text{ms}8_i}
 \end{aligned}$$

$$\begin{aligned}
 \text{spflux}_{Tl \text{sd}_i} := & (1 - t_{\text{qpf}f_i}) \cdot (1 - u_{T1\alpha_i}) \cdot (1 - v_{TkTl_i}) \cdot s_{\text{msd}1_i} \dots \\
 & + (t_{\text{qpf}f_i}) \cdot (1 - u_{T1\alpha_i}) \cdot (1 - v_{TkTl_i}) \cdot s_{\text{msd}2_i} \dots \\
 & + (t_{\text{qpf}f_i}) \cdot (u_{T1\alpha_i}) \cdot (1 - v_{TkTl_i}) \cdot s_{\text{msd}3_i} \dots \\
 & + (1 - t_{\text{qpf}f_i}) \cdot (u_{T1\alpha_i}) \cdot (1 - v_{TkTl_i}) \cdot s_{\text{msd}4_i} \dots \\
 & + (1 - t_{\text{qpf}f_i}) \cdot (1 - u_{T1\alpha_i}) \cdot (v_{TkTl_i}) \cdot s_{\text{msd}5_i} \dots \\
 & + (t_{\text{qpf}f_i}) \cdot (1 - u_{T1\alpha_i}) \cdot (v_{TkTl_i}) \cdot s_{\text{msd}6_i} \dots \\
 & + (t_{\text{qpf}f_i}) \cdot (u_{T1\alpha_i}) \cdot (v_{TkTl_i}) \cdot s_{\text{msd}7_i} \dots \\
 & + (1 - t_{\text{qpf}f_i}) \cdot (u_{T1\alpha_i}) \cdot (v_{TkTl_i}) \cdot s_{\text{msd}8_i}
 \end{aligned}$$

Calculate mean seepage for Tptpl Unit

$$QT11_{\text{std}i} := -1.7321 \cdot \text{spflux}_{Tl \text{sd}_i}$$

$$QT11_{\text{std}u_i} := 1.7321 \cdot \text{spflux}_{Tl \text{sd}_i}$$

$$QT1_{\text{std}i} := \text{if}(QT11_{\text{std}i} = 0, -0.00001, QT11_{\text{std}i})$$

$$QT1_{\text{std}i} := \text{qunif}(X_{i,10}, QT1_{\text{std}i}, QT11_{\text{std}u_i})$$

$$QT11_{\text{spm}_i} := \text{spflux}_{Tl m_i} + QT1_{\text{std}i}$$

$$QT12_{\text{spm}_i} := \text{if}(QT11_{\text{spm}_i} \leq 0.1, 0, QT11_{\text{spm}_i})$$

$$QT2_{\text{perc}_i} := \frac{QT12_{\text{spm}_i} \cdot 100}{q_{\text{pff}f_i} \cdot 28.052}$$

Equation to calculate seepage percent based on seepage rate (see SMPA data table) from DTN: LB0310AMRU0120.002 [DIRS 166116]

$$QT3_{\text{perc}_i} := \text{if}(QT2_{\text{perc}_i} \leq 0, 0, \text{if}(QT2_{\text{perc}_i} \geq 100, 100, QT2_{\text{perc}_i}))$$

Check seepage percent; if above 100 percent, then recalculate seepage back to 100 percent.

$$QTl_{spr_i} := QT3_{perc_i} \cdot q_{pff_i} \cdot \frac{2 \cdot 28.05}{100} \quad \text{Mean Seepage Rate (kg/yr per WP)}$$

$$\text{mean}(QTl_{spr}) = 486.156$$

Determine the seepage fraction for Tptpl Unit within the repository and then fit the output data to distribution

Seepage fraction represents the non-zero seepage rates based on the LHS sampling of all of the parameters

$$\text{sort}(QTl_{spr}) =$$

	0
7263	0
7264	0
7265	0.101
7266	0.101
7267	0.102

$$n_{Tl} := 7264$$

$$\text{spfr}_{Tl} := \frac{(n - 1) - n_{Tl}}{n} \quad \text{spfr}_{Tl} = 0.637 \quad \text{Seepage fraction (i.e., waste package locations that can see seepage)}$$

$$n1_{Tl} := (n - 1) - (n_{Tl} + 1)$$

$$Q1_{Tl} := \text{sort}(QTl_{spr})$$

$$Q1_{Tl} := \text{reverse}(Q1_{Tl})$$

$$ab := 0..n1_{Tl}$$

$$Q2_{Tl_{ab}} := \left(\frac{1}{998} \cdot Q1_{Tl_{ab}} \right)$$

$$QTl := \text{sort}(Q2_{Tl})$$

$$\text{mean}(QTl \cdot 998) = 763.497$$

$$CDF_{Tl_{ab}} := \frac{(ab + 1) - 0.375}{(n1_{Tl} + 1) - 0.25}$$

Fit the seepage rates to a Weibull distribution.

The following equations are from *What Every Engineer Should Know About Reliability and Risk Analysis* (Modarres 1993 [DIRS 104667], p. 109).

$$n1_{Tl} = 1.273 \times 10^4$$

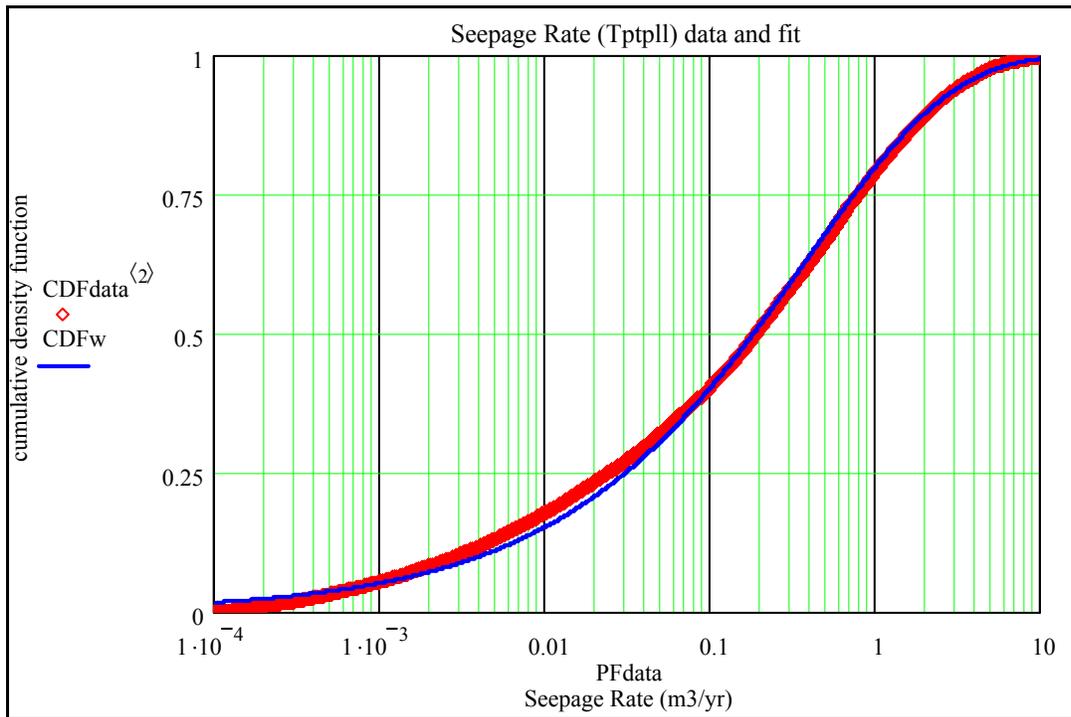
$$\beta := \text{root} \left[\left[\frac{\sum_{i=0}^{n1_{T1}} (Q_{T1_i})^r \cdot \ln(Q_{T1_i})}{\sum_{i=0}^{n1_{T1}} (Q_{T1_i})^r} - \left(\frac{1}{r}\right) - \left[\left(\frac{1}{n1_{T1}}\right) \cdot \sum_{i=0}^{n1_{T1}} \ln(Q_{T1_i})\right] \right], r, 0.1, 4 \right] \quad \beta = 0.494$$

$$\alpha := \left[\frac{\sum_{i=0}^{n1_{T1}} (Q_{T1_i})^\beta}{n1_{T1}} \right]^{\frac{1}{\beta}} \quad \alpha = 3.83 \times 10^{-1}$$

Plot of raw data versus Weibull distribution

```

ji := 0..n1_T1
PFdata_ji := Q_T1_ji
CDFdata_ji,2 := CDF_T1_ji
CDFw1_ji := 1 - exp[-(PFdata_ji)^beta / alpha]
CDFw_ji,0 := CDFw1_ji
    
```



IV.4 SEEPAGE ANALYSIS FOR LOWER INFILTRATION RATE IN THE NONLITHOPHYSAL ZONE

The following section presents the Mathcad analysis for the lower seepage infiltration rate of the glacial transition climate in the nonlithophysal zone. The seepage information used in this analysis was obtained from *Abstraction of Drift Seepage* (BSC 2003 [DIRS 165564]). The information contained in the section has been abstracted from the “seepage glac lower Ttpmn x1.2 report.mcd” Mathcad file of Attachment VII.

Seepage rate and seepage fraction calculation followed *Abstraction of Drift Seepage* (BSC 2003 [DIRS 165564], Section 6.7).

Latin Hypercube Sampling Routine to Generate Random Numbers

Sample Size: n := 20000

i := 1..n

RD_{i-1,0} := i RD_{i-1,3} := rnd(1.0) RD_{i-1,6} := rnd(1.0) RD_{i-1,9} := rnd(1.0) RD_{i-1,12} := rnd(1.0)
 RD_{i-1,1} := rnd(1.0) RD_{i-1,4} := rnd(1.0) RD_{i-1,7} := rnd(1.0) RD_{i-1,10} := rnd(1.0)
 RD_{i-1,2} := rnd(1.0) RD_{i-1,5} := rnd(1.0) RD_{i-1,8} := rnd(1.0) RD_{i-1,11} := rnd(1.0)

RKs are matrixes in which the first column contain a permutation on the integers on the interval [1,n].

RK1 := csort(RD, 1) RK4 := csort(RD, 4) RK7 := csort(RD, 7) RK10 := csort(RD, 10)
 RK2 := csort(RD, 2) RK5 := csort(RD, 5) RK8 := csort(RD, 8) RK11 := csort(RD, 11)
 RK3 := csort(RD, 3) RK6 := csort(RD, 6) RK9 := csort(RD, 9) RK12 := csort(RD, 12)

Define sets of random values. Each random value is selected within one of the equiprobable n intervals that partition [0,1], one set for each random variable.

$$\begin{aligned}
 X^{(0)} &:= \frac{RK1^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} & X^{(3)} &:= \frac{RK4^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} & X^{(6)} &:= \frac{RK7^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} \\
 X^{(1)} &:= \frac{RK2^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} & X^{(4)} &:= \frac{RK5^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} & X^{(7)} &:= \frac{RK8^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} \\
 X^{(2)} &:= \frac{RK3^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} & X^{(5)} &:= \frac{RK6^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} & X^{(8)} &:= \frac{RK9^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} \\
 X^{(9)} &:= \frac{RK10^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} & X^{(10)} &:= \frac{RK11^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} \\
 X^{(11)} &:= \frac{RK12^{(0)} - 1 + \text{runif}(n, 0, 1)}{n}
 \end{aligned}$$

i := 0..n - 1

Capillary Strength $1/\alpha$ in (Pa)

$\alpha_{1lb} := 402$ $\alpha_{1ub} := 780$ $\alpha_{1\mu} := 591$ **Spatial variability follows a uniform distribution**

$\Delta\alpha_{1l} := -105$ $\Delta\alpha_{1\mu} := 0$ $\Delta\alpha_{1u} := 105$ **Uncertainty follows a triangular distribution**

Sampling from spatial variability to obtain the $1/\alpha$ value

$\alpha_{1i} := \text{qunif}(X_{i,0}, \alpha_{1lb}, \alpha_{1ub})$ **$1/\alpha$ value**

Sample from uncertainty triangular distribution to obtain $\Delta 1/\alpha$

Determine which equation to use:

if Random Number $< RN_{\Delta\alpha 1}$ then use Equation 1 ($\Delta\alpha 1eq1$).

if Random Number $> RN_{\Delta\alpha 1}$ then use Equation 2 ($\Delta\alpha 1eq2$).

$$RN_{\Delta\alpha 1} := \frac{(\Delta\alpha_{1\mu} - \Delta\alpha_{1l})^2}{(\Delta\alpha_{1u} - \Delta\alpha_{1l}) \cdot (\Delta\alpha_{1\mu} - \Delta\alpha_{1l})}$$

$$\Delta\alpha_{1eq1_i} := \Delta\alpha_{1l} + \sqrt{X_{i,1} \cdot (\Delta\alpha_{1u} - \Delta\alpha_{1l}) \cdot (\Delta\alpha_{1\mu} - \Delta\alpha_{1l})}$$

$$\Delta\alpha_{1eq2_i} := \Delta\alpha_{1u} - \sqrt{(1 - X_{i,1}) \cdot (\Delta\alpha_{1u} - \Delta\alpha_{1l}) \cdot (\Delta\alpha_{1u} - \Delta\alpha_{1\mu})}$$

$$\Delta\alpha_{1i} := \text{if} \left[\left(X_{i,1} \leq RN_{\Delta\alpha 1} \right), \Delta\alpha_{1eq1_i}, \Delta\alpha_{1eq2_i} \right] \quad \mathbf{\Delta 1/\alpha \text{ value}}$$

Overall Capillary Strength $1/\alpha + \Delta 1/\alpha$

$$T_{1\alpha_i} := \alpha_{1i} + \Delta\alpha_{1i} \quad \mathbf{1/\alpha \text{ value}}$$

Permeability k in Tptpmn Unit (in log 10)

$\mu_{kTn} := -12.2$ **Mean of lognormal distribution**

$\sigma_{kTn} := 0.34$ **Standard deviation of lognormal distribution**

$$k_{Tn_i} := \ln(\text{qlnorm}(X_{i,2}, \mu_{kTn}, \sigma_{kTn}))$$

$$\text{mean}(k_{Tn}) = -12.2$$

$$\text{Stdev}(k_{Tn}) = 0.34$$

Permeability Δk in Tptpmn Unit (in log 10)

$\Delta k_{Tnl} := -0.68$ $\Delta k_{Tn\mu} := 0$ $\Delta k_{Tnu} := 0.68$ **Uncertainty follows a triangular distribution**

Sample from uncertainty triangular distribution to obtain Δk

Determine which equation to use:

if Random Number < $RN_{\Delta k Tn}$ then use Equation 1 ($\Delta k Tneq1$).

if Random Number > $RN_{\Delta k Tn}$ then use Equation 2 ($\Delta k Tneq2$).

$$RN_{\Delta k Tn} := \frac{(\Delta k_{Tn\mu} - \Delta k_{Tnl})^2}{(\Delta k_{Tnu} - \Delta k_{Tnl}) \cdot (\Delta k_{Tn\mu} - \Delta k_{Tnl})}$$

$$\Delta k_{Tneq1_i} := \Delta k_{Tnl} + \sqrt{X_{i,3} \cdot (\Delta k_{Tnu} - \Delta k_{Tnl}) \cdot (\Delta k_{Tn\mu} - \Delta k_{Tnl})}$$

$$\Delta k_{Tneq2_i} := \Delta k_{Tnu} - \sqrt{(1 - X_{i,3}) \cdot (\Delta k_{Tnu} - \Delta k_{Tnl}) \cdot (\Delta k_{Tnu} - \Delta k_{Tn\mu})}$$

$$\Delta k_{Tn_i} := \text{if} \left[\left(X_{i,3} \leq RN_{\Delta k Tn} \right), \Delta k_{Tneq1_i}, \Delta k_{Tneq2_i} \right] \quad \mathbf{\Delta k \text{ value}}$$

Overall Permeability $k + \Delta k$

$$T1_{kTn_i} := k_{Tn_i} + \Delta k_{Tn_i}$$

Permeability must lie between -14 and -10 (bounds of SMPA simulations)

$$T_{kTn_i} := \text{if} \left(T1_{kTn_i} \geq -10, -10, \text{if} \left(T1_{kTn_i} \leq -14, -14, T1_{kTn_i} \right) \right) \quad \mathbf{k \text{ value}}$$

Flow Focusing Factor (DTN: LB0104AMRU0185.012 [DIRS 163906])

$$f(x) := -0.3137x^4 + 5.4998x^3 - 35.66x^2 + 102.3x - 11.434$$

$$ff_i := \text{root} \left[f(x) - (X_{i,5} \cdot 100), x, 0, 6 \right]$$

Percolation Flux (mm/yr)

The percolation flux used here is for the glacial transition period only. The percolation flux is based on sampling from the lower bound TSPA repository location only (DTN: LB0310AMRU0120.002 [DIRS 166116])

$$n_{nn} := 0..468$$

Lower Bound Percolation Flux

$$PF1_i :=$$

	0
0	3.68
1	2.65
2	2.41
3	2.13
4	2.41
5	2.4
6	2.12
7	2.76
8	1.4
9	2.21

$$PFt_{1_{n_{nn}}} := PF1_{1_{n_{nn},0}}$$

$$Z^{(0)} := \text{round}(\text{runif}(n, 0, 468))$$

$$PF_i := PFt_{1_{(Z_i,0)}}$$

Adjusted Percolation Flux

Multiply the flow-focusing factor by the percolation flux, which will be used to obtain the seepage rate, seepage fraction, and seepage percentage.

$$q^1_{pff_i} := PF_i \cdot ff_i$$

Percolation Flux must lie between 1 and 1000 mm/yr (bounds of SMPA simulations)

$$q_{pff_i} := \text{if}(q^1_{pff_i} \leq 1, 1, \text{if}(q^1_{pff_i} \geq 1000, 1000, q^1_{pff_i}))$$

**Seepage Information from SMPA analysis
(DTN: LB0304SMDCREV2.002 [DIRS 163687])**

m := 2549 **Data points**

SMPA_{data}^{<0>} is permeability value log(k [m²])

SMPA_{data}^{<1>} is capillary strength 1/alpha [Pa]

SMPA_{data}^{<2>} is local percolation flux (mm/yr)

SMPA_{data}^{<3>} is Mean Seepage [kg/yr/WP]

SMPA_{data}^{<4>} is Std. Dev. Seepage [kg/yr/WP]

SMPA_{data}^{<5>} is Mean Seepage [%]

SMPA_{data}^{<6>} is Std. Dev. Seepage [%]

SMPA_{data} :=

	0	1	2	3	4	5	6
0	-14	100	1	27.73	4.09	98.86	14.59
1	-14	100	5	138.92	20.55	99.05	14.65
2	-14	100	10	277.9	41.19	99.07	14.68
3	-14	100	20	555.87	82.54	99.09	14.71
4	-14	100	50	1391.67	205.57	99.23	14.66
5	-14	100	100	2793.55	406.7	99.59	14.5
6	-14	100	200	5610	785	100	14
7	-14	100	300	8415	1178	100	14
8	-14	100	400	11220	1570	100	14
9	-14	100	500	14025	1963	100	14
10	-14	100	600	16830	2356	100	14
11	-14	100	700	19635	2748	100	14
12	-14	100	800	22440	3141	100	14
13	-14	100	900	25245	3590	100	14
14	-14	100	1000	28050	3989	100	14
15	-14	200	1	26.14	4.21	93.21	15

Develop routine to select correct mean seepage, seepage standard deviation, seepage percent, and seepage percent standard deviation based on sampled value of 1/ α , k, percolation flux.

nx := 14 ny := 9 nz := 16

ii := 0.. nx

x_{ii} := SMPA_{data}_{ii,2} xi_{ii} := ii

jj := 0.. ny

y_{jj} := 100-jj + 100 yj_{jj} := jj

kk := 0.. nz

z_{kk} := -14 + kk*0.25 zk_{kk} := kk

loc represents the location within the matrix of which value to pick for the interpolation process

$$\text{loc}_{1_i} := \left(\text{floor} \left(\text{linterp} \left(z, z_k, T_{kTn_i} \right) \right) \cdot (nx + 1) \cdot (ny + 1) + \text{floor} \left(\text{linterp} \left(y, y_j, T_{1\alpha_i} \right) \right) \cdot (nx + 1) \dots \right. \\ \left. + \text{floor} \left(\text{linterp} \left(x, x_i, q_{pff_i} \right) \right) \right)$$

$$s_{ms1_i} := \text{SMPA}_{\text{data}_{\text{loc}_{1_i}, 3}}$$

$$s_{msd1_i} := \text{SMPA}_{\text{data}_{\text{loc}_{1_i}, 4}}$$

$$s_{pms1_i} := \text{SMPA}_{\text{data}_{\text{loc}_{1_i}, 5}}$$

$$s_{psd1_i} := \text{SMPA}_{\text{data}_{\text{loc}_{1_i}, 6}}$$

$$\text{loc}_{2_i} := \left[\text{floor} \left(\text{linterp} \left(z, z_k, T_{kTn_i} \right) \right) \cdot (nx + 1) \cdot (ny + 1) \right] + \text{floor} \left(\text{linterp} \left(y, y_j, T_{1\alpha_i} \right) \right) \cdot (nx + 1) \dots \\ + \text{ceil} \left(\text{linterp} \left(x, x_i, q_{pff_i} \right) \right)$$

$$s_{ms2_i} := \text{SMPA}_{\text{data}_{\text{loc}_{2_i}, 3}}$$

$$s_{msd2_i} := \text{SMPA}_{\text{data}_{\text{loc}_{2_i}, 4}}$$

$$s_{pms2_i} := \text{SMPA}_{\text{data}_{\text{loc}_{2_i}, 5}}$$

$$s_{psd2_i} := \text{SMPA}_{\text{data}_{\text{loc}_{2_i}, 6}}$$

$$\text{loc}_{3_i} := \left(\text{floor} \left(\text{linterp} \left(z, z_k, T_{kTn_i} \right) \right) \cdot (nx + 1) \cdot (ny + 1) + \text{ceil} \left(\text{linterp} \left(y, y_j, T_{1\alpha_i} \right) \right) \cdot (nx + 1) \dots \right. \\ \left. + \text{ceil} \left(\text{linterp} \left(x, x_i, q_{pff_i} \right) \right) \right)$$

$$s_{ms3_i} := \text{SMPA}_{\text{data}_{\text{loc}_{3_i}, 3}}$$

$$s_{msd3_i} := \text{SMPA}_{\text{data}_{\text{loc}_{3_i}, 4}}$$

$$s_{pms3_i} := \text{SMPA}_{\text{data}_{\text{loc}_{3_i}, 5}}$$

$$s_{psd3_i} := \text{SMPA}_{\text{data}_{\text{loc}_{3_i}, 6}}$$

$$\text{loc}_{4_i} := \left(\text{floor} \left(\text{linterp} \left(z, z_k, T_{kTn_i} \right) \right) \cdot (nx + 1) \cdot (ny + 1) + \text{ceil} \left(\text{linterp} \left(y, y_j, T_{1\alpha_i} \right) \right) \cdot (nx + 1) \dots \right. \\ \left. + \text{floor} \left(\text{linterp} \left(x, x_i, q_{pff_i} \right) \right) \right)$$

$$s_{ms4_i} := \text{SMPA}_{\text{data}_{\text{loc}_{4_i}, 3}}$$

$$s_{msd4_i} := \text{SMPA}_{\text{data}_{\text{loc}_{4_i}, 4}}$$

$$s_{pms4_i} := \text{SMPA}_{\text{data}_{\text{loc}_{4_i}, 5}}$$

$$s_{psd4_i} := \text{SMPA}_{\text{data}_{\text{loc}_{4_i}, 6}}$$

$$\text{loc}_{5_i} := \left[\text{ceil} \left(\text{linterp} \left(z, z_k, T_k T_{n_i} \right) \right) \cdot (n_x + 1) \cdot (n_y + 1) \right] + \text{floor} \left(\text{linterp} \left(y, y_j, T_{1\alpha_i} \right) \right) \cdot (n_x + 1) \dots$$

$$+ \text{floor} \left(\text{linterp} \left(x, x_i, q_{\text{pff}_i} \right) \right)$$

$$s_{\text{ms}5_i} := \text{SMPA}_{\text{data loc}_{5_i}, 3}$$

$$s_{\text{msd}5_i} := \text{SMPA}_{\text{data loc}_{5_i}, 4}$$

$$s_{\text{pms}5_i} := \text{SMPA}_{\text{data loc}_{5_i}, 5}$$

$$s_{\text{psd}5_i} := \text{SMPA}_{\text{data loc}_{5_i}, 6}$$

$$\text{loc}_{6_i} := \text{ceil} \left(\text{linterp} \left(z, z_k, T_k T_{n_i} \right) \right) \cdot (n_x + 1) \cdot (n_y + 1) + \text{floor} \left(\text{linterp} \left(y, y_j, T_{1\alpha_i} \right) \right) \cdot (n_x + 1) \dots$$

$$+ \text{ceil} \left(\text{linterp} \left(x, x_i, q_{\text{pff}_i} \right) \right)$$

$$s_{\text{ms}6_i} := \text{SMPA}_{\text{data loc}_{6_i}, 3}$$

$$s_{\text{msd}6_i} := \text{SMPA}_{\text{data loc}_{6_i}, 4}$$

$$s_{\text{pms}6_i} := \text{SMPA}_{\text{data loc}_{6_i}, 5}$$

$$s_{\text{psd}6_i} := \text{SMPA}_{\text{data loc}_{6_i}, 6}$$

$$\text{loc}_{7_i} := \left[\text{ceil} \left(\text{linterp} \left(z, z_k, T_k T_{n_i} \right) \right) \cdot (n_x + 1) \cdot (n_y + 1) \right] + \text{ceil} \left(\text{linterp} \left(y, y_j, T_{1\alpha_i} \right) \right) \cdot (n_x + 1) \dots$$

$$+ \text{ceil} \left(\text{linterp} \left(x, x_i, q_{\text{pff}_i} \right) \right)$$

$$s_{\text{ms}7_i} := \text{SMPA}_{\text{data loc}_{7_i}, 3}$$

$$s_{\text{msd}7_i} := \text{SMPA}_{\text{data loc}_{7_i}, 4}$$

$$s_{\text{pms}7_i} := \text{SMPA}_{\text{data loc}_{7_i}, 5}$$

$$s_{\text{psd}7_i} := \text{SMPA}_{\text{data loc}_{7_i}, 6}$$

$$\text{loc}_{8_i} := \text{ceil} \left(\text{linterp} \left(z, z_k, T_k T_{n_i} \right) \right) \cdot (n_x + 1) \cdot (n_y + 1) + \text{ceil} \left(\text{linterp} \left(y, y_j, T_{1\alpha_i} \right) \right) \cdot (n_x + 1) \dots$$

$$+ \text{floor} \left(\text{linterp} \left(x, x_i, q_{\text{pff}_i} \right) \right)$$

$$s_{\text{ms}8_i} := \text{SMPA}_{\text{data loc}_{8_i}, 3}$$

$$s_{\text{msd}8_i} := \text{SMPA}_{\text{data loc}_{8_i}, 4}$$

$$s_{\text{pms}8_i} := \text{SMPA}_{\text{data loc}_{8_i}, 5}$$

$$s_{\text{psd}8_i} := \text{SMPA}_{\text{data loc}_{8_i}, 6}$$

Develop the upper and lower bound of the randomly generated $1/\alpha$, k, and adjusted percolation flux

Develop the upper and lower bound for permeability (k) for Tptpmn Unit

$$qq_i := -1 \cdot T_{kTn_i}$$

$$\text{mantissa}(x) := x - \text{floor}(qq)$$

$$tt_i := \text{floor}(qq_i)$$

$$rr := \text{round}(\text{mantissa}(qq), 2)$$

$$yy1_i := \text{if}(rr_i \leq 0.25, 0, \text{if}(0.25 < rr_i \leq 0.5, 0.25, rr_i))$$

$$zz1_i := \text{if}(yy1_i \leq 0.5, yy1_i, \text{if}(0.5 < yy1_i \leq 0.75, 0.5, 0.75))$$

$$T_{kTn2_i} := -1 \cdot (tt_i + zz1_i)$$

$$yy2_i := \text{if}(rr_i \leq 0.25, 0.25, \text{if}(0.25 < rr_i \leq 0.5, 0.5, rr_i))$$

$$zz2_i := \text{if}(yy2_i \leq 0.5, yy2_i, \text{if}(0.5 < yy2_i \leq 0.75, 0.75, 1))$$

$$T_{kTn1_i} := -1 \cdot (tt_i + zz2_i)$$

Develop the upper and lower bound for capillary strength ($1/\alpha$)

$$hh1_i := \text{floor}\left(\frac{T_{1\alpha_i}}{100}\right)$$

$$T_{1\alpha1_i} := (hh1_i \cdot 100)$$

$$hh2_i := \text{ceil}\left(\frac{T_{1\alpha_i}}{100}\right)$$

$$T_{1\alpha2_i} := (hh2_i \cdot 100)$$

Lower Bound value adjusted percolation flux (q_{pff})

$$aaa1_i := \text{if}(q_{pff_i} \leq 1, 1, \text{if}(1 < q_{pff_i} \leq 5, 1, q_{pff_i}))$$

$$bbb1_i := \text{if}(aaa1_i \leq 5, aaa1_i, \text{if}(5 < aaa1_i \leq 10, 5, aaa1_i))$$

$$ccc1_i := \text{if}(bbb1_i \leq 10, bbb1_i, \text{if}(10 < bbb1_i \leq 20, 10, bbb1_i))$$

$$ddd1_i := \text{if}(ccc1_i \leq 20, ccc1_i, \text{if}(20 < ccc1_i \leq 50, 20, ccc1_i))$$

$$eee1_i := \text{if}(ddd1_i \leq 50, ddd1_i, \text{if}(50 < ddd1_i \leq 100, 50, ddd1_i))$$

$$fff1_i := \text{if}(eee1_i \leq 100, eee1_i, \text{if}(100 < eee1_i \leq 200, 100, eee1_i))$$

$$\begin{aligned}
 ggg1_i &:= \text{if}(fff1_i \leq 200, fff1_i, \text{if}(200 < fff1_i \leq 300, 200, fff1_i)) \\
 hhh1_i &:= \text{if}(ggg1_i \leq 300, ggg1_i, \text{if}(300 < ggg1_i \leq 400, 300, ggg1_i)) \\
 iii1_i &:= \text{if}(hhh1_i \leq 400, hhh1_i, \text{if}(400 < hhh1_i \leq 500, 400, hhh1_i)) \\
 jjj1_i &:= \text{if}(iii1_i \leq 500, iii1_i, \text{if}(500 < iii1_i \leq 600, 500, iii1_i)) \\
 kkk1_i &:= \text{if}(jjj1_i \leq 600, jjj1_i, \text{if}(600 < jjj1_i \leq 700, 600, jjj1_i)) \\
 mmm1_i &:= \text{if}(kkk1_i \leq 700, kkk1_i, \text{if}(700 < kkk1_i \leq 800, 700, kkk1_i)) \\
 q_{pff1}_i &:= \text{if}(mmm1_i \leq 800, mmm1_i, \text{if}(800 < mmm1_i \leq 900, 800, 900))
 \end{aligned}$$

Upper Bound value adjusted percolation flux (q_{pff})

$$\begin{aligned}
 aaa2_i &:= \text{if}(q_{pff}_i \leq 1, 5, \text{if}(1 < q_{pff}_i \leq 5, 5, q_{pff}_i)) \\
 bbb2_i &:= \text{if}(aaa2_i \leq 5, aaa2_i, \text{if}(5 < aaa2_i \leq 10, 10, aaa2_i)) \\
 ccc2_i &:= \text{if}(bbb2_i \leq 10, bbb2_i, \text{if}(10 < bbb2_i \leq 20, 20, bbb2_i)) \\
 ddd2_i &:= \text{if}(ccc2_i \leq 20, ccc2_i, \text{if}(20 < ccc2_i \leq 50, 50, ccc2_i)) \\
 eee2_i &:= \text{if}(ddd2_i \leq 50, ddd2_i, \text{if}(50 < ddd2_i \leq 100, 100, ddd2_i)) \\
 fff2_i &:= \text{if}(eee2_i \leq 100, eee2_i, \text{if}(100 < eee2_i \leq 200, 200, eee2_i)) \\
 ggg2_i &:= \text{if}(fff2_i \leq 200, fff2_i, \text{if}(200 < fff2_i \leq 300, 300, fff2_i)) \\
 hhh2_i &:= \text{if}(ggg2_i \leq 300, ggg2_i, \text{if}(300 < ggg2_i \leq 400, 400, ggg2_i)) \\
 iii2_i &:= \text{if}(hhh2_i \leq 400, hhh2_i, \text{if}(400 < hhh2_i \leq 500, 500, hhh2_i)) \\
 jjj2_i &:= \text{if}(iii2_i \leq 500, iii2_i, \text{if}(500 < iii2_i \leq 600, 600, iii2_i)) \\
 kkk2_i &:= \text{if}(jjj2_i \leq 600, jjj2_i, \text{if}(600 < jjj2_i \leq 700, 700, jjj2_i)) \\
 mmm2_i &:= \text{if}(kkk2_i \leq 700, kkk2_i, \text{if}(700 < kkk2_i \leq 800, 800, kkk2_i)) \\
 q_{pff2}_i &:= \text{if}(mmm2_i \leq 800, mmm2_i, \text{if}(800 < mmm2_i \leq 900, 900, 1000))
 \end{aligned}$$

Solve for seepage rate (Ttpmn Unit)

$$t_{q_{pff}_i} := \frac{q_{pff}_i - q_{pff1}_i}{q_{pff2}_i - q_{pff1}_i} \quad u_{T1\alpha}_i := \frac{T_{1\alpha}_i - T_{1\alpha 1}_i}{T_{1\alpha 2}_i - T_{1\alpha 1}_i} \quad v_{TkTn}_i := \frac{T_{kTn}_i - T_{kTn 1}_i}{T_{kTn 2}_i - T_{kTn 1}_i}$$

$$\begin{aligned} \text{spflux}_{\text{Tnm}_i} := & \left(1 - t_{\text{qpf}_i}\right) \cdot \left(1 - u_{\text{T1}\alpha_i}\right) \cdot \left(1 - v_{\text{TkTn}_i}\right) \cdot s_{\text{ms1}_i} \dots \\ & + \left(t_{\text{qpf}_i}\right) \cdot \left(1 - u_{\text{T1}\alpha_i}\right) \cdot \left(1 - v_{\text{TkTn}_i}\right) \cdot s_{\text{ms2}_i} \dots \\ & + \left(t_{\text{qpf}_i}\right) \cdot \left(u_{\text{T1}\alpha_i}\right) \cdot \left(1 - v_{\text{TkTn}_i}\right) \cdot s_{\text{ms3}_i} \dots \\ & + \left(1 - t_{\text{qpf}_i}\right) \cdot \left(u_{\text{T1}\alpha_i}\right) \cdot \left(1 - v_{\text{TkTn}_i}\right) \cdot s_{\text{ms4}_i} \dots \\ & + \left(1 - t_{\text{qpf}_i}\right) \cdot \left(1 - u_{\text{T1}\alpha_i}\right) \cdot \left(v_{\text{TkTn}_i}\right) \cdot s_{\text{ms5}_i} \dots \\ & + \left(t_{\text{qpf}_i}\right) \cdot \left(1 - u_{\text{T1}\alpha_i}\right) \cdot \left(v_{\text{TkTn}_i}\right) \cdot s_{\text{ms6}_i} \dots \\ & + \left(t_{\text{qpf}_i}\right) \cdot \left(u_{\text{T1}\alpha_i}\right) \cdot \left(v_{\text{TkTn}_i}\right) \cdot s_{\text{ms7}_i} \dots \\ & + \left(1 - t_{\text{qpf}_i}\right) \cdot \left(u_{\text{T1}\alpha_i}\right) \cdot \left(v_{\text{TkTn}_i}\right) \cdot s_{\text{ms8}_i} \end{aligned}$$

$$\begin{aligned} \text{spflux}_{\text{Tnsd}_i} := & \left(1 - t_{\text{qpf}_i}\right) \cdot \left(1 - u_{\text{T1}\alpha_i}\right) \cdot \left(1 - v_{\text{TkTn}_i}\right) \cdot s_{\text{msd1}_i} \dots \\ & + \left(t_{\text{qpf}_i}\right) \cdot \left(1 - u_{\text{T1}\alpha_i}\right) \cdot \left(1 - v_{\text{TkTn}_i}\right) \cdot s_{\text{msd2}_i} \dots \\ & + \left(t_{\text{qpf}_i}\right) \cdot \left(u_{\text{T1}\alpha_i}\right) \cdot \left(1 - v_{\text{TkTn}_i}\right) \cdot s_{\text{msd3}_i} \dots \\ & + \left(1 - t_{\text{qpf}_i}\right) \cdot \left(u_{\text{T1}\alpha_i}\right) \cdot \left(1 - v_{\text{TkTn}_i}\right) \cdot s_{\text{msd4}_i} \dots \\ & + \left(1 - t_{\text{qpf}_i}\right) \cdot \left(1 - u_{\text{T1}\alpha_i}\right) \cdot \left(v_{\text{TkTn}_i}\right) \cdot s_{\text{msd5}_i} \dots \\ & + \left(t_{\text{qpf}_i}\right) \cdot \left(1 - u_{\text{T1}\alpha_i}\right) \cdot \left(v_{\text{TkTn}_i}\right) \cdot s_{\text{msd6}_i} \dots \\ & + \left(t_{\text{qpf}_i}\right) \cdot \left(u_{\text{T1}\alpha_i}\right) \cdot \left(v_{\text{TkTn}_i}\right) \cdot s_{\text{msd7}_i} \dots \\ & + \left(1 - t_{\text{qpf}_i}\right) \cdot \left(u_{\text{T1}\alpha_i}\right) \cdot \left(v_{\text{TkTn}_i}\right) \cdot s_{\text{msd8}_i} \end{aligned}$$

Calculate mean seepage for Ttpmn Unit

$$Q_{\text{Tn1std}_i} := -1.7321 \cdot \text{spflux}_{\text{Tnsd}_i}$$

$$Q_{\text{Tn1stdu}_i} := 1.7321 \cdot \text{spflux}_{\text{Tnsd}_i}$$

$$Q_{\text{Tnstd}_i} := \text{if}\left(Q_{\text{Tn1std}_i} = 0, -0.00001, Q_{\text{Tn1std}_i}\right)$$

$$Q_{\text{Tnstd}_i} := \text{qunif}\left(X_{i,10}, Q_{\text{Tnstd}_i}, Q_{\text{Tn1stdu}_i}\right)$$

$$Q_{\text{Tn1spm}_i} := 1.2 \cdot \left(\text{spflux}_{\text{Tnm}_i} + Q_{\text{Tnstd}_i}\right)$$

Increase the seepage rate by 20 percent to account for drift degradation.

$$Q_{\text{Tn2spm}_i} := \text{if}\left(Q_{\text{Tn1spm}_i} \leq 0.1, 0, Q_{\text{Tn1spm}_i}\right)$$

$$Q_{\text{T2perc}_i} := \frac{Q_{\text{Tn2spm}_i} \cdot 100}{q_{\text{pff}_i} \cdot 28.05}$$

Equation to calculate seepage percent based on seepage rate (see SMPA data table) from DTN: LB0310AMRU0120.002 [DIRS 166116]

$$Q_{\text{T3perc}_i} := \text{if}\left(Q_{\text{T2perc}_i} \leq 0, 0, \text{if}\left(Q_{\text{T2perc}_i} \geq 100, 100, Q_{\text{T2perc}_i}\right)\right)$$

Check seepage percent; if above 100 percent, then recalculate seepage back to 100 percent.

$$QTl_{spr_i} := QT3_{perc_i} \cdot q_{pff_i} \cdot \frac{28.05}{100} \quad \text{Mean Seepage Rate (kg/yr per WP)}$$

$$\text{mean}(QTl_{spr}) = 1.613$$

Determine the seepage fraction for Tptpmn Unit within the repository and then fit the output data to distribution

Seepage fraction represents the non-zero seepage rates based on the LHS sampling of all of the parameters

$$\text{sort}(QTl_{spr}) =$$

	0
16913	0
16914	0
16915	0.1
16916	0.1
16917	0.1

$$n_{Tl} := 16914$$

$$\text{spfr}_{Tl} := \frac{(n - 1) - n_{Tl}}{n} \quad \text{spfr}_{Tl} = 0.154 \quad \text{Seepage fraction (i.e., waste package locations that can see seepage)}$$

$$n1_{Tl} := (n - 1) - (n_{Tl} + 1)$$

$$Q11_{Tl} := \text{sort}(QTl_{spr})$$

$$Q1_{Tl} := \text{reverse}(Q11_{Tl})$$

$$ab := 0..n1_{Tl}$$

$$Q2_{Tl_{ab}} := \left(\frac{1}{998} \cdot Q1_{Tl_{ab}} \right)$$

$$Q_{Tl} := \text{sort}(Q2_{Tl})$$

$$\text{mean}(Q_{Tl} \cdot 998) = 10.457$$

$$\text{CDF}_{Tl_{ab}} := \frac{(ab + 1) - 0.375}{(n1_{Tl} + 1) - 0.25}$$

Fit the seepage rates to a Weibull distribution.

The following equations are from *What Every Engineer Should Know About Reliability and Risk Analysis* (Modarres 1993 [DIRS 104667], p. 109).

$$n1_{Tl} = 3.084 \times 10^3$$

$$\beta := \text{root} \left[\left[\frac{\sum_{i=0}^{n1_{T1}} (Q_{T1_i})^r \cdot \ln(Q_{T1_i})}{\sum_{i=0}^{n1_{T1}} (Q_{T1_i})^r} - \left(\frac{1}{r}\right) - \left[\left(\frac{1}{n1_{T1}}\right) \cdot \sum_{i=0}^{n1_{T1}} \ln(Q_{T1_i})\right], r, 0.1, 4 \right] \right] \quad \beta = 0.536$$

$$\alpha := \left[\frac{\sum_{i=0}^{n1_{T1}} (Q_{T1_i})^\beta}{n1_{T1}} \right]^{\frac{1}{\beta}} \quad \alpha = 4.949 \times 10^{-3}$$

Plot of raw data versus Weibull distribution

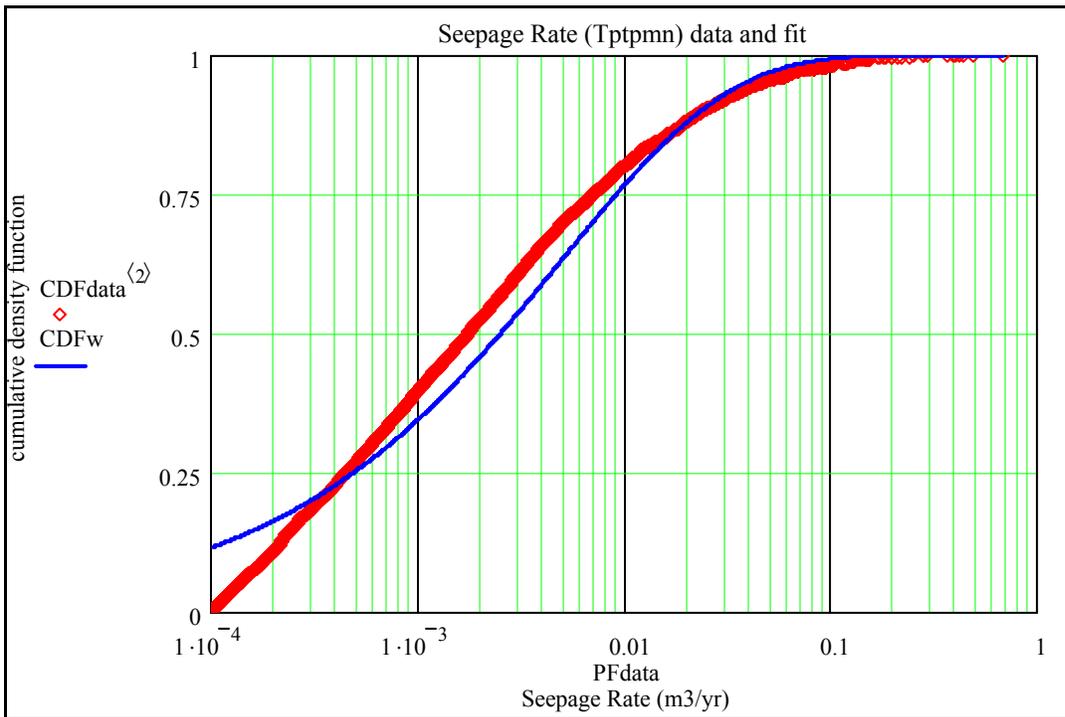
ji := 0..n1_T1

PFdata_ji := QT1_ji

CDFdata_ji,2 := CDF_T1_ji

CDFw1_ji := 1 - exp[-(PFdata_ji/alpha)^beta]

CDFw_ji,0 := CDFw1_ji



IV.5 SEEPAGE ANALYSIS FOR MEAN INFILTRATION RATE IN THE NONLITHOPHYSAL ZONE

The following section presents the Mathcad analysis for the mean seepage infiltration rate of the glacial transition climate in the nonlithophysal zone. The seepage information used in this analysis was obtained from *Abstraction of Drift Seepage* (BSC 2003 [DIRS 165564]). The information contained in the section has been abstracted from the “seepage glac mean Tptpmn x1.2 report.mcd” Mathcad file of Attachment VII.

Seepage Rate and Seepage Fraction Calculation using *Abstraction of Drift Seepage* (BSC 2003 [DIRS 165564], Section 6.7)

Latin Hypercube Sampling Routine to Generate Random Numbers

Sample Size: $n := 20000$

$i := 1..n$

$RD_{i-1,0} := i$ $RD_{i-1,3} := \text{rnd}(1.0)$ $RD_{i-1,6} := \text{rnd}(1.0)$ $RD_{i-1,9} := \text{rnd}(1.0)$ $RD_{i-1,12} := \text{rnd}(1.0)$
 $RD_{i-1,1} := \text{rnd}(1.0)$ $RD_{i-1,4} := \text{rnd}(1.0)$ $RD_{i-1,7} := \text{rnd}(1.0)$ $RD_{i-1,10} := \text{rnd}(1.0)$
 $RD_{i-1,2} := \text{rnd}(1.0)$ $RD_{i-1,5} := \text{rnd}(1.0)$ $RD_{i-1,8} := \text{rnd}(1.0)$ $RD_{i-1,11} := \text{rnd}(1.0)$

RKs are matrixes in which the first column contain a permutation on the integers on the interval [1,n]

$RK1 := \text{csort}(RD, 1)$ $RK4 := \text{csort}(RD, 4)$ $RK7 := \text{csort}(RD, 7)$ $RK10 := \text{csort}(RD, 10)$
 $RK2 := \text{csort}(RD, 2)$ $RK5 := \text{csort}(RD, 5)$ $RK8 := \text{csort}(RD, 8)$ $RK11 := \text{csort}(RD, 11)$
 $RK3 := \text{csort}(RD, 3)$ $RK6 := \text{csort}(RD, 6)$ $RK9 := \text{csort}(RD, 9)$ $RK12 := \text{csort}(RD, 12)$

Define sets of random values. Each random value is selected within one of the equiprobable n intervals that partition [0,1], one set for each random variable

$$\begin{aligned}
 X^{(0)} &:= \frac{RK1^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} & X^{(3)} &:= \frac{RK4^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} & X^{(6)} &:= \frac{RK7^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} \\
 X^{(1)} &:= \frac{RK2^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} & X^{(4)} &:= \frac{RK5^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} & X^{(7)} &:= \frac{RK8^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} \\
 X^{(2)} &:= \frac{RK3^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} & X^{(5)} &:= \frac{RK6^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} & X^{(8)} &:= \frac{RK9^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} \\
 X^{(9)} &:= \frac{RK10^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} & X^{(10)} &:= \frac{RK11^{(0)} - 1 + \text{runif}(n, 0, 1)}{n} \\
 X^{(11)} &:= \frac{RK12^{(0)} - 1 + \text{runif}(n, 0, 1)}{n}
 \end{aligned}$$

$i := 0..n - 1$

Capillary Strength $1/\alpha$ in (Pa)

$\alpha_{1lb} := 402$ $\alpha_{1ub} := 780$ $\alpha_{1\mu} := 591$ **Spatial variability follows a uniform distribution**

$\Delta\alpha_{1l} := -105$ $\Delta\alpha_{1\mu} := 0$ $\Delta\alpha_{1u} := 105$ **Uncertainty follows a triangular distribution**

Sampling from spatial variability to obtain the $1/\alpha$ value

$\alpha_{1i} := \text{qunif}(X_{i,0}, \alpha_{1lb}, \alpha_{1ub})$ **$1/\alpha$ value**

Sample from uncertainty triangular distribution to obtain $\Delta 1/\alpha$

Determine which equation to use:

if Random Number $< \text{RN}_{\Delta\alpha 1}$ then use Equation 1 ($\Delta\alpha 1eq1$).

if Random Number $> \text{RN}_{\Delta\alpha 1}$ then use Equation 2 ($\Delta\alpha 1eq2$).

$$\text{RN}_{\Delta\alpha 1} := \frac{(\Delta\alpha_{1\mu} - \Delta\alpha_{1l})^2}{(\Delta\alpha_{1u} - \Delta\alpha_{1l}) \cdot (\Delta\alpha_{1\mu} - \Delta\alpha_{1l})}$$

$$\Delta\alpha_{1eq1i} := \Delta\alpha_{1l} + \sqrt{X_{i,1} \cdot (\Delta\alpha_{1u} - \Delta\alpha_{1l}) \cdot (\Delta\alpha_{1\mu} - \Delta\alpha_{1l})}$$

$$\Delta\alpha_{1eq2i} := \Delta\alpha_{1u} - \sqrt{(1 - X_{i,1}) \cdot (\Delta\alpha_{1u} - \Delta\alpha_{1l}) \cdot (\Delta\alpha_{1u} - \Delta\alpha_{1\mu})}$$

$$\Delta\alpha_{1i} := \text{if} \left[\left(X_{i,1} \leq \text{RN}_{\Delta\alpha 1} \right), \Delta\alpha_{1eq1i}, \Delta\alpha_{1eq2i} \right] \quad \mathbf{\Delta 1/\alpha \text{ value}}$$

Overall Capillary Strength $1/\alpha + \Delta 1/\alpha$

$T_{1\alpha_i} := \alpha_{1i} + \Delta\alpha_{1i}$ **$1/\alpha$ value**

Permeability k in Tptpmn Unit (in log 10)

$\mu_{kTn} := -12.2$ **Mean of lognormal distribution**

$\sigma_{kTn} := 0.34$ **Standard deviation of lognormal distribution**

$$k_{Tn_i} := \ln(\text{qlnorm}(X_{i,2}, \mu_{kTn}, \sigma_{kTn}))$$

$$\text{mean}(k_{Tn}) = -12.2$$

$$\text{Stdev}(k_{Tn}) = 0.34$$

Permeability Δk in Tptpmn Unit (in log 10)

$\Delta k_{Tnl} := -0.68$ $\Delta k_{Tn\mu} := 0$ $\Delta k_{Tnu} := 0.68$ **Uncertainty follows a triangular distribution**

Sample from uncertainty triangular distribution to obtain Δk

Determine which equation to use:

if Random Number < $RN_{\Delta k Tn}$ then use Equation 1 ($\Delta k Tneq1$).

if Random Number > $RN_{\Delta k Tn}$ then use Equation 2 ($\Delta k Tneq2$).

$$RN_{\Delta k Tn} := \frac{(\Delta k_{Tn\mu} - \Delta k_{Tnl})^2}{(\Delta k_{Tnu} - \Delta k_{Tnl}) \cdot (\Delta k_{Tn\mu} - \Delta k_{Tnl})}$$

$$\Delta k_{Tneq1_i} := \Delta k_{Tnl} + \sqrt{X_{i,3} \cdot (\Delta k_{Tnu} - \Delta k_{Tnl}) \cdot (\Delta k_{Tn\mu} - \Delta k_{Tnl})}$$

$$\Delta k_{Tneq2_i} := \Delta k_{Tnu} - \sqrt{(1 - X_{i,3}) \cdot (\Delta k_{Tnu} - \Delta k_{Tnl}) \cdot (\Delta k_{Tnu} - \Delta k_{Tn\mu})}$$

$$\Delta k_{Tn_i} := \text{if} \left[\left(X_{i,3} \leq RN_{\Delta k Tn} \right), \Delta k_{Tneq1_i}, \Delta k_{Tneq2_i} \right] \quad \mathbf{\Delta k \text{ value}}$$

Overall Permeability $k + \Delta k$

$$T1_{kTn_i} := k_{Tn_i} + \Delta k_{Tn_i}$$

Permeability must lie between -14 and -10 (bounds of SMPA simulations)

$$T_{kTn_i} := \text{if} \left(T1_{kTn_i} \geq -10, -10, \text{if} \left(T1_{kTn_i} \leq -14, -14, T1_{kTn_i} \right) \right) \quad \mathbf{k \text{ value}}$$

Flow Focusing Factor (DTN: LB0104AMRU0185.012 [DIRS 163906])

$$f(x) := -0.3137x^4 + 5.4998x^3 - 35.66x^2 + 102.3x - 11.434$$

$$ff_i := \text{root} \left[f(x) - (X_{i,5} \cdot 100), x, 0, 6 \right]$$

Percolation Flux (mm/yr)

The percolation flux used here is for the glacial transition period only. The percolation flux is based on sampling from the mean bound TSPA repository location only (DTN: LB0310AMRU0120.002 [DIRS 166116])

$$n := 0..468$$

Mean Bound Percolation Flux

$PF1_m :=$

	0
0	15.97
1	19.87
2	14.2
3	7.59
4	16.94
5	17.76
6	10.45
7	27.77
8	8.95
9	16.02

$$PFt_{m_{nnn}} := PF1_{m_{nnn}, 0}$$

$$Z^{(0)} := \text{round}(\text{runif}(n, 0, 468))$$

$$PF_i := PFt_m(Z_i, 0)$$

Adjusted Percolation Flux

Multiply the flow-focusing factor by the percolation flux, which will be used to obtain the seepage rate, seepage fraction, and seepage percentage

$$q1_{pff_i} := PF_i \cdot ff_i$$

Percolation Flux must lie between 1 and 1000 mm/yr (bounds of SMPA simulations)

$$q_{pff_i} := \text{if}(q1_{pff_i} \leq 1, 1, \text{if}(q1_{pff_i} \geq 1000, 1000, q1_{pff_i}))$$

**Seepage Information from SMPA analysis
(DTN: LB0304SMDCREV2.002 [DIRS 163687])**

m := 2549 **Data points**

SMPA_{data}^{<0>} is permeability value log(k [m²])

SMPA_{data}^{<1>} is capillary strength 1/alpha [Pa]

SMPA_{data}^{<2>} is local percolation flux (mm/yr)

SMPA_{data}^{<3>} is Mean Seepage [kg/yr/WP]

SMPA_{data}^{<4>} is Std. Dev. Seepage [kg/yr/WP]

SMPA_{data}^{<5>} is Mean Seepage [%]

SMPA_{data}^{<6>} is Std. Dev. Seepage [%]

SMPA_{data} :=

	0	1	2	3	4	5	6
0	-14	100	1	27.73	4.09	98.86	14.59
1	-14	100	5	138.92	20.55	99.05	14.65
2	-14	100	10	277.9	41.19	99.07	14.68
3	-14	100	20	555.87	82.54	99.09	14.71
4	-14	100	50	1391.67	205.57	99.23	14.66
5	-14	100	100	2793.55	406.7	99.59	14.5
6	-14	100	200	5610	785	100	14
7	-14	100	300	8415	1178	100	14
8	-14	100	400	11220	1570	100	14
9	-14	100	500	14025	1963	100	14
10	-14	100	600	16830	2356	100	14
11	-14	100	700	19635	2748	100	14
12	-14	100	800	22440	3141	100	14
13	-14	100	900	25245	3590	100	14
14	-14	100	1000	28050	3989	100	14
15	-14	200	1	26.14	4.21	93.21	15

Develop routine to select correct mean seepage, seepage standard deviation, seepage percent, and seepage percent standard deviation based on sampled value of 1/ α , k, percolation flux.

nx := 14 ny := 9 nz := 16

ii := 0..nx

x_{ii} := SMPA_{data}_{ii,2} xi_{ii} := ii

jj := 0..ny

y_{jj} := 100·jj + 100 yj_{jj} := jj

kk := 0..nz

z_{kk} := -14 + kk·0.25 zk_{kk} := kk

loc represents the location within the matrix of which value to pick for the interpolation process

$$\text{loc}_{1_i} := \left(\text{floor}\left(\text{linterp}\left(z, z_k, T_{kTn_i}\right)\right) \cdot (nx + 1) \cdot (ny + 1) + \text{floor}\left(\text{linterp}\left(y, y_j, T_{1\alpha_i}\right)\right) \cdot (nx + 1) \dots \right. \\ \left. + \text{floor}\left(\text{linterp}\left(x, x_i, q_{pff_i}\right)\right) \right)$$

$$s_{ms1_i} := \text{SMPA}_{\text{data}_{\text{loc}_{1_i}, 3}}$$

$$s_{msd1_i} := \text{SMPA}_{\text{data}_{\text{loc}_{1_i}, 4}}$$

$$s_{pms1_i} := \text{SMPA}_{\text{data}_{\text{loc}_{1_i}, 5}}$$

$$s_{psd1_i} := \text{SMPA}_{\text{data}_{\text{loc}_{1_i}, 6}}$$

$$\text{loc}_{2_i} := \left[\text{floor}\left(\text{linterp}\left(z, z_k, T_{kTn_i}\right)\right) \cdot (nx + 1) \cdot (ny + 1) \right] + \text{floor}\left(\text{linterp}\left(y, y_j, T_{1\alpha_i}\right)\right) \cdot (nx + 1) \dots \\ + \text{ceil}\left(\text{linterp}\left(x, x_i, q_{pff_i}\right)\right)$$

$$s_{ms2_i} := \text{SMPA}_{\text{data}_{\text{loc}_{2_i}, 3}}$$

$$s_{msd2_i} := \text{SMPA}_{\text{data}_{\text{loc}_{2_i}, 4}}$$

$$s_{pms2_i} := \text{SMPA}_{\text{data}_{\text{loc}_{2_i}, 5}}$$

$$s_{psd2_i} := \text{SMPA}_{\text{data}_{\text{loc}_{2_i}, 6}}$$

$$\text{loc}_{3_i} := \left(\text{floor}\left(\text{linterp}\left(z, z_k, T_{kTn_i}\right)\right) \cdot (nx + 1) \cdot (ny + 1) + \text{ceil}\left(\text{linterp}\left(y, y_j, T_{1\alpha_i}\right)\right) \cdot (nx + 1) \dots \right. \\ \left. + \text{ceil}\left(\text{linterp}\left(x, x_i, q_{pff_i}\right)\right) \right)$$

$$s_{ms3_i} := \text{SMPA}_{\text{data}_{\text{loc}_{3_i}, 3}}$$

$$s_{msd3_i} := \text{SMPA}_{\text{data}_{\text{loc}_{3_i}, 4}}$$

$$s_{pms3_i} := \text{SMPA}_{\text{data}_{\text{loc}_{3_i}, 5}}$$

$$s_{psd3_i} := \text{SMPA}_{\text{data}_{\text{loc}_{3_i}, 6}}$$

$$\text{loc}_{4_i} := \left(\text{floor}\left(\text{linterp}\left(z, z_k, T_{kTn_i}\right)\right) \cdot (nx + 1) \cdot (ny + 1) + \text{ceil}\left(\text{linterp}\left(y, y_j, T_{1\alpha_i}\right)\right) \cdot (nx + 1) \dots \right. \\ \left. + \text{floor}\left(\text{linterp}\left(x, x_i, q_{pff_i}\right)\right) \right)$$

$$s_{ms4_i} := \text{SMPA}_{\text{data}_{\text{loc}_{4_i}, 3}}$$

$$s_{msd4_i} := \text{SMPA}_{\text{data}_{\text{loc}_{4_i}, 4}}$$

$$s_{pms4_i} := \text{SMPA}_{\text{data}_{\text{loc}_{4_i}, 5}}$$

$$s_{psd4_i} := \text{SMPA}_{\text{data}_{\text{loc}_{4_i}, 6}}$$

$$\text{loc}_{5_i} := \left[\text{ceil} \left(\text{linterp} \left(z, z_k, T_k T_{n_i} \right) \right) \cdot (n_x + 1) \cdot (n_y + 1) \right] + \text{floor} \left(\text{linterp} \left(y, y_j, T_{1\alpha_i} \right) \right) \cdot (n_x + 1) \dots \\ + \text{floor} \left(\text{linterp} \left(x, x_i, q_{\text{pff}_i} \right) \right)$$

$$s_{\text{ms}5_i} := \text{SMPA}_{\text{data loc}_{5_i}, 3}$$

$$s_{\text{msd}5_i} := \text{SMPA}_{\text{data loc}_{5_i}, 4}$$

$$s_{\text{pms}5_i} := \text{SMPA}_{\text{data loc}_{5_i}, 5}$$

$$s_{\text{psd}5_i} := \text{SMPA}_{\text{data loc}_{5_i}, 6}$$

$$\text{loc}_{6_i} := \text{ceil} \left(\text{linterp} \left(z, z_k, T_k T_{n_i} \right) \right) \cdot (n_x + 1) \cdot (n_y + 1) + \text{floor} \left(\text{linterp} \left(y, y_j, T_{1\alpha_i} \right) \right) \cdot (n_x + 1) \dots \\ + \text{ceil} \left(\text{linterp} \left(x, x_i, q_{\text{pff}_i} \right) \right)$$

$$s_{\text{ms}6_i} := \text{SMPA}_{\text{data loc}_{6_i}, 3}$$

$$s_{\text{msd}6_i} := \text{SMPA}_{\text{data loc}_{6_i}, 4}$$

$$s_{\text{pms}6_i} := \text{SMPA}_{\text{data loc}_{6_i}, 5}$$

$$s_{\text{psd}6_i} := \text{SMPA}_{\text{data loc}_{6_i}, 6}$$

$$\text{loc}_{7_i} := \left[\text{ceil} \left(\text{linterp} \left(z, z_k, T_k T_{n_i} \right) \right) \cdot (n_x + 1) \cdot (n_y + 1) \right] + \text{ceil} \left(\text{linterp} \left(y, y_j, T_{1\alpha_i} \right) \right) \cdot (n_x + 1) \dots \\ + \text{ceil} \left(\text{linterp} \left(x, x_i, q_{\text{pff}_i} \right) \right)$$

$$s_{\text{ms}7_i} := \text{SMPA}_{\text{data loc}_{7_i}, 3}$$

$$s_{\text{msd}7_i} := \text{SMPA}_{\text{data loc}_{7_i}, 4}$$

$$s_{\text{pms}7_i} := \text{SMPA}_{\text{data loc}_{7_i}, 5}$$

$$s_{\text{psd}7_i} := \text{SMPA}_{\text{data loc}_{7_i}, 6}$$

$$\text{loc}_{8_i} := \text{ceil} \left(\text{linterp} \left(z, z_k, T_k T_{n_i} \right) \right) \cdot (n_x + 1) \cdot (n_y + 1) + \text{ceil} \left(\text{linterp} \left(y, y_j, T_{1\alpha_i} \right) \right) \cdot (n_x + 1) \dots \\ + \text{floor} \left(\text{linterp} \left(x, x_i, q_{\text{pff}_i} \right) \right)$$

$$s_{\text{ms}8_i} := \text{SMPA}_{\text{data loc}_{8_i}, 3}$$

$$s_{\text{msd}8_i} := \text{SMPA}_{\text{data loc}_{8_i}, 4}$$

$$s_{\text{pms}8_i} := \text{SMPA}_{\text{data loc}_{8_i}, 5}$$

$$s_{\text{psd}8_i} := \text{SMPA}_{\text{data loc}_{8_i}, 6}$$

Develop the upper and lower bound of the randomly generated $1/\alpha$, k, and adjusted percolation flux

Develop the upper and lower bound for permeability (k) for Tptpmn Unit

$$qq_i := -1 \cdot T_{kTn_i}$$

$$\text{mantissa}(x) := x - \text{floor}(qq)$$

$$tt_i := \text{floor}(qq_i)$$

$$rr := \text{round}(\text{mantissa}(qq), 2)$$

$$yy1_i := \text{if}(rr_i \leq 0.25, 0, \text{if}(0.25 < rr_i \leq 0.5, 0.25, rr_i))$$

$$zz1_i := \text{if}(yy1_i \leq 0.5, yy1_i, \text{if}(0.5 < yy1_i \leq 0.75, 0.5, 0.75))$$

$$T_{kTn2_i} := -1 \cdot (tt_i + zz1_i)$$

$$yy2_i := \text{if}(rr_i \leq 0.25, 0.25, \text{if}(0.25 < rr_i \leq 0.5, 0.5, rr_i))$$

$$zz2_i := \text{if}(yy2_i \leq 0.5, yy2_i, \text{if}(0.5 < yy2_i \leq 0.75, 0.75, 1))$$

$$T_{kTn1_i} := -1 \cdot (tt_i + zz2_i)$$

Develop the upper and lower bound for capillary strength ($1/\alpha$)

$$hh1_i := \text{floor}\left(\frac{T_{1\alpha_i}}{100}\right)$$

$$T_{1\alpha1_i} := (hh1_i \cdot 100)$$

$$hh2_i := \text{ceil}\left(\frac{T_{1\alpha_i}}{100}\right)$$

$$T_{1\alpha2_i} := (hh2_i \cdot 100)$$

Lower Bound value adjusted percolation flux (q_{pff})

$$aaa1_i := \text{if}(q_{pff_i} \leq 1, 1, \text{if}(1 < q_{pff_i} \leq 5, 1, q_{pff_i}))$$

$$bbb1_i := \text{if}(aaa1_i \leq 5, aaa1_i, \text{if}(5 < aaa1_i \leq 10, 5, aaa1_i))$$

$$ccc1_i := \text{if}(bbb1_i \leq 10, bbb1_i, \text{if}(10 < bbb1_i \leq 20, 10, bbb1_i))$$

$$ddd1_i := \text{if}(ccc1_i \leq 20, ccc1_i, \text{if}(20 < ccc1_i \leq 50, 20, ccc1_i))$$

$$eee1_i := \text{if}(ddd1_i \leq 50, ddd1_i, \text{if}(50 < ddd1_i \leq 100, 50, ddd1_i))$$

$$fff1_i := \text{if}(eee1_i \leq 100, eee1_i, \text{if}(100 < eee1_i \leq 200, 100, eee1_i))$$

$$\begin{aligned}
 ggg1_i &:= \text{if}(fff1_i \leq 200, fff1_i, \text{if}(200 < fff1_i \leq 300, 200, fff1_i)) \\
 hhh1_i &:= \text{if}(ggg1_i \leq 300, ggg1_i, \text{if}(300 < ggg1_i \leq 400, 300, ggg1_i)) \\
 iii1_i &:= \text{if}(hhh1_i \leq 400, hhh1_i, \text{if}(400 < hhh1_i \leq 500, 400, hhh1_i)) \\
 jjj1_i &:= \text{if}(iii1_i \leq 500, iii1_i, \text{if}(500 < iii1_i \leq 600, 500, iii1_i)) \\
 kkk1_i &:= \text{if}(jjj1_i \leq 600, jjj1_i, \text{if}(600 < jjj1_i \leq 700, 600, jjj1_i)) \\
 mmm1_i &:= \text{if}(kkk1_i \leq 700, kkk1_i, \text{if}(700 < kkk1_i \leq 800, 700, kkk1_i)) \\
 q_{pff1}_i &:= \text{if}(mmm1_i \leq 800, mmm1_i, \text{if}(800 < mmm1_i \leq 900, 800, 900))
 \end{aligned}$$

Upper Bound value adjusted percolation flux (q_{pff})

$$\begin{aligned}
 aaa2_i &:= \text{if}(q_{pff1}_i \leq 1, 5, \text{if}(1 < q_{pff1}_i \leq 5, 5, q_{pff1}_i)) \\
 bbb2_i &:= \text{if}(aaa2_i \leq 5, aaa2_i, \text{if}(5 < aaa2_i \leq 10, 10, aaa2_i)) \\
 ccc2_i &:= \text{if}(bbb2_i \leq 10, bbb2_i, \text{if}(10 < bbb2_i \leq 20, 20, bbb2_i)) \\
 ddd2_i &:= \text{if}(ccc2_i \leq 20, ccc2_i, \text{if}(20 < ccc2_i \leq 50, 50, ccc2_i)) \\
 eee2_i &:= \text{if}(ddd2_i \leq 50, ddd2_i, \text{if}(50 < ddd2_i \leq 100, 100, ddd2_i)) \\
 fff2_i &:= \text{if}(eee2_i \leq 100, eee2_i, \text{if}(100 < eee2_i \leq 200, 200, eee2_i)) \\
 ggg2_i &:= \text{if}(fff2_i \leq 200, fff2_i, \text{if}(200 < fff2_i \leq 300, 300, fff2_i)) \\
 hhh2_i &:= \text{if}(ggg2_i \leq 300, ggg2_i, \text{if}(300 < ggg2_i \leq 400, 400, ggg2_i)) \\
 iii2_i &:= \text{if}(hhh2_i \leq 400, hhh2_i, \text{if}(400 < hhh2_i \leq 500, 500, hhh2_i)) \\
 jjj2_i &:= \text{if}(iii2_i \leq 500, iii2_i, \text{if}(500 < iii2_i \leq 600, 600, iii2_i)) \\
 kkk2_i &:= \text{if}(jjj2_i \leq 600, jjj2_i, \text{if}(600 < jjj2_i \leq 700, 700, jjj2_i)) \\
 mmm2_i &:= \text{if}(kkk2_i \leq 700, kkk2_i, \text{if}(700 < kkk2_i \leq 800, 800, kkk2_i)) \\
 q_{pff2}_i &:= \text{if}(mmm2_i \leq 800, mmm2_i, \text{if}(800 < mmm2_i \leq 900, 900, 1000))
 \end{aligned}$$

Solve for seepage rate (Tptpmn Unit)

$$t_{q_{pff}_i} := \frac{q_{pff1}_i - q_{pff2}_i}{q_{pff2}_i - q_{pff1}_i} \quad u_{T1\alpha}_i := \frac{T_{1\alpha_i} - T_{1\alpha1_i}}{T_{1\alpha2_i} - T_{1\alpha1_i}} \quad v_{TKTn}_i := \frac{T_{kTn_i} - T_{kTn1_i}}{T_{kTn2_i} - T_{kTn1_i}}$$

$$\begin{aligned}
 \text{spflux}_{\text{Tnm}_i} := & \left(1 - t_{\text{qpf}_i}\right) \cdot \left(1 - u_{\text{T1}\alpha_i}\right) \cdot \left(1 - v_{\text{TkTn}_i}\right) \cdot s_{\text{ms1}_i} \dots \\
 & + \left(t_{\text{qpf}_i}\right) \cdot \left(1 - u_{\text{T1}\alpha_i}\right) \cdot \left(1 - v_{\text{TkTn}_i}\right) \cdot s_{\text{ms2}_i} \dots \\
 & + \left(t_{\text{qpf}_i}\right) \cdot \left(u_{\text{T1}\alpha_i}\right) \cdot \left(1 - v_{\text{TkTn}_i}\right) \cdot s_{\text{ms3}_i} \dots \\
 & + \left(1 - t_{\text{qpf}_i}\right) \cdot \left(u_{\text{T1}\alpha_i}\right) \cdot \left(1 - v_{\text{TkTn}_i}\right) \cdot s_{\text{ms4}_i} \dots \\
 & + \left(1 - t_{\text{qpf}_i}\right) \cdot \left(1 - u_{\text{T1}\alpha_i}\right) \cdot \left(v_{\text{TkTn}_i}\right) \cdot s_{\text{ms5}_i} \dots \\
 & + \left(t_{\text{qpf}_i}\right) \cdot \left(1 - u_{\text{T1}\alpha_i}\right) \cdot \left(v_{\text{TkTn}_i}\right) \cdot s_{\text{ms6}_i} \dots \\
 & + \left(t_{\text{qpf}_i}\right) \cdot \left(u_{\text{T1}\alpha_i}\right) \cdot \left(v_{\text{TkTn}_i}\right) \cdot s_{\text{ms7}_i} \dots \\
 & + \left(1 - t_{\text{qpf}_i}\right) \cdot \left(u_{\text{T1}\alpha_i}\right) \cdot \left(v_{\text{TkTn}_i}\right) \cdot s_{\text{ms8}_i}
 \end{aligned}$$

$$\begin{aligned}
 \text{spflux}_{\text{Tnsd}_i} := & \left(1 - t_{\text{qpf}_i}\right) \cdot \left(1 - u_{\text{T1}\alpha_i}\right) \cdot \left(1 - v_{\text{TkTn}_i}\right) \cdot s_{\text{msd1}_i} \dots \\
 & + \left(t_{\text{qpf}_i}\right) \cdot \left(1 - u_{\text{T1}\alpha_i}\right) \cdot \left(1 - v_{\text{TkTn}_i}\right) \cdot s_{\text{msd2}_i} \dots \\
 & + \left(t_{\text{qpf}_i}\right) \cdot \left(u_{\text{T1}\alpha_i}\right) \cdot \left(1 - v_{\text{TkTn}_i}\right) \cdot s_{\text{msd3}_i} \dots \\
 & + \left(1 - t_{\text{qpf}_i}\right) \cdot \left(u_{\text{T1}\alpha_i}\right) \cdot \left(1 - v_{\text{TkTn}_i}\right) \cdot s_{\text{msd4}_i} \dots \\
 & + \left(1 - t_{\text{qpf}_i}\right) \cdot \left(1 - u_{\text{T1}\alpha_i}\right) \cdot \left(v_{\text{TkTn}_i}\right) \cdot s_{\text{msd5}_i} \dots \\
 & + \left(t_{\text{qpf}_i}\right) \cdot \left(1 - u_{\text{T1}\alpha_i}\right) \cdot \left(v_{\text{TkTn}_i}\right) \cdot s_{\text{msd6}_i} \dots \\
 & + \left(t_{\text{qpf}_i}\right) \cdot \left(u_{\text{T1}\alpha_i}\right) \cdot \left(v_{\text{TkTn}_i}\right) \cdot s_{\text{msd7}_i} \dots \\
 & + \left(1 - t_{\text{qpf}_i}\right) \cdot \left(u_{\text{T1}\alpha_i}\right) \cdot \left(v_{\text{TkTn}_i}\right) \cdot s_{\text{msd8}_i}
 \end{aligned}$$

Calculate mean seepage for Ttpmn Unit

$$Q_{\text{Tn1std}_i} := -1.7321 \cdot \text{spflux}_{\text{Tnsd}_i}$$

$$Q_{\text{Tn1stdu}_i} := 1.7321 \cdot \text{spflux}_{\text{Tnsd}_i}$$

$$Q_{\text{Tnstd}_i} := \text{if}(Q_{\text{Tn1std}_i} = 0, -0.00001, Q_{\text{Tn1std}_i})$$

$$Q_{\text{Tnstd}_i} := \text{qunif}(X_{i,10}, Q_{\text{Tnstd}_i}, Q_{\text{Tn1stdu}_i})$$

$$Q_{\text{Tn1spm}_i} := 1.2 \cdot (\text{spflux}_{\text{Tnm}_i} + Q_{\text{Tnstd}_i})$$

Increase the seepage rate by 20 percent to account for drift degradation

$$Q_{\text{Tn2spm}_i} := \text{if}(Q_{\text{Tn1spm}_i} \leq 0.1, 0, Q_{\text{Tn1spm}_i})$$

$$Q_{\text{T2perc}_i} := \frac{Q_{\text{Tn2spm}_i} \cdot 100}{q_{\text{pff}_i} \cdot 28.05}$$

Equation to calculate seepage percent based on seepage rate (see SMPA data table) from DTN: LB0310AMRU0120.002 [DIRS 166116]

$$Q_{\text{T3perc}_i} := \text{if}(Q_{\text{T2perc}_i} \leq 0, 0, \text{if}(Q_{\text{T2perc}_i} \geq 100, 100, Q_{\text{T2perc}_i}))$$

Check seepage percent; if above 100 percent, then recalculate seepage back to 100 percent

$$QTl_{spr_i} := QT3_{perc_i} \cdot q_{pff_i} \cdot \frac{28.05}{100} \quad \text{Mean Seepage Rate (kg/yr per WP)}$$

$$\text{mean}(QTl_{spr}) = 102.895$$

Determine the seepage fraction for Tptpmn Unit within the repository and then fit the output data to distribution

Seepage fraction represents the non-zero seepage rates based on the LHS sampling of all of the parameters

$$\text{sort}(QTl_{spr}) =$$

	0
9520	0
9521	0
9522	0.1
9523	0.1
9524	0.1

$$n_{Tl} := 9521$$

$$\text{spfr}_{Tl} := \frac{(n - 1) - n_{Tl}}{n} \quad \text{spfr}_{Tl} = 0.524 \quad \text{Seepage fraction (i.e., waste package locations that can see seepage)}$$

$$n1_{Tl} := (n - 1) - (n_{Tl} + 1)$$

$$Q11_{Tl} := \text{sort}(QTl_{spr})$$

$$Q1_{Tl} := \text{reverse}(Q11_{Tl})$$

$$ab := 0..n1_{Tl}$$

$$Q2_{Tl_{ab}} := \left(\frac{1}{998} \cdot Q1_{Tl_{ab}} \right)$$

$$Q_{Tl} := \text{sort}(Q2_{Tl})$$

$$\text{mean}(Q_{Tl} \cdot 998) = 196.403$$

$$CDF_{Tl_{ab}} := \frac{(ab + 1) - 0.375}{(n1_{Tl} + 1) - 0.25}$$

Fit the seepage rates to a Weibull distribution.

The following equations are from *What Every Engineer Should Know About Reliability and Risk Analysis* (Modarres 1993 [DIRS 104667] p. 109).

$$n1_{Tl} = 1.048 \times 10^4$$

$$\beta := \text{root} \left[\left[\frac{\sum_{i=0}^{n1_{T1}} (Q_{T1_i})^r \cdot \ln(Q_{T1_i})}{\sum_{i=0}^{n1_{T1}} (Q_{T1_i})^r} - \left(\frac{1}{r}\right) - \left[\left(\frac{1}{n1_{T1}}\right) \cdot \sum_{i=0}^{n1_{T1}} \ln(Q_{T1_i})\right] \right], r, 0.1, 4 \right] \quad \beta = 0.473$$

$$\alpha := \left[\frac{\sum_{i=0}^{n1_{T1}} (Q_{T1_i})^\beta}{n1_{T1}} \right]^{\frac{1}{\beta}} \quad \alpha = 8.559 \times 10^{-2}$$

Plot of raw data versus Weibull distribution

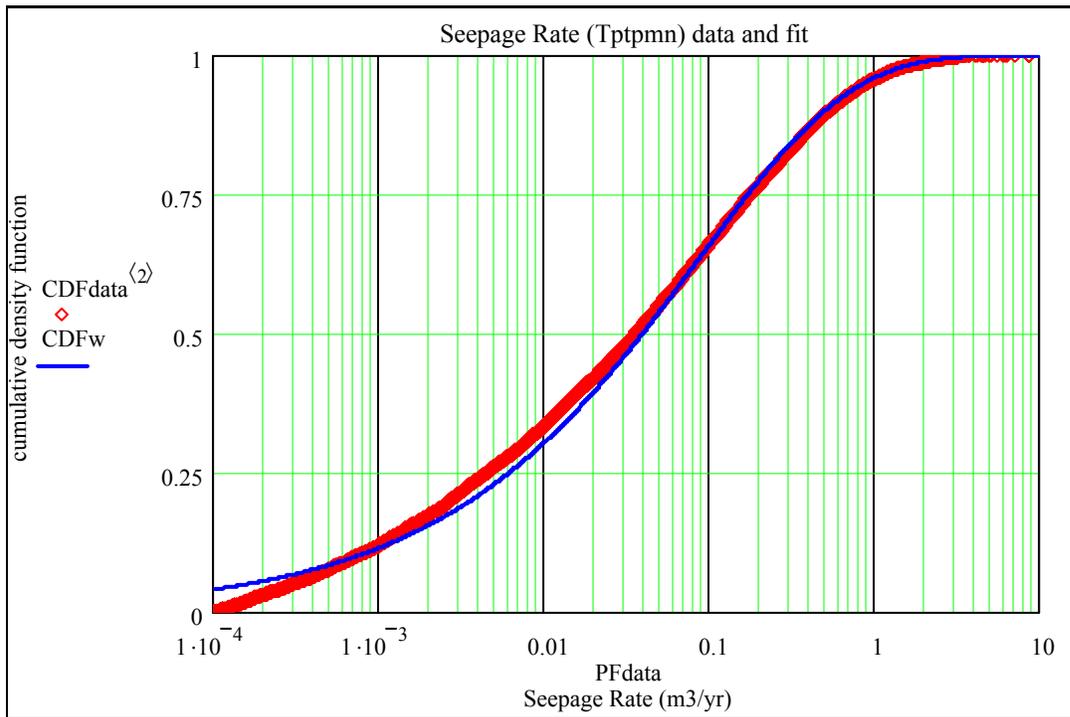
ji := 0.. n1_T1

PFdata_ji := Q_T1_ji

CDFdata_ji,2 := CDF_T1_ji

CDFw1_ji := 1 - exp $\left[- \left(\frac{\text{PFdata}_j_i^\beta}{\alpha} \right) \right]$

CDFw_ji,0 := CDFw1_ji



IV.6 SEEPAGE ANALYSIS FOR UPPER INFILTRATION RATE IN THE NONLITHOPHYSAL ZONE

The following section presents the Mathcad analysis for the upper seepage infiltration rate of the glacial transition climate in the nonlithophysal zone. The seepage information used in this analysis was obtained from *Abstraction of Drift Seepage* (BSC 2003 [DIRS 165564]). The information contained in the section has been abstracted from the “seepage glac upper Tptpmn x1.2 report.mcd” Mathcad file of Attachment VII.

Seepage Rate and Seepage Fraction Calculation using *Abstraction of Drift Seepage* (BSC 2003 [DIRS 165564], Section 6.7)

Latin Hypercube Sampling Routine to Generate Random Numbers

Sample Size: $n := 20000$

$i := 1..n$

$RD_{i-1,0} := i$ $RD_{i-1,3} := \text{rnd}(1.0)$ $RD_{i-1,6} := \text{rnd}(1.0)$ $RD_{i-1,9} := \text{rnd}(1.0)$ $RD_{i-1,12} := \text{rnd}(1.0)$
 $RD_{i-1,1} := \text{rnd}(1.0)$ $RD_{i-1,4} := \text{rnd}(1.0)$ $RD_{i-1,7} := \text{rnd}(1.0)$ $RD_{i-1,10} := \text{rnd}(1.0)$
 $RD_{i-1,2} := \text{rnd}(1.0)$ $RD_{i-1,5} := \text{rnd}(1.0)$ $RD_{i-1,8} := \text{rnd}(1.0)$ $RD_{i-1,11} := \text{rnd}(1.0)$

RKs are matrixes in which the first column contain a permutation on the integers on the interval [1,n]

$RK1 := \text{csort}(RD, 1)$ $RK4 := \text{csort}(RD, 4)$ $RK7 := \text{csort}(RD, 7)$ $RK10 := \text{csort}(RD, 10)$
 $RK2 := \text{csort}(RD, 2)$ $RK5 := \text{csort}(RD, 5)$ $RK8 := \text{csort}(RD, 8)$ $RK11 := \text{csort}(RD, 11)$
 $RK3 := \text{csort}(RD, 3)$ $RK6 := \text{csort}(RD, 6)$ $RK9 := \text{csort}(RD, 9)$ $RK12 := \text{csort}(RD, 12)$

Define sets of random values. Each random value is selected within one of the equiprobable n intervals that partition [0,1], one set for each random variable

$X^{(0)} := \frac{RK1^{(0)} - 1 + \text{runif}(n, 0, 1)}{n}$ $X^{(3)} := \frac{RK4^{(0)} - 1 + \text{runif}(n, 0, 1)}{n}$ $X^{(6)} := \frac{RK7^{(0)} - 1 + \text{runif}(n, 0, 1)}{n}$
 $X^{(1)} := \frac{RK2^{(0)} - 1 + \text{runif}(n, 0, 1)}{n}$ $X^{(4)} := \frac{RK5^{(0)} - 1 + \text{runif}(n, 0, 1)}{n}$ $X^{(7)} := \frac{RK8^{(0)} - 1 + \text{runif}(n, 0, 1)}{n}$
 $X^{(2)} := \frac{RK3^{(0)} - 1 + \text{runif}(n, 0, 1)}{n}$ $X^{(5)} := \frac{RK6^{(0)} - 1 + \text{runif}(n, 0, 1)}{n}$ $X^{(8)} := \frac{RK9^{(0)} - 1 + \text{runif}(n, 0, 1)}{n}$
 $X^{(9)} := \frac{RK10^{(0)} - 1 + \text{runif}(n, 0, 1)}{n}$ $X^{(10)} := \frac{RK11^{(0)} - 1 + \text{runif}(n, 0, 1)}{n}$
 $X^{(11)} := \frac{RK12^{(0)} - 1 + \text{runif}(n, 0, 1)}{n}$

$i := 0..n - 1$

Capillary Strength $1/\alpha$ in (Pa)

$\alpha_{1lb} := 402$ $\alpha_{1ub} := 780$ $\alpha_{1\mu} := 591$ **Spatial variability follows a uniform distribution**

$\Delta\alpha_{1l} := -105$ $\Delta\alpha_{1\mu} := 0$ $\Delta\alpha_{1u} := 105$ **Uncertainty follows a triangular distribution**

Sampling from spatial variability to obtain the $1/\alpha$ value

$\alpha_{1i} := \text{qunif}(X_{i,0}, \alpha_{1lb}, \alpha_{1ub})$ **$1/\alpha$ value**

Sample from uncertainty triangular distribution to obtain $\Delta 1/\alpha$

Determine which equation to use:

if Random Number $< \text{RN}_{\Delta\alpha 1}$ then use Equation 1 ($\Delta\alpha 1_{eq1}$).

if Random Number $> \text{RN}_{\Delta\alpha 1}$ then use Equation 2 ($\Delta\alpha 1_{eq2}$).

$$\text{RN}_{\Delta\alpha 1} := \frac{(\Delta\alpha_{1\mu} - \Delta\alpha_{1l})^2}{(\Delta\alpha_{1u} - \Delta\alpha_{1l}) \cdot (\Delta\alpha_{1\mu} - \Delta\alpha_{1l})}$$

$$\Delta\alpha_{1_{eq1}} := \Delta\alpha_{1l} + \sqrt{X_{i,1} \cdot (\Delta\alpha_{1u} - \Delta\alpha_{1l}) \cdot (\Delta\alpha_{1\mu} - \Delta\alpha_{1l})}$$

$$\Delta\alpha_{1_{eq2}} := \Delta\alpha_{1u} - \sqrt{(1 - X_{i,1}) \cdot (\Delta\alpha_{1u} - \Delta\alpha_{1l}) \cdot (\Delta\alpha_{1u} - \Delta\alpha_{1\mu})}$$

$$\Delta\alpha_{1i} := \text{if} \left[\left(X_{i,1} \leq \text{RN}_{\Delta\alpha 1} \right), \Delta\alpha_{1_{eq1}}, \Delta\alpha_{1_{eq2}} \right] \quad \mathbf{\Delta 1/\alpha \text{ value}}$$

Overall Capillary Strength $1/\alpha + \Delta 1/\alpha$

$T_{1\alpha_i} := \alpha_{1i} + \Delta\alpha_{1i}$ **$1/\alpha$ value**

Permeability k in Tptpmn Unit (in log 10)

$\mu_{kTn} := -12.2$ **Mean of lognormal distribution**

$\sigma_{kTn} := 0.34$ **Standard deviation of lognormal distribution**

$$k_{Tn_i} := \ln(\text{qlnorm}(X_{i,2}, \mu_{kTn}, \sigma_{kTn}))$$

$$\text{mean}(k_{Tn}) = -12.2$$

$$\text{Stdev}(k_{Tn}) = 0.34$$

Permeability Δk in Tptpmn Unit (in log 10)

$\Delta k_{Tnl} := -0.68$ $\Delta k_{Tn\mu} := 0$ $\Delta k_{Tnu} := 0.68$ **Uncertainty follows a triangular distribution**

Sample from uncertainty triangular distribution to obtain Δk

Determine which equation to use:

if Random Number < $RN_{\Delta kTn}$ then use Equation 1 ($\Delta kTneq1$).

if Random Number > $RN_{\Delta kTn}$ then use Equation 2 ($\Delta kTneq2$).

$$RN_{\Delta kTn} := \frac{(\Delta k_{Tn\mu} - \Delta k_{Tnl})^2}{(\Delta k_{Tnu} - \Delta k_{Tnl}) \cdot (\Delta k_{Tn\mu} - \Delta k_{Tnl})}$$

$$\Delta k_{Tneq1_i} := \Delta k_{Tnl} + \sqrt{X_{i,3} \cdot (\Delta k_{Tnu} - \Delta k_{Tnl}) \cdot (\Delta k_{Tn\mu} - \Delta k_{Tnl})}$$

$$\Delta k_{Tneq2_i} := \Delta k_{Tnu} - \sqrt{(1 - X_{i,3}) \cdot (\Delta k_{Tnu} - \Delta k_{Tnl}) \cdot (\Delta k_{Tnu} - \Delta k_{Tn\mu})}$$

$$\Delta k_{Tn_i} := \text{if} \left[\left(X_{i,3} \leq RN_{\Delta kTn} \right), \Delta k_{Tneq1_i}, \Delta k_{Tneq2_i} \right] \quad \Delta k \text{ value}$$

Overall Permeability $k + \Delta k$

$$T1_{kTn_i} := k_{Tn_i} + \Delta k_{Tn_i}$$

Permeability must lie between -14 and -10 (bounds of SMPA simulations)

$$T1_{kTn_i} := \text{if} \left(T1_{kTn_i} \geq -10, -10, \text{if} \left(T1_{kTn_i} \leq -14, -14, T1_{kTn_i} \right) \right) \quad k \text{ value}$$

Flow Focusing Factor (DTN: LB0104AMRU0185.012 [DIRS 163906])

$$f(x) := -0.3137x^4 + 5.4998x^3 - 35.66x^2 + 102.3x - 11.434$$

$$ff_i := \text{root} \left[f(x) - (X_{i,5} \cdot 100), x, 0, 6 \right]$$

Percolation Flux (mm/yr)

The percolation flux used here is for the glacial transition period only. The percolation flux is based on sampling from the upper bound TSPA repository location only (DTN: LB0310AMRU0120.002 [DIRS 166116])

$$nnn := 0..468$$

Upper Bound Percolation Flux

PF1_u :=

	0
0	40
1	36.19
2	35.73
3	27.83
4	30.74
5	40.03
6	31.86
7	57.08
8	18.33
9	27.91

$$PFt_{u_{nnn}} := PF1_{u_{nnn},0}$$

$$Z^{(0)} := \text{round}(\text{runif}(n, 0, 468))$$

$$PF_i := PFt_u(Z_i, 0)$$

Adjusted Percolation Flux

Multiply the flow-focusing factor by the percolation flux, which will be used to obtain the seepage rate, seepage fraction, and seepage percentage.

$$q^1_{pff_i} := PF_i \cdot ff_i$$

Percolation Flux must lie between 1 and 1000 mm/yr (bounds of SMPA simulations)

$$q_{pff_i} := \text{if}(q^1_{pff_i} \leq 1, 1, \text{if}(q^1_{pff_i} \geq 1000, 1000, q^1_{pff_i}))$$

**Seepage Information from SMPA analysis
(DTN: LB0304SMDCREV2.002 [DIRS 163687])**

m := 2549 **Data points**

$SMPA_{data}^{<0>}$ is permeability value $\log(k [m^2])$

$SMPA_{data}^{<1>}$ is capillary strength $1/\alpha [Pa]$

$SMPA_{data}^{<2>}$ is local percolation flux (mm/yr)

$SMPA_{data}^{<3>}$ is Mean Seepage [kg/yr/WP]

$SMPA_{data}^{<4>}$ is Std. Dev. Seepage [kg/yr/WP]

$SMPA_{data}^{<5>}$ is Mean Seepage [%]

$SMPA_{data}^{<6>}$ is Std. Dev. Seepage [%]

$SMPA_{data} :=$

	0	1	2	3	4	5	6
0	-14	100	1	27.73	4.09	98.86	14.59
1	-14	100	5	138.92	20.55	99.05	14.65
2	-14	100	10	277.9	41.19	99.07	14.68
3	-14	100	20	555.87	82.54	99.09	14.71
4	-14	100	50	1391.67	205.57	99.23	14.66
5	-14	100	100	2793.55	406.7	99.59	14.5
6	-14	100	200	5610	785	100	14
7	-14	100	300	8415	1178	100	14
8	-14	100	400	11220	1570	100	14
9	-14	100	500	14025	1963	100	14
10	-14	100	600	16830	2356	100	14
11	-14	100	700	19635	2748	100	14
12	-14	100	800	22440	3141	100	14
13	-14	100	900	25245	3590	100	14
14	-14	100	1000	28050	3989	100	14
15	-14	200	1	26.14	4.21	93.21	15

Develop routine to select correct mean seepage, seepage standard deviation, seepage percent, and seepage percent standard deviation based on sampled value of $1/\alpha$, k, percolation flux.

$nx := 14$ $ny := 9$ $nz := 16$

$ii := 0..nx$

$x_{ii} := SMPA_{data_{ii,2}}$ $x_{ii} := ii$

$jj := 0..ny$

$y_{jj} := 100 - jj + 100$ $y_{jj} := jj$

$kk := 0..nz$

$z_{kk} := -14 + kk \cdot 0.25$ $z_{kk} := kk$

loc represents the location within the matrix of which value to pick for the interpolation process.

$$\text{loc}_{1_i} := \text{floor}\left(\text{linterp}\left(z, z_k, T_k T_{n_i}\right)\right) \cdot (n_x + 1) \cdot (n_y + 1) + \text{floor}\left(\text{linterp}\left(y, y_j, T_{1\alpha_i}\right)\right) \cdot (n_x + 1) \dots \\ + \text{floor}\left(\text{linterp}\left(x, x_i, q_{\text{pff}_i}\right)\right)$$

$$s_{\text{ms}1_i} := \text{SMPA}_{\text{data}_{\text{loc}_{1_i}, 3}}$$

$$s_{\text{msd}1_i} := \text{SMPA}_{\text{data}_{\text{loc}_{1_i}, 4}}$$

$$s_{\text{pms}1_i} := \text{SMPA}_{\text{data}_{\text{loc}_{1_i}, 5}}$$

$$s_{\text{psd}1_i} := \text{SMPA}_{\text{data}_{\text{loc}_{1_i}, 6}}$$

$$\text{loc}_{2_i} := \left[\text{floor}\left(\text{linterp}\left(z, z_k, T_k T_{n_i}\right)\right) \cdot (n_x + 1) \cdot (n_y + 1) \right] + \text{floor}\left(\text{linterp}\left(y, y_j, T_{1\alpha_i}\right)\right) \cdot (n_x + 1) \dots \\ + \text{ceil}\left(\text{linterp}\left(x, x_i, q_{\text{pff}_i}\right)\right)$$

$$s_{\text{ms}2_i} := \text{SMPA}_{\text{data}_{\text{loc}_{2_i}, 3}}$$

$$s_{\text{msd}2_i} := \text{SMPA}_{\text{data}_{\text{loc}_{2_i}, 4}}$$

$$s_{\text{pms}2_i} := \text{SMPA}_{\text{data}_{\text{loc}_{2_i}, 5}}$$

$$s_{\text{psd}2_i} := \text{SMPA}_{\text{data}_{\text{loc}_{2_i}, 6}}$$

$$\text{loc}_{3_i} := \text{floor}\left(\text{linterp}\left(z, z_k, T_k T_{n_i}\right)\right) \cdot (n_x + 1) \cdot (n_y + 1) + \text{ceil}\left(\text{linterp}\left(y, y_j, T_{1\alpha_i}\right)\right) \cdot (n_x + 1) \dots \\ + \text{ceil}\left(\text{linterp}\left(x, x_i, q_{\text{pff}_i}\right)\right)$$

$$s_{\text{ms}3_i} := \text{SMPA}_{\text{data}_{\text{loc}_{3_i}, 3}}$$

$$s_{\text{msd}3_i} := \text{SMPA}_{\text{data}_{\text{loc}_{3_i}, 4}}$$

$$s_{\text{pms}3_i} := \text{SMPA}_{\text{data}_{\text{loc}_{3_i}, 5}}$$

$$s_{\text{psd}3_i} := \text{SMPA}_{\text{data}_{\text{loc}_{3_i}, 6}}$$

$$\text{loc}_{4_i} := \text{floor}\left(\text{linterp}\left(z, z_k, T_k T_{n_i}\right)\right) \cdot (n_x + 1) \cdot (n_y + 1) + \text{ceil}\left(\text{linterp}\left(y, y_j, T_{1\alpha_i}\right)\right) \cdot (n_x + 1) \dots \\ + \text{floor}\left(\text{linterp}\left(x, x_i, q_{\text{pff}_i}\right)\right)$$

$$s_{\text{ms}4_i} := \text{SMPA}_{\text{data}_{\text{loc}_{4_i}, 3}}$$

$$s_{\text{msd}4_i} := \text{SMPA}_{\text{data}_{\text{loc}_{4_i}, 4}}$$

$$s_{\text{pms}4_i} := \text{SMPA}_{\text{data}_{\text{loc}_{4_i}, 5}}$$

$$s_{\text{psd}4_i} := \text{SMPA}_{\text{data}_{\text{loc}_{4_i}, 6}}$$

$$\text{loc}_{5_i} := \left[\text{ceil} \left(\text{linterp} \left(z, z_k, T_k T_{n_i} \right) \right) \cdot (n_x + 1) \cdot (n_y + 1) \right] + \text{floor} \left(\text{linterp} \left(y, y_j, T_{1\alpha_i} \right) \right) \cdot (n_x + 1) \dots \\ + \text{floor} \left(\text{linterp} \left(x, x_i, q_{\text{pff}_i} \right) \right)$$

$$s_{\text{ms}5_i} := \text{SMPA}_{\text{data loc}_{5_i}, 3}$$

$$s_{\text{msd}5_i} := \text{SMPA}_{\text{data loc}_{5_i}, 4}$$

$$s_{\text{pms}5_i} := \text{SMPA}_{\text{data loc}_{5_i}, 5}$$

$$s_{\text{psd}5_i} := \text{SMPA}_{\text{data loc}_{5_i}, 6}$$

$$\text{loc}_{6_i} := \text{ceil} \left(\text{linterp} \left(z, z_k, T_k T_{n_i} \right) \right) \cdot (n_x + 1) \cdot (n_y + 1) + \text{floor} \left(\text{linterp} \left(y, y_j, T_{1\alpha_i} \right) \right) \cdot (n_x + 1) \dots \\ + \text{ceil} \left(\text{linterp} \left(x, x_i, q_{\text{pff}_i} \right) \right)$$

$$s_{\text{ms}6_i} := \text{SMPA}_{\text{data loc}_{6_i}, 3}$$

$$s_{\text{msd}6_i} := \text{SMPA}_{\text{data loc}_{6_i}, 4}$$

$$s_{\text{pms}6_i} := \text{SMPA}_{\text{data loc}_{6_i}, 5}$$

$$s_{\text{psd}6_i} := \text{SMPA}_{\text{data loc}_{6_i}, 6}$$

$$\text{loc}_{7_i} := \left[\text{ceil} \left(\text{linterp} \left(z, z_k, T_k T_{n_i} \right) \right) \cdot (n_x + 1) \cdot (n_y + 1) \right] + \text{ceil} \left(\text{linterp} \left(y, y_j, T_{1\alpha_i} \right) \right) \cdot (n_x + 1) \dots \\ + \text{ceil} \left(\text{linterp} \left(x, x_i, q_{\text{pff}_i} \right) \right)$$

$$s_{\text{ms}7_i} := \text{SMPA}_{\text{data loc}_{7_i}, 3}$$

$$s_{\text{msd}7_i} := \text{SMPA}_{\text{data loc}_{7_i}, 4}$$

$$s_{\text{pms}7_i} := \text{SMPA}_{\text{data loc}_{7_i}, 5}$$

$$s_{\text{psd}7_i} := \text{SMPA}_{\text{data loc}_{7_i}, 6}$$

$$\text{loc}_{8_i} := \text{ceil} \left(\text{linterp} \left(z, z_k, T_k T_{n_i} \right) \right) \cdot (n_x + 1) \cdot (n_y + 1) + \text{ceil} \left(\text{linterp} \left(y, y_j, T_{1\alpha_i} \right) \right) \cdot (n_x + 1) \dots \\ + \text{floor} \left(\text{linterp} \left(x, x_i, q_{\text{pff}_i} \right) \right)$$

$$s_{\text{ms}8_i} := \text{SMPA}_{\text{data loc}_{8_i}, 3}$$

$$s_{\text{msd}8_i} := \text{SMPA}_{\text{data loc}_{8_i}, 4}$$

$$s_{\text{pms}8_i} := \text{SMPA}_{\text{data loc}_{8_i}, 5}$$

$$s_{\text{psd}8_i} := \text{SMPA}_{\text{data loc}_{8_i}, 6}$$

Develop the upper and lower bound of the randomly generated $1/\alpha$, k, and adjusted percolation flux

Develop the upper and lower bound for permeability (k) for Ttpmn Unit

$$\begin{aligned}
 qq_i &:= -1 \cdot T_{kTn_i} \\
 \text{mantissa}(x) &:= x - \text{floor}(qq) \\
 tt_i &:= \text{floor}(qq_i) \\
 rr &:= \text{round}(\text{mantissa}(qq), 2) \\
 yy1_i &:= \text{if}(rr_i \leq 0.25, 0, \text{if}(0.25 < rr_i \leq 0.5, 0.25, rr_i)) \\
 zz1_i &:= \text{if}(yy1_i \leq 0.5, yy1_i, \text{if}(0.5 < yy1_i \leq 0.75, 0.5, 0.75)) \\
 T_{kTn2_i} &:= -1 \cdot (tt_i + zz1_i) \\
 yy2_i &:= \text{if}(rr_i \leq 0.25, 0.25, \text{if}(0.25 < rr_i \leq 0.5, 0.5, rr_i)) \\
 zz2_i &:= \text{if}(yy2_i \leq 0.5, yy2_i, \text{if}(0.5 < yy2_i \leq 0.75, 0.75, 1)) \\
 T_{kTn1_i} &:= -1 \cdot (tt_i + zz2_i)
 \end{aligned}$$

Develop the upper and lower bound for capillary strength ($1/\alpha$)

$$\begin{aligned}
 hh1_i &:= \text{floor}\left(\frac{T_{1\alpha_i}}{100}\right) \\
 T_{1\alpha1_i} &:= (hh1_i \cdot 100) \\
 hh2_i &:= \text{ceil}\left(\frac{T_{1\alpha_i}}{100}\right) \\
 T_{1\alpha2_i} &:= (hh2_i \cdot 100)
 \end{aligned}$$

Lower Bound value adjusted percolation flux (q_{pff})

$$\begin{aligned}
 aaa1_i &:= \text{if}(q_{pff_i} \leq 1, 1, \text{if}(1 < q_{pff_i} \leq 5, 1, q_{pff_i})) \\
 bbb1_i &:= \text{if}(aaa1_i \leq 5, aaa1_i, \text{if}(5 < aaa1_i \leq 10, 5, aaa1_i)) \\
 ccc1_i &:= \text{if}(bbb1_i \leq 10, bbb1_i, \text{if}(10 < bbb1_i \leq 20, 10, bbb1_i)) \\
 ddd1_i &:= \text{if}(ccc1_i \leq 20, ccc1_i, \text{if}(20 < ccc1_i \leq 50, 20, ccc1_i)) \\
 eee1_i &:= \text{if}(ddd1_i \leq 50, ddd1_i, \text{if}(50 < ddd1_i \leq 100, 50, ddd1_i)) \\
 fff1_i &:= \text{if}(eee1_i \leq 100, eee1_i, \text{if}(100 < eee1_i \leq 200, 100, eee1_i))
 \end{aligned}$$

$$\begin{aligned} \text{ggg1}_i &:= \text{if}(\text{fff1}_i \leq 200, \text{fff1}_i, \text{if}(200 < \text{fff1}_i \leq 300, 200, \text{fff1}_i)) \\ \text{hhh1}_i &:= \text{if}(\text{ggg1}_i \leq 300, \text{ggg1}_i, \text{if}(300 < \text{ggg1}_i \leq 400, 300, \text{ggg1}_i)) \\ \text{iii1}_i &:= \text{if}(\text{hhh1}_i \leq 400, \text{hhh1}_i, \text{if}(400 < \text{hhh1}_i \leq 500, 400, \text{hhh1}_i)) \\ \text{jjj1}_i &:= \text{if}(\text{iii1}_i \leq 500, \text{iii1}_i, \text{if}(500 < \text{iii1}_i \leq 600, 500, \text{iii1}_i)) \\ \text{kkk1}_i &:= \text{if}(\text{jjj1}_i \leq 600, \text{jjj1}_i, \text{if}(600 < \text{jjj1}_i \leq 700, 600, \text{jjj1}_i)) \\ \text{mmm1}_i &:= \text{if}(\text{kkk1}_i \leq 700, \text{kkk1}_i, \text{if}(700 < \text{kkk1}_i \leq 800, 700, \text{kkk1}_i)) \\ \text{q}_{\text{pff1}_i} &:= \text{if}(\text{mmm1}_i \leq 800, \text{mmm1}_i, \text{if}(800 < \text{mmm1}_i \leq 900, 800, 900)) \end{aligned}$$

Upper Bound value adjusted percolation flux (q_{pff})

$$\begin{aligned} \text{aaa2}_i &:= \text{if}(\text{q}_{\text{pff}_i} \leq 1, 5, \text{if}(1 < \text{q}_{\text{pff}_i} \leq 5, 5, \text{q}_{\text{pff}_i})) \\ \text{bbb2}_i &:= \text{if}(\text{aaa2}_i \leq 5, \text{aaa2}_i, \text{if}(5 < \text{aaa2}_i \leq 10, 10, \text{aaa2}_i)) \\ \text{ccc2}_i &:= \text{if}(\text{bbb2}_i \leq 10, \text{bbb2}_i, \text{if}(10 < \text{bbb2}_i \leq 20, 20, \text{bbb2}_i)) \\ \text{ddd2}_i &:= \text{if}(\text{ccc2}_i \leq 20, \text{ccc2}_i, \text{if}(20 < \text{ccc2}_i \leq 50, 50, \text{ccc2}_i)) \\ \text{eee2}_i &:= \text{if}(\text{ddd2}_i \leq 50, \text{ddd2}_i, \text{if}(50 < \text{ddd2}_i \leq 100, 100, \text{ddd2}_i)) \\ \text{fff2}_i &:= \text{if}(\text{eee2}_i \leq 100, \text{eee2}_i, \text{if}(100 < \text{eee2}_i \leq 200, 200, \text{eee2}_i)) \\ \text{ggg2}_i &:= \text{if}(\text{fff2}_i \leq 200, \text{fff2}_i, \text{if}(200 < \text{fff2}_i \leq 300, 300, \text{fff2}_i)) \\ \text{hhh2}_i &:= \text{if}(\text{ggg2}_i \leq 300, \text{ggg2}_i, \text{if}(300 < \text{ggg2}_i \leq 400, 400, \text{ggg2}_i)) \\ \text{iii2}_i &:= \text{if}(\text{hhh2}_i \leq 400, \text{hhh2}_i, \text{if}(400 < \text{hhh2}_i \leq 500, 500, \text{hhh2}_i)) \\ \text{jjj2}_i &:= \text{if}(\text{iii2}_i \leq 500, \text{iii2}_i, \text{if}(500 < \text{iii2}_i \leq 600, 600, \text{iii2}_i)) \\ \text{kkk2}_i &:= \text{if}(\text{jjj2}_i \leq 600, \text{jjj2}_i, \text{if}(600 < \text{jjj2}_i \leq 700, 700, \text{jjj2}_i)) \\ \text{mmm2}_i &:= \text{if}(\text{kkk2}_i \leq 700, \text{kkk2}_i, \text{if}(700 < \text{kkk2}_i \leq 800, 800, \text{kkk2}_i)) \\ \text{q}_{\text{pff2}_i} &:= \text{if}(\text{mmm2}_i \leq 800, \text{mmm2}_i, \text{if}(800 < \text{mmm2}_i \leq 900, 900, 1000)) \end{aligned}$$

Solve for seepage rate (Tptpmn Unit)

$$\begin{aligned} t_{\text{qpff}_i} &:= \frac{q_{\text{pff}_i} - q_{\text{pff1}_i}}{q_{\text{pff2}_i} - q_{\text{pff1}_i}} & u_{T1\alpha_i} &:= \frac{T_{1\alpha_i} - T_{1\alpha1_i}}{T_{1\alpha2_i} - T_{1\alpha1_i}} & v_{\text{TKTn}_i} &:= \frac{T_{\text{kTn}_i} - T_{\text{kTn1}_i}}{T_{\text{kTn2}_i} - T_{\text{kTn1}_i}} \end{aligned}$$

$$\begin{aligned}
 \text{spflux}_{\text{Tnm}_i} := & \left(1 - t_{\text{qpf}_i}\right) \cdot \left(1 - u_{\text{T1}\alpha_i}\right) \cdot \left(1 - v_{\text{TkTn}_i}\right) \cdot s_{\text{ms1}_i} \dots \\
 & + \left(t_{\text{qpf}_i}\right) \cdot \left(1 - u_{\text{T1}\alpha_i}\right) \cdot \left(1 - v_{\text{TkTn}_i}\right) \cdot s_{\text{ms2}_i} \dots \\
 & + \left(t_{\text{qpf}_i}\right) \cdot \left(u_{\text{T1}\alpha_i}\right) \cdot \left(1 - v_{\text{TkTn}_i}\right) \cdot s_{\text{ms3}_i} \dots \\
 & + \left(1 - t_{\text{qpf}_i}\right) \cdot \left(u_{\text{T1}\alpha_i}\right) \cdot \left(1 - v_{\text{TkTn}_i}\right) \cdot s_{\text{ms4}_i} \dots \\
 & + \left(1 - t_{\text{qpf}_i}\right) \cdot \left(1 - u_{\text{T1}\alpha_i}\right) \cdot \left(v_{\text{TkTn}_i}\right) \cdot s_{\text{ms5}_i} \dots \\
 & + \left(t_{\text{qpf}_i}\right) \cdot \left(1 - u_{\text{T1}\alpha_i}\right) \cdot \left(v_{\text{TkTn}_i}\right) \cdot s_{\text{ms6}_i} \dots \\
 & + \left(t_{\text{qpf}_i}\right) \cdot \left(u_{\text{T1}\alpha_i}\right) \cdot \left(v_{\text{TkTn}_i}\right) \cdot s_{\text{ms7}_i} \dots \\
 & + \left(1 - t_{\text{qpf}_i}\right) \cdot \left(u_{\text{T1}\alpha_i}\right) \cdot \left(v_{\text{TkTn}_i}\right) \cdot s_{\text{ms8}_i}
 \end{aligned}$$

$$\begin{aligned}
 \text{spflux}_{\text{Tnsd}_i} := & \left(1 - t_{\text{qpf}_i}\right) \cdot \left(1 - u_{\text{T1}\alpha_i}\right) \cdot \left(1 - v_{\text{TkTn}_i}\right) \cdot s_{\text{msd1}_i} \dots \\
 & + \left(t_{\text{qpf}_i}\right) \cdot \left(1 - u_{\text{T1}\alpha_i}\right) \cdot \left(1 - v_{\text{TkTn}_i}\right) \cdot s_{\text{msd2}_i} \dots \\
 & + \left(t_{\text{qpf}_i}\right) \cdot \left(u_{\text{T1}\alpha_i}\right) \cdot \left(1 - v_{\text{TkTn}_i}\right) \cdot s_{\text{msd3}_i} \dots \\
 & + \left(1 - t_{\text{qpf}_i}\right) \cdot \left(u_{\text{T1}\alpha_i}\right) \cdot \left(1 - v_{\text{TkTn}_i}\right) \cdot s_{\text{msd4}_i} \dots \\
 & + \left(1 - t_{\text{qpf}_i}\right) \cdot \left(1 - u_{\text{T1}\alpha_i}\right) \cdot \left(v_{\text{TkTn}_i}\right) \cdot s_{\text{msd5}_i} \dots \\
 & + \left(t_{\text{qpf}_i}\right) \cdot \left(1 - u_{\text{T1}\alpha_i}\right) \cdot \left(v_{\text{TkTn}_i}\right) \cdot s_{\text{msd6}_i} \dots \\
 & + \left(t_{\text{qpf}_i}\right) \cdot \left(u_{\text{T1}\alpha_i}\right) \cdot \left(v_{\text{TkTn}_i}\right) \cdot s_{\text{msd7}_i} \dots \\
 & + \left(1 - t_{\text{qpf}_i}\right) \cdot \left(u_{\text{T1}\alpha_i}\right) \cdot \left(v_{\text{TkTn}_i}\right) \cdot s_{\text{msd8}_i}
 \end{aligned}$$

Calculate mean seepage for Ttpmn Unit

$$\text{QTn1}_{\text{std}_i} := -1.7321 \cdot \text{spflux}_{\text{Tnsd}_i}$$

$$\text{QTn1}_{\text{stdu}_i} := 1.7321 \cdot \text{spflux}_{\text{Tnsd}_i}$$

$$\text{QTn}_{\text{std}_i} := \text{if}\left(\text{QTn1}_{\text{std}_i} = 0, -0.00001, \text{QTn1}_{\text{std}_i}\right)$$

$$\text{QTn}_{\text{std}_i} := \text{qunif}\left(X_{i,10}, \text{QTn}_{\text{std}_i}, \text{QTn1}_{\text{stdu}_i}\right)$$

$$\text{QTn1}_{\text{spm}_i} := 1.2 \cdot \left(\text{spflux}_{\text{Tnm}_i} + \text{QTn}_{\text{std}_i}\right)$$

Increase the seepage rate by 20 percent to account for drift degradation

$$\text{QTn2}_{\text{spm}_i} := \text{if}\left(\text{QTn1}_{\text{spm}_i} \leq 0.1, 0, \text{QTn1}_{\text{spm}_i}\right)$$

$$\text{QT2}_{\text{perc}_i} := \frac{\text{QTn2}_{\text{spm}_i} \cdot 100}{q_{\text{pff}_i} \cdot 28.05}$$

Equation to calculate seepage percent based on seepage rate (see SMPA data table) from DTN: LB0310AMRU0120.002 [DIRS 166116]

$$\text{QT3}_{\text{perc}_i} := \text{if}\left(\text{QT2}_{\text{perc}_i} \leq 0, 0, \text{if}\left(\text{QT2}_{\text{perc}_i} \geq 100, 100, \text{QT2}_{\text{perc}_i}\right)\right)$$

Check seepage percent; if above 100 percent, then recalculate seepage back to 100 percent

$$QT_{spr_i} := QT_{3perc_i} \cdot q_{pff_i} \cdot \frac{28.05}{100} \quad \text{Mean Seepage Rate (kg/yr per WP)}$$

$$\text{mean}(QT_{spr}) = 296.006$$

Determine the seepage fraction for Tptpmn Unit within the repository and then fit the output data to distribution

Seepage fraction represents the non-zero seepage rates based on the LHS sampling of all of the parameters

$$\text{sort}(QT_{spr}) =$$

	0
6561	0
6562	0
6563	0.101
6564	0.101
6565	0.101

$$n_{T1} := 6562$$

$$\text{spfr}_{T1} := \frac{(n - 1) - n_{T1}}{n} \quad \text{spfr}_{T1} = 0.672 \quad \text{Seepage fraction (i.e., waste package locations that can see seepage)}$$

$$n1_{T1} := (n - 1) - (n_{T1} + 1)$$

$$Q1_{T1} := \text{sort}(QT_{spr})$$

$$Q1_{T1} := \text{reverse}(Q1_{T1})$$

$$ab := 0..n1_{T1}$$

$$Q2_{T1_{ab}} := \left(\frac{1}{998} \cdot Q1_{T1_{ab}} \right)$$

$$Q_{T1} := \text{sort}(Q2_{T1})$$

$$\text{mean}(Q_{T1} \cdot 998) = 440.583$$

$$\text{CDF}_{T1_{ab}} := \frac{(ab + 1) - 0.375}{(n1_{T1} + 1) - 0.25}$$

Fit the seepage rates to a Weibull distribution.

The following equations are from *What Every Engineer Should Know About Reliability and Risk Analysis* (Modarres 1993 [DIRS 104667], p. 109).

$$n1_{T1} = 1.344 \times 10^4$$

$$\beta := \text{root} \left[\left[\frac{\sum_{i=0}^{n1_{T1}} (Q_{T1_i})^r \cdot \ln(Q_{T1_i})}{\sum_{i=0}^{n1_{T1}} (Q_{T1_i})^r} - \left(\frac{1}{r}\right) - \left[\left(\frac{1}{n1_{T1}}\right) \cdot \sum_{i=0}^{n1_{T1}} \ln(Q_{T1_i}) \right] \right], r, 0.1, 4 \right] \quad \beta = 0.501$$

$$\alpha := \left[\frac{\sum_{i=0}^{n1_{T1}} (Q_{T1_i})^\beta}{n1_{T1}} \right]^{\frac{1}{\beta}} \quad \alpha = 2.251 \times 10^{-1}$$

Plot of raw data versus Weibull distribution

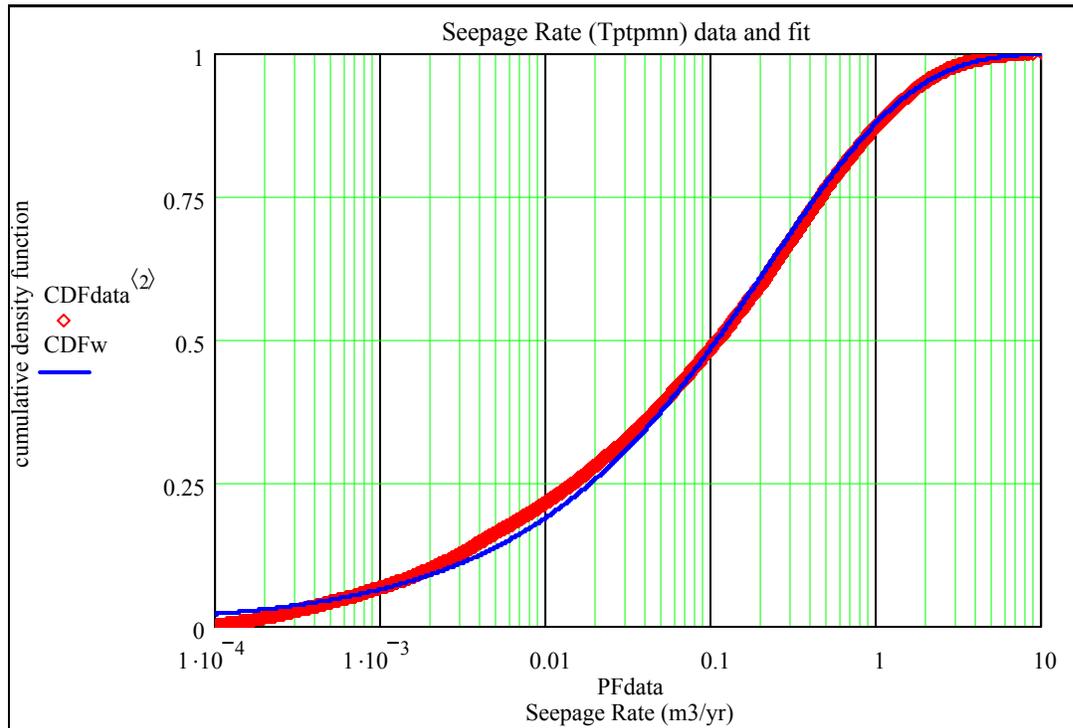
ji := 0..n1_T1

PFdata_ji := Q_T1_ji

CDFdata_ji,2 := CDF_T1_ji

CDFw1_ji := 1 - exp $\left[- \left(\frac{\text{PFdata}_j_i^\beta}{\alpha} \right) \right]$

CDFw_ji,0 := CDFw1_ji



ATTACHMENT V

NEUTRONIT CORROSION SPREADSHEET (OUTPUT FROM MATHCAD FILE)

INTENTIONALLY LEFT BLANK

ATTACHMENT V - NEUTRONIT CORROSION SPREADSHEET (MATHCAD FILE)

The following presents the Mathcad analysis for the sampling of the Neutronit corrosion rate for input to the minimum required seepage analysis of Attachment III. The stainless steel type 316 corrosion information used in this analysis was obtained from DTN: MO0303SPAMCRAQ.000 (BSC 2003 [DIRS 162353]). The information contained in the section has been abstracted from the "Attachment III.mcd" Mathcad file of Attachment VII.

Stainless steel type 316 corrosion rate information from experiments listed in DTN: MO0303SPAMCRAQ.000 (BSC 2003 [DIRS 162353]) is fit to a Weibull Distribution .

SS₃₁₆ is the stainless steel type 316 corrosion rate data (μm/yr), which is obtained from DTN: MO0303SPAMCRAQ.000 (aqueous-316L.xls), only the J-13 well water data is used (BSC 2003 [DIRS 162353]).

$$SS_{316} := \begin{pmatrix} 0.037 \\ 0.102 \\ 0.109 \\ 0.152 \\ 0.154 \\ 0.178 \\ 0.203 \\ 0.229 \\ 0.229 \\ 0.254 \\ 0.254 \\ 0.254 \\ 0.279 \end{pmatrix} \quad \begin{array}{l} nn := 13 \quad \text{Total data points} \\ mm := 12 \\ jj := 0..mm \end{array}$$

c := 1.5 c is used to increase the corrosion rate for Neutronit versus stainless steel 316.

$$SS_{316,jj} := SS_{316,jj} \cdot c$$

The following equations are from *What Every Engineer Should Know About Reliability and Risk Analysis*, (Modarres 1993 [DIRS 104667] p. 109).

$$\beta_{316} := \text{root} \left[\left[\frac{\sum_{jj=0}^{mm} (SS_{316,jj})^r \cdot \ln(SS_{316,jj})}{\sum_{jj=0}^{mm} (SS_{316,jj})^r} - \left(\frac{1}{r}\right) - \left[\left(\frac{1}{nn}\right) \cdot \sum_{jj=0}^{mm} \ln(SS_{316,jj})\right] \right], r, 0.1, 5 \right]$$

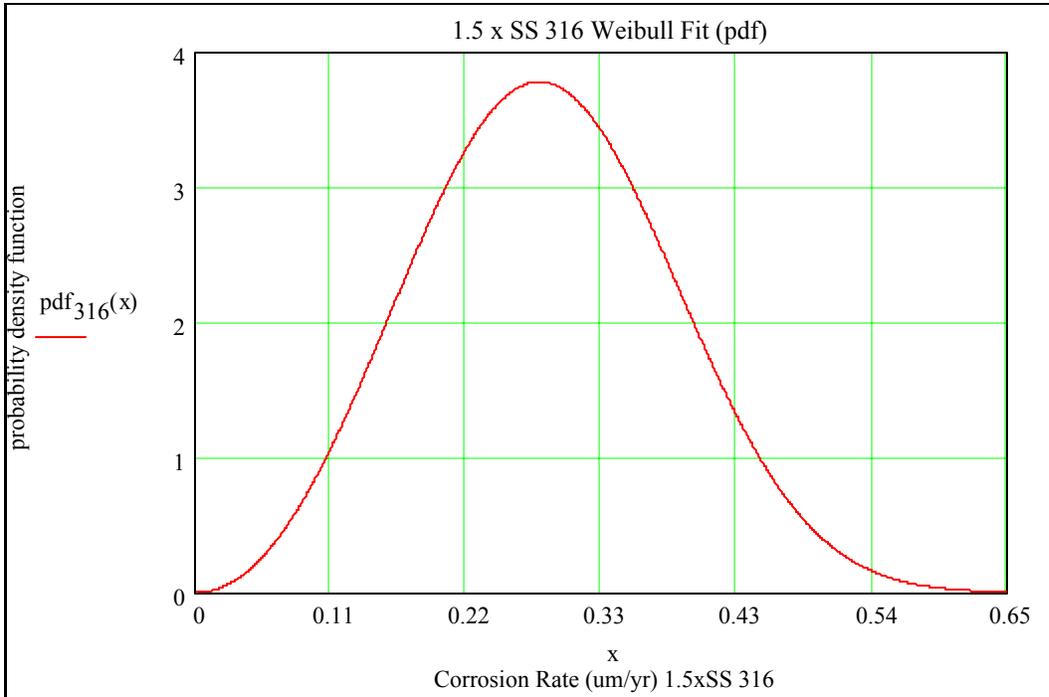
$$\beta_{316} = 3.027$$

$$\alpha_{316} := \left[\frac{\sum_{jj=0}^{mm} (SS_{316,jj})^{\beta_{316}}}{nn} \right]^{\frac{1}{\beta_{316}}}$$

$$\alpha_{316} = 0.314$$

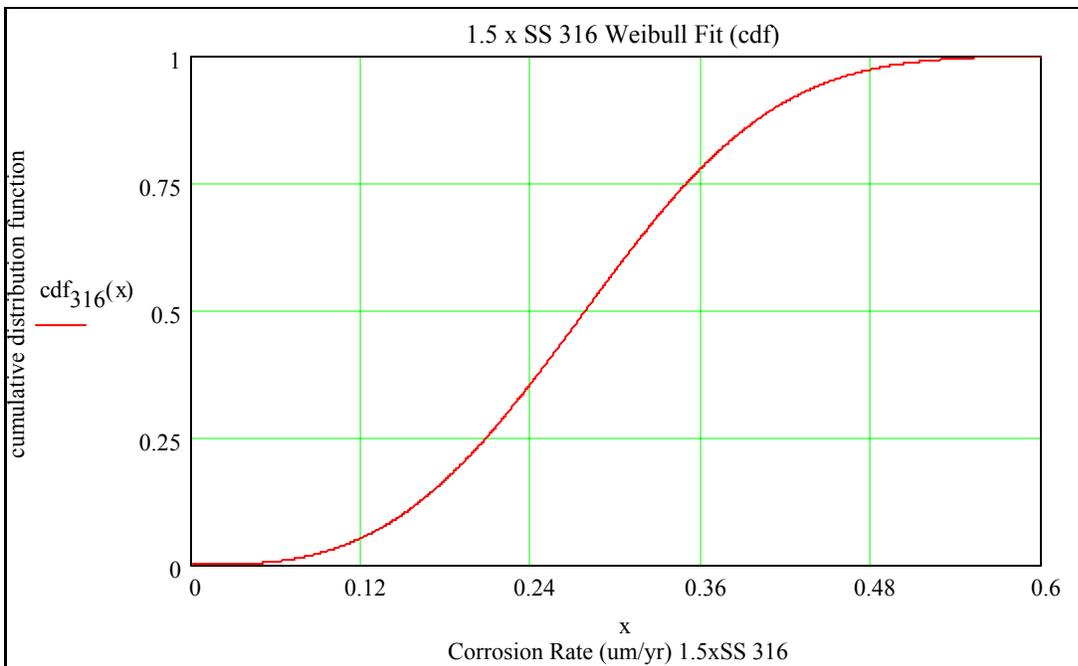
$$pdf_{316}(x) := \left[\frac{\beta_{316} x^{\beta_{316}-1}}{\alpha_{316}^{\beta_{316}}} \right] \cdot \exp \left[- \left(\frac{x}{\alpha_{316}} \right)^{\beta_{316}} \right]$$

pdf₃₁₆(x) is the probability density function of Neutronit using a Weibull distribution.



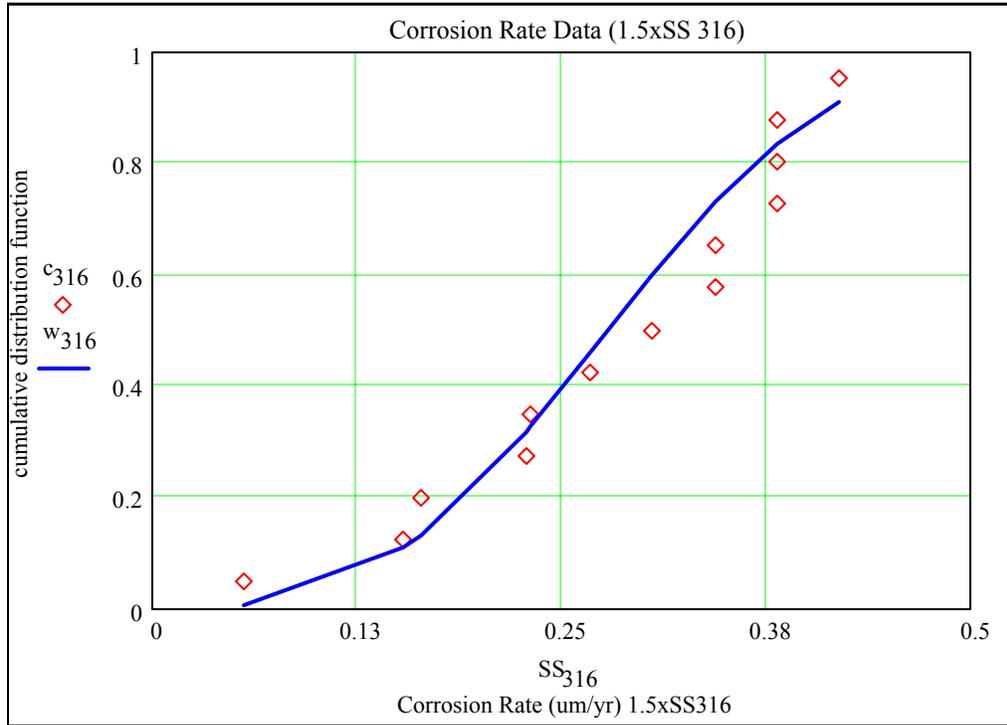
$$cdf_{316}(x) := 1 - \exp \left[- \left(\frac{x}{\alpha_{316}} \right)^{\beta_{316}} \right]$$

cdf₃₁₆(x) is the cumulative distribution function of the Neutronit data fit to a Weibull distribution.



Plot of raw data versus Weibull distribution

$$w_{316,jj} := 1 - \exp \left[- \left(\frac{SS_{316,jj}}{\alpha_{316}} \right)^{\beta_{316}} \right] \quad c_{316,jj} := \frac{(jj + 1) - 0.375}{nn + 0.25}$$



The distribution was checked to see if it can be used to represent the corrosion rate ($\mu\text{m/yr}$) for Neutronit. The Kolmogorov-Smirnov (K-S) Test was chosen to determine the goodness-of-fit of the data to the Weibull distribution. The K-S Test is used according to *Goodness-Of-Fit Techniques* (D'Agostino and Stephens 1986 [DIRS 160320], Chapter 4).

$$\text{sigw} := \begin{pmatrix} 10 & 0.819 \\ 20 & 0.843 \\ 50 & 0.856 \end{pmatrix} \quad \text{KSw2} := 0.874$$

$$\begin{aligned} \text{numw} &:= \text{sigw}^{\langle 0 \rangle} & \text{testw} &:= \text{sigw}^{\langle 1 \rangle} \\ \text{KSw1} &:= \text{linterp}(\text{numw}, \text{testw}, \text{nn}) \\ \text{KSw1} &= 0.826 \\ \text{KSw} &:= \text{if}(\text{nn} > 50, \text{KSw2}, \text{KSw1}) \end{aligned}$$

This is used to interpret the 0.05 significance level for the Weibull distribution as shown by D'Agostino and Stephens (1986 [DIRS 160320], p. 148).

$$\text{KSw} = 0.826 \quad \text{KSw is the Weibull test value at the 0.05 significance shown by D'Agostino and Stephens (1986 [DIRS 160320], p. 148).}$$

Set up the K-S test by determining the data functional form and the distribution fit of the data.

$$we_{316, jj} := 1 - \exp \left[- \left(\frac{SS_{316, jj}}{\alpha_{316}} \right)^{\beta_{316}} \right]$$

we₃₁₆ is the Weibull cumulative distribution function of the fitted corrosion rate.

$$DP_{316, jj} := \frac{(jj + 1)}{nn} + -we_{316, jj} \quad DM_{316, jj} := we_{316, jj} + \frac{-(jj)}{nn}$$

$$KS_{316} := \max(DM_{316}, DP_{316}) \quad KS_{316} = 0.194$$

$$KS_{316, mw} := KS_{316}(\sqrt{nn}) \quad KS_{316, mw} = 0.698$$

$$KSw = 0.826$$

If KSm is less than KSn, then distribution cannot be rejected at 0.05 significance level.

$$pass := \text{if} \left[(KS_{316, mw} > KSw), 0, 1 \right]$$

pass = 1 **0 equals reject hypothesis of correct distribution type at the 0.05 significance level.**
1 equals cannot reject hypothesis of correct distribution type at the 0.05 significance level.

INTENTIONALLY LEFT BLANK

ATTACHMENT VI

LISTING OF FILES ON CD-ROM

INTENTIONALLY LEFT BLANK

EXCEL Directory

File Name	Date	Time	Size (bytes)
Igneous Files			
Feplgn1.xls	07/30/2003	08:23a	29,184
FEP Results Binomial Distribution Files			
Binom Dist.xls	11/09/2003	05:20p	20,992

MCNP (Igneous) Directory

File Name	Date	Time	Size (bytes)
cpinf01	7/23/2003	12:39p	1,369
cpinf01o	7/23/2003	12:39p	189,249
cpinf02	7/23/2003	12:39p	1,369
cpinf02o	7/23/2003	12:39p	186,863
cpinf03	7/23/2003	12:39p	1,369
cpinf03o	7/23/2003	12:39p	188,937
cpinf04	7/23/2003	12:39p	1,369
cpinf04o	7/23/2003	12:39p	189,249
cpinf05	7/23/2003	12:39p	1,369
cpinf05o	7/23/2003	12:39p	187,773
cpinf06	7/23/2003	12:39p	1,369
cpinf06o	7/23/2003	12:39p	189,873
cpinf07	7/23/2003	12:39p	1,369
cpinf07o	7/23/2003	12:39p	188,069
cpinf08	7/23/2003	12:39p	1,369
cpinf08o	7/23/2003	12:39p	190,020
cpinf09	7/23/2003	12:39p	1,369
cpinf09o	7/23/2003	12:39p	189,873
cpinf10	7/23/2003	12:39p	1,369
cpinf10o	7/23/2003	12:39p	188,457

MATHCAD (Seismic) Directory

File Name	Date	Time	Size (bytes)
Attachment III.mcd	02/10/2004	10:59a	221,219
seepage glac lower Tptpll driftcollapse report.mcd	02/02/2004	04:03p	257,153
seepage glac lower Tptpmn x1.2 report.mcd	02/02/2004	04:18p	257,683
seepage glac mean Tptpll driftcollapse report.mcd	02/02/2004	04:07p	257,057
seepage glac mean Tptpmn x1.2 report.mcd	02/02/2004	04:21p	257,299
seepage glac upper Tptpll driftcollapse report.mcd	02/02/2004	04:14p	257,028
seepage glac upper Tptpmn x1.2 report.mcd	02/02/2004	04:25p	257,363

SAPHIRE Directory

File Name	Date	Time	Size (bytes)
SAPHIRE.zip	01/14/2004	03:07p	231,569

INTENTIONALLY LEFT BLANK