OCRWM	MODEL COVER SHEET	1. QA: QA Page 1 of 124

2. Type of Mathematical Model:

☒ Process Model ☐ Abstraction Model ☐ System Model

Describe Intended Use of Model:

The purpose of the configuration generator model is to provide a method for determining configurations that have the potential for criticality and then evaluate the probability of occurrence for those configurations.

3. Title:

Configuration Generator Model for In-Package Criticality

4. DI (including Rev. No. and Change No., if applicable):

MDL-EBS-NU-000001 REV 01 ICN 01

5. Total Attachments:	6. Attachment Numbers - No. of Pages in Each:
Twelve (12)	I-34, II-12, III-8, IV-10, V-2, VI-34, VII-4, VIII-4, IX-4, X-4, XI-2, XII-CD

	Printed Name	Signature	Date
7. Originator:	James K. Knudsen John A. McClure	John A McClure	08/29/2003
8. CSO:	Bruce E. Kirstein	[signature]	8/29/03
9. Checker:	Shyang-Feng Deng	[signature]	08/29/03
10. QER:	Judith E. Gebhart	J E Gebhart	8/29/03
11. Responsible Manager/Lead:	Daniel A. Thomas	Daniel A Thomas	08/29/2003
12. Responsible Manager:	Robert W. Andrews	[signature]	8/29/03

13. Remarks:

ENCLOSURE 3

2. Title:

Configuration Generator Model for In-Package Criticality

3. DI (including Rev. No. and Change No., if applicable):

MDL-EBS-NU-000001 REV 01 ICN 01

4. Revision / Change Number:	5. Description of Revision/Change:
00	Initial Issue
00 / 01	Editorial Corrections and Revisions Figure Titles – Correct upper and lower case usage Table titles - Correct upper and lower case usage Acronym list corrected Unused definitions removed from nomenclature list Document corrected to use acronyms consistently – all sections Minor syntax corrections – all sections References to Assumptions – Section 5, 6.6.4, 6.6.5, 6.7.2.6.2, 6.7.2.6.3
01	Complete revision Executive Summary added Sections 1, 4, 5, and 6 reorganized.
01/01	Document modified to incorporate comments from DOE AP-6.28Q review. Changes are indicated by a black vertical line in the margin. Modifications were made in the following areas: Executive Summary; Acronyms and Abbreviations; List of Nomenclature; Sections 1, 2, 3.1, 3.2, 3.3, 3.4, 3.6, 4.1, 4.2, 4.3, 5, 6, 6.1, 6.1, 6.2, 6.3, 6.4, 6.5, 6.6, 6.7, 7, 8, 9.1, and 9.2; and Attachments I and IX.

EXECUTIVE SUMMARY

The Disposal Criticality Analysis Methodology Topical Report[a] prescribes an approach to the methodology for performing postclosure criticality analyses within the monitored geologic repository at Yucca Mountain, Nevada. An essential component of the methodology is the *Configuration Generator Model for In-Package Criticality* that provides a tool to evaluate the probabilities of degraded configurations achieving a critical state. The configuration generator model is a risk-informed, performance-based process for evaluating the criticality potential of degraded configurations in the monitored geologic repository. The method uses event tree/fault tree methods to define configuration classes derived from criticality scenarios and to identify configuration class characteristics (parameters, ranges, etc.). The probabilities of achieving the various configuration classes are derived in part from probability density functions for degradation parameters.

Configuration Generator Model for In-Package Criticality documents the model, the validation of the model, and illustrates its application through a demonstration analysis using commercial spent nuclear fuel in a 21-PWR with Absorber Plates Waste Package. The configuration generator model is validated in a manner to assure that all in-package criticality scenarios from the *Disposal Criticality Analysis Methodology Topical Report* are addressed. Example event trees showing the top events from the degradation scenarios and fault trees showing inputs to the event trees are included in the document.

The NRC has issued *Safety Evaluation Report for Disposal Criticality Analysis Methodology Topical Report, Revision 0*[b]. That report contained 28 open items that required resolution through additional documentation. Of the 28 open items, numbers 5, 6, 9, 10, 18, and 19 were concerned with a previously proposed software approach to the configuration generator methodology and, in particular, the k_{eff} regression analysis associated with the methodology. However, the use of a k_{eff} regression analysis is not part of the current configuration generator methodology and, thus, the referenced open items are no longer considered applicable and will not be further addressed.

Configuration Generator Model for In-Package Criticality provides the scope of the document, the intended use of the model, the limitations of the model, and a discussion of how the configuration generator model is integrated into the overall methodology of the *Disposal Criticality Analysis Methodology Topical Report.*

Based upon the model validation and supported by the demonstration analysis, the *Configuration Generator Model for In-Package Criticality* concludes that the configuration generator model is a valid process for evaluating the probability of in-package criticality in the monitored geologic repository. The report recommends that the configuration generator model be implemented as part of the disposal criticality methodology for the Yucca Mountain Project.

---

[a] YMP (Yucca Mountain Site Characterization Project) 2003. *Disposal Criticality Analysis Methodology Topical Report.* YMP/TR-004Q, Rev. 02D. Las Vegas, Nevada: Yucca Mountain Site Characterization Office. ACC: MOL.20030617.0322. TBV-5172.

[b] Reamer, C.W. 2000. "Safety Evaluation Report for Disposal Criticality Analysis Methodology Topical Report, Revision 0." Letter from C.W. Reamer (NRC) to S.J. Brocoum (DOE/YMSCO), June 26, 2000, with enclosure. ACC: MOL.20000919.0157.

INTENTIONALLY LEFT BLANK

CONTENTS

FIGURES

Page

TABLES

ACRONYMS AND ABBREVIATIONS

BWR	boiling water reactor
CGC	Configuration Generator Code
CGM	Configuration Generator Model
CRWMS	Civilian Radioactive Waste Management System
CSNF	commercial spent nuclear fuel
DOE	U.S. Department of Energy
DTN	data tracking number
FEPs	features, events, and processes
HLW	high-level radioactive waste
IP	inside the waste package
M&O	Management and Operating Contractor
MTHM	metric tons of heavy metal
NRC	U.S. Nuclear Regulatory Commission
OCRWM	Office of Civilian Radioactive Waste Management
PWR	pressurized water reactor
SAPHIRE	Systems Analysis Programs for Hands-on Integrated Reliability Evaluations
SCC	stress corrosion cracking
STN	Software Tracking Number
TSPA	Total System Performance Assessment
WAPDEG	Waste Package Degradation

LIST OF NOMENCLATURE

F_{SF_D}	cumulative distribution function for seepage fraction
$F_{Q_{seep}}$	cumulative distribution function for seepage flux rate
FR_{WF_SCC}	fraction of rods that experience stress corrosion crack failure
FR_{WF}	fraction of perforated Zircaloy cladding
FR_{WF_INI}	fraction of initially failed rods
FR_{WF_CREEP}	fraction of rods that experience creep failure
$F_x(x)$	cumulative distribution function
$f_x(x)$	probability density function
k_{eff}	effective neutron multiplication factor
L_{DS}	length of drip shield
L_{DS_Patch}	length of drip shield patch
L_{DS_PO}	penetration opening through drip shield
L_{WP}	length of the waste package
L_{WP_Patch}	length of the waste package patch
L_{WP_SCC}	length of the waste package stress corrosion crack
$N(t < t_t)$	Boron loss while Neutronit is degrading
$N(t > t_t)$	Boron loss after Neutronit has degraded
$Q_{evaporate}$	evaporative flux rate
$Q_{required}$	required seepage flux rate to degrade and flush Neutronit
Q_{seep}	seepage flux rate
P_{FTDS}	probability of water flow through drip shield
P_{FTWP}	probability of water flow through the outer barrier of a failed waste package
P_{WP_Patch}	probability of water flow through patches due to general corrosion
P_{WP_SCC}	probability of water flow through stress corrosion cracks
SF_D	seepage fraction
wt%	weight percent of Uranium-235
λ_{LID}	diameter of the lid within the waste package skirt
α	maximum tilt angle of the waste package (degrees)

1. PURPOSE

The *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003) presents an approach to the methodology for evaluating potential criticality situations in the monitored geologic repository. An overview of this approach from *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003) is provided in Figure 1-1 that illustrates the flow process of the major analysis components. Figure 1-1 shows the input required for the methodology as well as the decision points that include tests against performance and design criteria imposed on the methodology. These criteria are intended to ensure sufficient measures are implemented to satisfy the 10 CFR Part 63 acceptance criteria applicable to the postclosure performance assessment for the Yucca Mountain site (Section 4.2). These measures include examining the significant factors contributing to the probability of criticality in the repository and implementing additional critical consequence analyses or design enhancements to reduce the overall criticality risk if the respective criteria are exceeded.

The configuration generator model (CGM) can be used to identify configuration classes for the various waste forms expected for disposal in the proposed monitored geologic repository that have potential for criticality and to evaluate their probability of criticality. The CGM is an integral part of the disposal criticality analysis methodology (Figure 1-1) where the CGM components are indicated by shaded blocks. The CGM will not provide direct input to the total system performance assessment for license application but, rather, it is used to evaluate the overall probability of criticality for the repository based upon the probabilities of potentially critical configuration classes. These latter classes may require additional criticality consequence assessments depending on the calculated total probability of criticality. Any such criticality consequence results would, in turn, be input to the total system performance assessment for the license application (YMP 2003, Section 3.8).

The scope of this configuration generator model report is to: (1) document a model for evaluating the overall probability of criticality for the monitored geologic repository; (2) document the validation of the model; and (3) provide a demonstration analysis using the model. The CGM provides a systematic process to address the standard criticality scenarios (identified in *Disposal Criticality Analysis Methodology Topical Report* [YMP 2003, Section 3.3]) having the potential to increase the reactivity of the in-package system and the parameters associated with these identified scenarios. The approach is to use an event tree/fault tree method to define end states of configuration classes derived from criticality scenarios. Note that multiple configuration classes can result from a criticality scenario. Furthermore, the event tree/fault tree structure is flexible, permitting both the event trees and fault trees to be tailored to specific requirements. The probabilities of achieving the various configuration classes are derived in part from probability density functions for the configuration parameters. A configuration class is considered to have *potential for criticality* if the probability of achieving the class does not satisfy the probability screening criterion as shown in Figure 1-1. The *probability of criticality*, derived from the probability values of the configuration class parameters, is evaluated only for classes that exceed the criticality potential criterion, i.e., have a k_{eff} range exceeding the critical limit for the waste form.

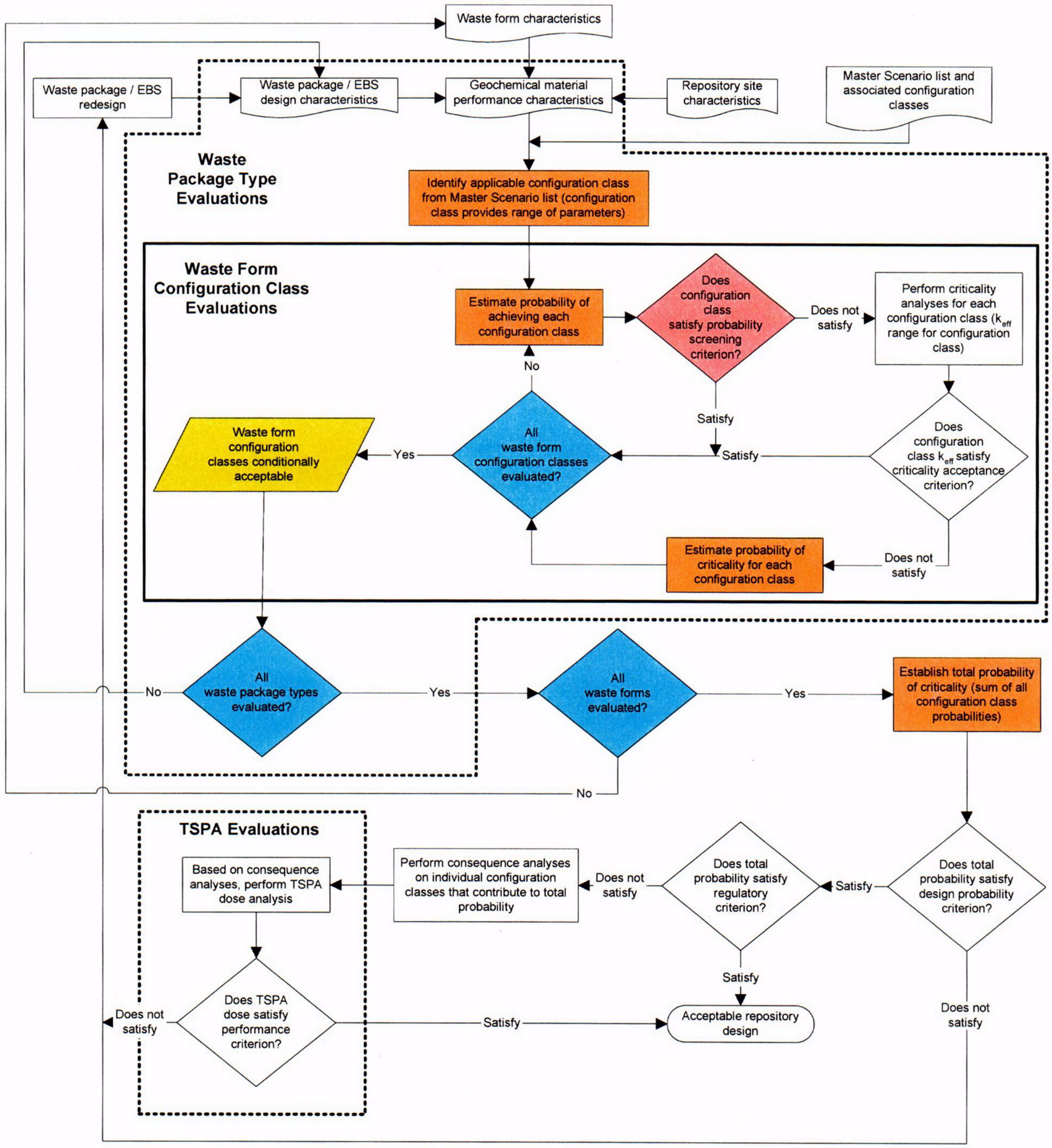


Figure 1-1. Overview of Approach to the Disposal Criticality Analysis Methodology

The purpose of the CGM can be summarized as follows:

- Identify the various possible sequences of top events required for the development of event trees/fault trees and their various end states for configuration classes
- Evaluate the probability of occurrence for the configuration classes

- Provide configuration classes and their associated parameter ranges to the criticality model to identify configuration classes with potential for criticality
- Evaluate the probability of criticality for configuration classes that have potential for criticality
- Evaluate the total probability of criticality for the monitored geologic repository.

Limitations of the configuration generator model include:

- The requirement that probability density functions be specified for the set of basic parameters that are themselves derived from model abstractions.
- Mineral losses from the waste packages are evaluated for soluble species transport only.
- Degradation scenarios for waste forms other than commercial spent nuclear fuel (CSNF) have not been fully evaluated.

Anticipated revisions to the model report are expected to address, in part, these limitations.

The NRC has issued *Safety Evaluation Report for Disposal Criticality Analysis Methodology Topical Report, Revision 0* (Reamer 2000). That report contained 28 open items (Reamer 2000, pp. 77 to 79) that required resolution through additional documentation. The strategy for resolution of these open items included, but was not restricted to, the development of model reports (such as the CGM report) that addressed open item issues. In particular, Open Items 5, 6, 9, 10, 18, and 19 were concerned with a previously proposed software approach to the configuration generator methodology and, in particular, the k_{eff} regression analysis associated with the methodology (Section 6.1). However, the use of a k_{eff} regression analysis is not part of the current configuration generator and, thus, the referenced open items are no longer considered applicable and will not be further addressed.

This report contains a discussion of the CGM and the results from an analysis of CSNF as defined in the baseline configuration from *Yucca Mountain Preliminary Site Suitability Evaluation* (DOE 2001a). The CSNF analysis is included in this report as a demonstration of, and a guide through, the CGM process. Analyses of the various waste forms proposed for disposal in the monitored geologic repository are expected to be documented in reports referenced in the License Application. Sections 6 through 6.4 discuss the CGM. Section 6.5 discusses the procedural steps and inputs required for analyses of the various waste forms (CSNF, U.S. Department of Energy [DOE]-owned spent nuclear fuel, and DOE high-level waste [HLW]). Section 6.6 discusses the input generation with assumptions involved in developing a demonstration analysis using the CGM. Section 6.7 presents the results from the demonstration analysis applying the CGM process to the 21-pressurized water reactor (PWR) waste package and waste form. Section 7 describes the validation process for the CGM and Section 8 contains the conclusions.

The development of this model is consistent with the specifications included in *Technical Work Plan for: Risk and Criticality Department* (BSC 2002a).

2. QUALITY ASSURANCE

The preparation of this report and the supporting activities were conducted in accordance with the YMP quality assurance program. The CGM development activity is encompassed by the activity evaluation "*ACRM01 – Waste Package Neutronic Methodology - LA*" that is part of the technical work plan (BSC 2002a) prepared in accordance with AP-2.27Q, *Planning for Science Activities.* The result of that evaluation was that the above Neutronics Methodology activity is subject to *Quality Assurance Requirements and Description* (DOE 2003).

This model report was prepared in accordance with AP-SIII.10Q, *Models*, and reviewed in accordance with AP-2.14Q, *Review of Technical Products and Data.* Development of this CGM and subsequent analysis did not require the classification of items in accordance with AP-2.22Q, *Classification Criteria and Maintenance of the Monitored Geologic Repository Q–List.* However, the overall quality assurance classifications of the waste packages have been established as QL-1 (YMP 2001, Appendix A). The present activity (CGM model development) is not a field activity. Therefore, an evaluation in accordance with LP-SA-001Q-BSC, *Determination of Importance and Site Performance Protection Evaluations*, was not required.

The control of the electronic management of information was evaluated in accordance with AP-SV.1Q, *Control of the Electronic Management of Information*, as specified in the technical work plan (BSC 2002a). Methods used for electronic information control for this model and analysis include:

- Records submitted in accordance with AP-17.1Q, *Record Source Responsibilities for Inclusionary Records,* and AP-6.1Q, *Document Control,* readily retrievable through the records center (BSC 2002a, Section 8.a)

- Engineering technical information stored on writeable CD-ROMs that are not rewriteable

- Security of the data accomplished through the use of writeable CD-ROMs that are not rewriteable (BSC 2002a, Section 8.d)

- Media identified in accordance with AP-17.1Q and AP-SIII.10Q (BSC 2002a, Section 8.e).

Conditions, location, retention time, and access to electronic media are through the records center following submittal in accordance with AP-17.1Q and AP-6.1Q (BSC 2002a, Section 8.c).

3. USE OF SOFTWARE

The software used in the model and analysis sections of this report includes SAPHIRE, EXCEL, and MATHCAD. This model report also references software codes and routines that are used in the supporting calculations and/or analyses, but these software products were not used in the development of the model itself. The software used in the supporting calculations and/or analyses include EQ6, EQ3/6, and MCNP.

3.1 EXCEL

- Title: Excel
- Version/Revision number: Microsoft® Excel 97 SR-2
- Computer processing unit number: Software is installed on a DELL OptiPlex GX400 PC, Civilian Radioactive Waste Management System (CRWMS) Management and Operating Contractor (M&O) Tag number 151293, running Microsoft Windows NT, Version 4.

Microsoft Excel for Windows, Version 97 SR-2, is used in calculations and 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 an exempt software product in accordance with Subsection 2, AP-SI.1Q, *Software Management*.

The spreadsheet files for the Excel calculations are documented in Attachment XI and XII (Attachment XI gives the list of the files in Attachment XII, a read-only compact disk). The files in Attachment XII are such that an independent repetition of the software use may be performed.

3.2 MATHCAD

- Title: Mathcad
- Version/Revision number: Mathsoft Engineering and Education, Inc. Mathcad® 2001 Professional
- Computer processing unit number: Software is installed on a DELL OptiPlex GX400 PC, CRWMS M&O Tag number 151293, running Microsoft Windows NT, Version 4.

Mathcad® for Windows 2000, Version Mathcad 2001 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 2001 Professional is an exempt software product in accordance with Subsection 2, AP-SI.1Q, *Software Management*.

The input and output files for the various Mathcad® calculations are documented in Attachments XI and XII (Attachment XI gives the list of the files in Attachment XII, a read-only compact disk). The calculation files in Attachment XII are such that an independent repetition of the software use may be performed.

3.3 SAPHIRE

- Title: SAPHIRE
- Version/Revision number: 7.18
- Software Tracking Number (STN): 10325-7.18-00
- Computer processing unit number: Software is installed on a DELL OptiPlex GX400 PC, CRWMS M&O Tag number 151293, running Windows NT Version 4.

The baselined SAPHIRE (Systems Analysis Programs for Hands-on Integrated Reliability Evaluations) Software version 7.18 is a state-of-the-art probabilistic risk analysis software program (SAPHIRE V7.18, STN: 10325-7.18-00). The software is used to create and analyze both event trees and fault trees. The software is appropriate to the application for this calculation and it is used within its range as described in the qualification documentation. The software was obtained from Software Configuration Management.

The SAPHIRE software has been upgraded to Version 7.18 from Version 6.69 (SAPHIRE V6.69, STN: 10325-6.69-00) that was used for the initial analysis documented in Sections 6 and 7 of this report. Files for Version 6.69 are fully compatible with Version 7.18 and there is no impact on results from analyses using Version 6.69.

The file, "saph-config-gen.zip," from the SAPHIRE calculations is documented in Attachments XI and XII (Attachment XI gives the list of the files in Attachment XII, a read-only compact disk). This file is in a compressed format and contains the relational database files from SAPHIRE. Since the SAPHIRE files must be in a read/write mode for use by the SAPHIRE software, the compressed files in Attachment XII must be first extracted from the compressed format and their status then changed from read-only to read/write.

3.4 EQ6

The baselined EQ6 code (EQ6 7.2bLV, STN: 10075-7.2bLV-02) is a reaction path code that models water/rock interactions or fluid mixing in either a pure reaction progress mode or a time mode. The software specifications are as follows:

- Title: EQ6
- Version/Revision number: Version 7.2bLV
- STN: 10075-7.2bLV-02.

The EQ6 software was not used for any calculation in this report and no input or output files were created. The software is included in this model report for reference only as it is a major component of the waste package/waste form degradation analysis and model abstraction methodology for criticality (BSC 2002b). The software has been verified as appropriate for its intended use and was obtained from the Software Configuration Management.

3.5 EQ3/6

The baselined EQ3/6 code (EQ3/6 V7.2b, STN: LLNL: UCRL-MA-110662) is a speciation-solubility code with a data file preprocessor, EQPT. The software specifications are as follows:

- Title: EQ3/6
- Version/Revision number: Version 7.2b
- STN: LLNL:UCRL-MA-110662.

The EQ3/6 software was not used for any calculation in this report and no input or output files were created. The software is included in this model report for reference only as it is a major component of the waste package/waste form degradation analysis and model abstraction methodology for criticality (BSC 2002b). The software has been verified as appropriate for its intended use and was obtained from the Software Configuration Management.

3.6 MCNP

The baselined MCNP code (MCNP V.4B2, STN: 30033 V4B2LV) is used to calculate the effective neutron multiplication factors (k_{eff}) of the end state configurations in the waste package. The software specifications are as follows:

- Title: MCNP
- Version/Revision number: Version 4B2
- STN: 30033 V4B2LV
- Computer type: Hewlett Packard 9000 Series Workstations
- Computer processing unit number: Software is installed on the CRWMS M&O workstation "bloom" whose CRWMS M&O Tag number is 700887.

The MCNP software was not used for any calculation in this report and no input or output files were created. The software is included in this model report for reference only as it is a major component of the criticality analysis methodology (BSC 2003a). The software is appropriate for the calculation of criticality (MCNP is a Monte Carlo computer program designed for criticality calculations) and was obtained from the Software Configuration Management.

4. INPUTS

4.1 MODEL INPUT DATA AND PARAMETERS

The configuration generator model is a systematic process for identifying configurations that have potential for criticality in the postclosure period of the repository and for estimating the probability of occurrence for such identified configurations. The CGM addresses the standard criticality scenarios, identified in Subsection 6.2.2, as having the potential to increase the reactivity of the in-package system. The model provides a systematic process to evaluate the outcome of the various scenarios. Therefore, the only input used in the development of the CGM consists of the criticality scenarios as listed in Table 4-1.

Table 4-1. Scenario Input Source

Scenarios and Top Events	Input	Reference Document	Section
Degradation scenarios IP-1 – IP-6	Scenarios leading to in-package criticality	*Disposal Criticality Analysis Methodology Topical Report* (YMP 2003)	6.2.1 and 6.2.2
	Generic degradation configuration classes		6.2.3

4.2 CRITERIA

The acceptance criteria applicable to the Yucca Mountain site are identified in the requirements for postclosure performance assessment specified in the NRC rule 10 CFR Part 63. The following requirements extracted from 10 CFR Part 63 are applicable to the development of this CGM report:

- "...The features, events, and processes considered in the performance assessment should represent a wide range of both beneficial and potentially adverse effects on performance (e.g., beneficial effects on radionuclide sorption; potentially adverse effects of fracture flow or a criticality event)..." (10 CFR 63.102(j))

- "The engineered barrier system must be designed so that, working in combination with natural barriers, radiological exposures to the reasonably maximally exposed individual are within the limits specified at §63.311 of subpart L of this part. Compliance with this paragraph must be demonstrated through a performance assessment that meets the requirements specified at §63.114 of this subpart..." (10 CFR 63.113(b))

- "Account for uncertainties and variabilities in parameter values and provide for the technical basis for parameter ranges, probability distributions, or bounding values used in the performance assessment." (10 CFR 63.114(b))

- "Consider only events that have at least one chance in 10,000 of occurring over 10,000 years." (10 CFR 63.114(d)).

The methods in the CGM for meeting or addressing these criteria are discussed in Section 8.

4.3 CODES AND STANDARDS

The following code was used to develop criteria for the Configuration Generator Model:

10 CFR 63. *Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada.*

5. ASSUMPTIONS

No assumptions were used in the CGM.

6. CONFIGURATION GENERATOR MODEL

The waste packages in the monitored geologic repository can, over time, undergo various degradation processes. These processes have major effects on the isotopic content and spatial distribution of the waste form within the waste packages as well as for the waste packages themselves. Potential effects of the degradation processes are separation of neutron absorbers from fissile material and rearrangement of the degraded waste package components into a (possibly) more reactive geometry that may increase the chance for criticality. Note that a critical system for the repository is defined as one having an effective neutron multiplication factor, k_{eff}, larger than the critical limit (YMP 2003, Subsection 3.2.1). The critical limit is the value of k_{eff} at which a system configuration is considered potentially critical as characterized by statistical tolerance limits. The methodology for evaluating waste form-dependent critical limit values has been documented in *Criticality Model Report* (BSC 2003a) that is part of the analysis methodology.

The degradation processes of interest for criticality are related to a combination of features, events, and processes (FEPs) that result in configurations that have the potential for criticality requiring further evaluation of this potential. Generic degradation scenarios and potential critical configuration classes have been identified in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Section 3.3) by considering the features of the site and the characteristics of the waste form and other waste package internal components. Potential critical configuration classes are states of a degraded waste package defined by a set of parameters characterizing the quantity and physical arrangement of the materials that have a significant effect on criticality. There are various uncertainties associated with these parameters depending on the particular scenario sequences that result in degraded configurations. These uncertainties need to be accounted for in the criticality evaluations.

An important component of the approach in the *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003) shown in Figure 1-1 is a model for identifying degraded configurations and evaluating the probability of these configurations achieving a critical state. In order to address parameter uncertainty, analyses (with this model) will use an approach that is part of a risk-informed methodology to evaluate the range and physical arrangement of parameters associated with waste package configurations. The method uses event trees to define configuration class characteristics (e.g., range of parameters) associated with the various end states, fault trees to define top event inputs, and probability density functions to evaluate random variables (e.g., seepage rates). Since the probability functions required for analyses with this model will normally have upper and lower bounds, sensitivity studies provide a means to evaluate the effects of these bounds on analysis results. An overview of the CGM is given in this section with a detailed description of the model provided in Sections 6.2 through 6.4.

The CGM methodology is a probability based analysis tool that, in accordance with *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003), specifies use of such methodology to demonstrate how the potential for postclosure criticality will be evaluated. The use of risk-informed, performance-based analyses in regulatory matters is likewise consistent with the U.S. Nuclear Regulatory Commission (NRC) policy statement "Use of Probabilistic Risk Assessment Methods in Nuclear Regulatory Activities" (60 FR 42622).

The CGM is a consistent methodology to follow and document in-package criticality scenarios through possible degradation sequences to identify potential critical configurations and to provide the basis for evaluating the probability of achieving any such configurations. These processes and their connections with the overall methodology (Figure 1-1) are illustrated in more detail in Figure 6-1. The CGM provides a systematic process to address the standard degradation scenarios, identified in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Section 3.3), as having the potential to increase the reactivity of the in-package system, and the parameters associated with potentially critical waste package configuration classes. The approach is to use event tree/fault tree methods to define end states of the possible configuration classes. The probabilities of the end states that have potential for criticality are derived from the evaluation of probability density functions for degradation parameters and probability values for fault tree inputs.

In order to determine what parameters are required for the CGM, the various degradation sequences of a configuration class need to be established which is accomplished through a graphical representation in the form of an event tree structure. The event tree representation provides the processes and sequences required to achieve the configuration classes discussed in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Figures 3-2a and 3-2b). These processes are time dependent, which must be considered when performing analyses to evaluate both the criticality potential and probability of criticality. All of the intermediate and end-state configurations identified in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Section 3.3) and "believed to be comprehensive with respect to the spectrum of scenarios that might occur in the repository and might affect criticality risk" (YMP 2003, Section 3-1) are addressed in the event tree.

The top events on the event tree define the parameters and sequences necessary to achieve each configuration class. These top events are expressed as fault tree models, the majority of which contain single inputs. However, some fault trees may require multiple inputs depending upon the various mechanisms required to achieve the top event.

The CGM event tree lists the different waste forms that are expected for disposal in the monitored geologic repository. Waste forms described in this report refer to high-level radioactive waste and spent nuclear fuel[1]. The procedure for generating the configurations using the CGM event tree is partially waste form independent. However during an analysis, the waste form type must be defined for bookkeeping purposes and to determine the configuration class parameter ranges for criticality evaluations if a configuration class cannot be screened out on the

[1] The process described in this report will be applied to commercial SNF (including PWR, BWR, and mixed oxide fuels), DOE SNF (including degraded Naval Nuclear Propulsion Program SNF), and vitrified HLW. The methodology used to address intact Naval Nuclear Propulsion Program SNF is described in *Transmittal of the Naval Nuclear Propulsion Program Addendum to the* Yucca *Mountain Site Characterization Office "Disposal Criticality Analysis Methodology Topical Report."* (Mowbray 1999).

basis of a low probability of occurrence. The CGM event tree provides the basis for identifying the degraded configuration parameters and provides assistance in the probability calculation.

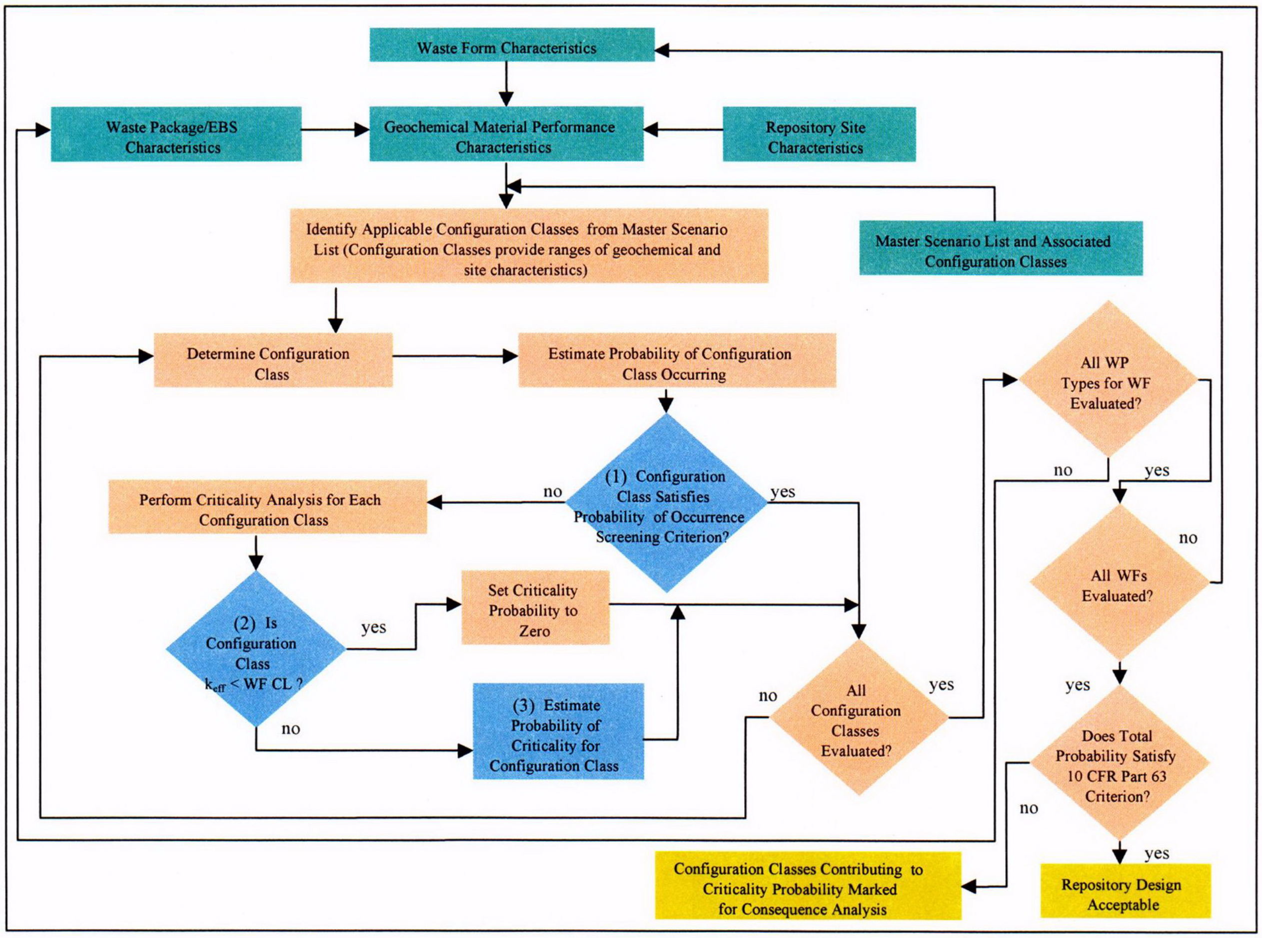


Figure 6-1. Block Diagram of the Configuration Generator Process

Preclosure events that can adversely impact postclosure criticality evaluations are included in the event tree/fault tree models. These events are limited to mechanisms contributing to early waste package failures (e.g., improper heat treatment), early drip shield failures (e.g., emplacement errors), and waste package misloads. These events result from undetected situations during the preclosure period.

The CGM, illustrated in Figure 6-1, uses two screening levels in determining the total probability of criticality of the repository to minimize calculations to those necessary. The first screening level [box (1), Figure 6-1] tests the estimated probability of occurrence for a configuration class (evaluated over all end states) against a probability screening criterion. This criterion is set well below the 10 CFR 63.114(d) criterion of one chance in 10,000 of an event occurring over 10,000 years (Section 4.2). If the probability of occurrence for the class is below the probability screening level, then no criticality evaluation is performed for this configuration class and the probability of potential criticality for the configuration class is set to zero. The second screening level [box (2)] tests the criticality potential criterion for those configuration classes where the estimated probability of occurrence exceeds the probability screening criterion. The criticality

C02

potential of the configuration classes, which includes the uncertainty in the requisite parameters, is evaluated using the CGM to determine the range of parameters and the criticality model (BSC 2003a) to determine the k_{eff} range for the classes. If the k_{eff} from the criticality analysis is less than the critical limit over the range of parameters for the configuration class (criticality potential criterion), then the probability of criticality for the class is set to zero. However, if the criticality analysis shows that the criticality potential criterion is exceeded over some range of the configuration class parameters, then an evaluation of the probability of criticality [box (3)] is performed. This evaluation is a detailed analysis of the probability of criticality of the waste form configuration class utilizing the probability values for the range of waste form parameters required to obtain a k_{eff} greater than the critical limit.

All of the configuration classes identified for the waste form are evaluated using the two screening levels. This process is continued until the waste package and waste form configuration classes have all been analyzed. Since configuration classes are mutually exclusive entities, the probabilities from all the configuration classes that have potential for criticality are summed to obtain the total probability of criticality for the repository. This total probability is compared to the 10 CFR 63.114(d) criterion (Section 4.2)[2]. If the total probability of criticality is less than that criterion, then the repository design is acceptable with respect to criticality concerns. However, if the total probability is above the 10 CFR Part 63 criterion, then all of the waste package and waste form configuration classes that contributed to the total criticality probability are marked for consequence analysis with results to be included in the TSPA as appropriate.

The potential for criticality is based on the configuration class waste form parameters and waste package internal parameters. The probability of achieving a critical configuration class is based on the probabilities of the fault tree inputs and the probability density functions for the independent variables associated with the configuration class. A detailed description of the CGM event tree/fault tree structure is provided in the Sections 6.2 through 6.4 of this report. Sections 6.5 and 6.6 provide direction concerning the use of the CGM and method for developing parameter probability values. Section 6.7 illustrates the CGM process through a demonstration analysis. The sections are summarized as follows:

- Section 6.1 addresses an alternate model proposed in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2000).
- Section 6.2 discusses internal waste package criticality and degradation scenarios.
- Section 6.3 discusses the mathematical concepts of probability used in the CGM.
- Section 6.4 discusses the development of the model for internal waste package criticality scenarios and degradation sequences based upon event tree/fault tree logic.
- Section 6.5 describes the analysis steps and development of input data required for the CGM using a demonstration analysis.

[2] The total probability of all analyzed waste forms is also checked against the design probability criterion (Figure 1-1), and if the total probability is above the design probability criterion of less than one criticality over 10,000 years, then implementation of criticality mitigation strategies would be necessary.

- Section 6.6 discusses the CGM configuration parameters and probability density function abstractions for the demonstration analysis.
- Section 6.7 describes the results of a demonstration application of the CGM process to a specific waste package/waste form combination, i.e., CSNF.

6.1 ALTERNATIVE SOFTWARE BASED MODEL TO THE PROCESS BASED MODEL

A proposed outline for a Configuration Generator Code (CGC), an alternative approach given in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2000) for evaluating the probability of criticality of waste forms, was based upon both deterministic and probabilistic methods. Coupled differential equations for tracking isotopic concentrations were proposed as the deterministic method and Monte Carlo sampling was proposed as the probabilistic method. The CGM uses an event tree/fault tree methodology coupled with probability density functions for parameters to evaluate the probability of criticality. Differences between the CGC and CGM are primarily in the approach to the computational task. The proposed CGC model from *Disposal Criticality Analysis Methodology Topical Report* (YMP 2000) is described as follows:

> ..."Deterministic analyses are used to evaluate the various long-term processes, the combination of events, and any potential criticality. Similarly, the analysis of any potential consequence resulting from a criticality (e.g., increase in radionuclide inventory) is a deterministic analysis. However, it is not possible to state with certainty what will actually happen, which events will occur, and what actual values the parameters will have, so the individual deterministic calculations must be applied in a probabilistic context. In addition, the potential for criticality is related to various processes and events that take place over long periods and have associated uncertainties that must be considered. Therefore, establishing the likelihood of a criticality occurring involves probabilistic analysis. Hence, the disposal criticality analysis methodology is a blend of deterministic and probabilistic aspects." (YMP 2000, Section 1-1).
>
> "...The purpose for the CGC is to track the concentrations (or amounts) of neutronically significant isotopes (either fissionable or neutron absorbing) and chemical species which can effect the solubility of the neutronically significant elements. The concentrations, or amounts, are tracked by time-dependent first-order differential equations, which are solved by numerical integration. Some of these differential equations represent chemical transformations of elements or compounds. These equations form heuristic model(s) with coefficients determined by fitting data from the detailed EQ3/6 geochemistry calculations..."
>
> "...the CGC will generally be used for two purposes: (1) to provide bookkeeping for the transport between sites of application of EQ3/6, such as the interior of the waste package where the source term for external criticality is generated, and the external location where a chemistry change might cause significant precipitation, as may be determined by PHREEQC; (2) to provide more rapid calculation of

> Monte Carlo statistics in situations where the EQ3/6 and PHREEQC results can be used to develop heuristic models for the few most significant ions for a few solution parameters, such as pH…" (YMP 2000, Subsection 3.6.3.3).

The Monte Carlo approach in the CGC would allow random sampling from the input parameters for different degradation processes until some end time was reached. The sampling process results in parameter sets that are input to a criticality evaluation performed to determine the k_{eff} of the sets. The CGC would then continue this process until all configurations had been evaluated up to the termination time. The outcome from the CGC would be a multidimensional surface for k_{eff} as a function of the parameter space variables. The CGC would finally calculate the average criticality probability by dividing the number of critical realizations by the total number of realizations (YMP 1998, p. 4-36).

The CGC model as proposed in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2000) was a single-probability model contained within a software system and assumed to be amenable to numerical integration. Furthermore, the CGC model did not provide a method for determining the probability of any particular critical configuration.

A review of the proposed CGC method of performing the probability calculations indicated that there was an opportunity to improve the manner in which the model handled parameter probabilities and uncertainties. The CGM provides a traceable set of sequences to end-states in each configuration class and identifiable probability and uncertainty values for parameters through the fault tree events. In addition, the use of event tree/fault tree logical structures minimizes the computational complexity of the model.

6.2 IN-PACKAGE CRITICALITY

The Master Scenario List and the companion flow charts presented in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Section 3.3) provide the basis for identifying the degradation processes that define the different degraded configuration classes (defined in Subsections 6.2.2 and 6.2.3). An event tree model, created from the Master Scenario List and flow charts, defines the processes and sequences that lead to the different degraded configuration class end states. The degraded configuration classes identified by the event tree and fault tree model are evaluated for criticality potential and, if necessary, the probability of criticality. The evaluations are specific to the waste form and waste package type. The top events of the event tree represent the degradation processes that are required to obtain the different configuration classes. The top events are represented by fault tree models having either single inputs (i.e., basic events) or multiple inputs, depending on the complexity of the top event.

6.2.1 Degradation Configuration Definition

Degradation scenarios are related to a combination of FEPs that result in degraded configuration classes to be evaluated for potential criticality. FEPs are defined in *The Development of Information Catalogued in REV00 of the YMP FEP Database* (Freeze et al. 2001, Appendix A). Features are objects, structures, or conditions that have potential to affect a disposal system performance (Freeze et al. 2001, Appendix A). In particular, features may affect the configuration parameters and thereby influence the outcome of the criticality analyses. The principal examples of features applicable to internal criticality analyses are faults that may focus or block the flow of groundwater, thereby affecting the drip rate onto waste packages. Processes are natural or anthropogenic phenomena that have potential to affect a disposal system performance and that operate during all or a significant part of the period of performance. Examples of processes include groundwater flow, corrosion, and precipitation. Events are similar to processes but operate during an interval that is short compared to the period of performance. Examples of events would be a rockfall onto a waste package or a seismic event, either of which could potentially cause the waste package basket to collapse.

A configuration is defined by a set of parameters characterizing the quantity and physical arrangement of materials at a specific location that have a significant effect on criticality (e.g., fissile materials, neutron absorbing materials, reflecting materials, and moderators). The numerous possible configurations are best understood by grouping them into classes. A configuration class is a set of similar configurations whose composition and geometry are defined by specific parameters that distinguish one class from another. Within a class, the configuration parameters may vary over a given range.

The internal degradation scenarios identified in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Section 3.3) are the basis for deriving the different configuration classes that are related to the consequences of criticality FEPs (DTN: MO0301SEPFEPS1.000 [FEPs 2.1.14.03.0A, 2.1.14.04.0A, and 2.1.14.05.0A, respectively]) that affect the contents of the waste package. The activities from these FEPs that most directly impact the potential for internal criticality include:

- Rearrangements to a more reactive geometry
- Accumulation/retention of moderator and reflector
- Separation of neutron absorbers from fissile material
- Changes of moderator and reflector.

6.2.2 Internal Criticality Master Scenarios

Tracing through the Master Scenario List, six degradation scenario groups internal to the waste package [designated as (IP) - inside the waste package] are identified that have potential for criticality. The six groups are IP-1 through IP-6 (YMP 2003, Section 3.3). The CGM event tree, based on the Master Scenario List, generates all of the various possible sequences of top events that comprise the six in-package degradation scenario groups. These degradation scenarios are dependent on the degradation processes and degradation rates for the waste package and the components inside the waste package, including the waste forms.

Groups IP-1, IP-2, and IP-3 are associated with degradation scenarios representing a bathtub configuration. A bathtub configuration is defined as one having a breach near the top of the waste package allowing the in-flux of water to collect and pool in the waste package. Any out-flux of water and degradation products occur through the waste package breach at the same elevation as the breach. This is a conservative approach for internal waste package criticality evaluations; however, for evaluations of other types of waste package events (e.g., external radionuclide accumulation), use of the bathtub geometry may not be a conservative approach. Degradation scenario groups IP-1, IP-2, or IP-3 are described as configurations where the waste form either degrades slower than, equal to, or faster than that of the other internal components, respectively.

Degradation scenario groups IP-4, IP-5, and IP-6 represent flow-through configurations. A flow-through configuration is defined as one having a breach in the waste package bottom either before or after a breach of the top section of the waste package. Consequently, there is no flooding inside the waste package. Flow-through geometry can be obtained from two different event sequences:

1. The bottom of the waste package can breach prior to the top of the waste package.

2. Degradation processes from IP-1 to IP-3 start and then the bottom of the waste package breaches.

Configurations belonging to degradation scenario groups IP-4 through IP-6 would require hydration of degraded waste package components to achieve criticality. Silica may provide some neutron moderation but the critical mass with silica as the only moderator exceeds the fissile loading of a waste package, thus excluding an internal waste package criticality on that basis.

The following descriptions provide additional information about the six in-package degradation scenario groups and configuration classes:

IP-1 Waste form degrades faster than other internal components inside the waste package. Possible generic configuration classes in this scenario include:

(a) Waste form degrades in place and non-soluble neutron absorber remains in place (IP-1a).

(b) Degraded waste form is mobilized and separated from non-soluble neutron absorbers that remain in place (IP-1b).

IP-2 Waste form degrades at the same rate as the other internal components inside the waste package. The possible generic configuration classes in this scenario includes:

(a) Degraded waste form and internal components collect at the bottom of waste package and soluble neutron absorbers flushed from waste package (IP-2a).

IP-3 Waste form degrades slower than the other internal components inside the waste package. There are four possible generic configuration classes for this scenario that include:

(a) Carbon steel basket structural supports mechanically collapse, allowing separation of the waste form and neutron absorber that remains in place (IP-3a).

(b) After basket structures collapse, waste form and insoluble degradation products stratified at the bottom of the waste package with soluble neutron absorbers from the degraded portion of structure flushed from the waste package (IP-3b).

(c) Structures containing neutron absorbers fully degrade with stratified waste form and degradation products. Soluble neutron absorbers flushed from waste package (IP-3c).

(d) Significant neutron absorber degradation before structural collapse occurs (IP–3d).

IP-4 Waste form degrades faster than other internal components inside the waste package and the waste package has a flow-through geometry. Possible generic configuration classes for this scenario include:

(a) Waste form degrades in place and degradation products hydrate in initial location (IP–4a).

(b) Degraded waste form is mobilized and separates from the neutron absorber that remains in the initial location. Degradation products are hydrated (IP-4b).

IP-5 Waste form degrades at the same rate as the other internal components inside the waste package. Possible generic configuration classes for this scenario include hydrated waste forms and internal components collecting at the bottom of waste package while flow-through flushing removes soluble neutron absorbers (IP-5a).

IP-6 Waste form degrades slower than the other internal components. Possible generic configuration classes for this scenario include structures containing neutron absorbers fully degrade and the flow-through geometry flush soluble neutron absorbers from the waste package. This scenario also has the waste form collecting on the bottom of the waste package mixed with hydrated corrosion products from waste package internal components (IP-6a).

6.2.3 Generic In-Package Degradation Configuration Classes

As stated previously, a configuration class is a set of similar configurations whose composition and geometry are defined by specific parameters that distinguish one class from another. The following paragraphs list and discuss the configuration classes resulting from the standard scenarios presented previously that have potential for criticality with emphasis on their end states (YMP 2003, Subsection 3.3.1). The configuration classes are intended to comprehensively represent the configurations that can result from physically realizable scenarios, are generic to the waste form, and waste package type.

Configuration class IP-1a: For this configuration class, the fissile material separates from the neutron absorber, which remains in place within the waste package. This configuration class can be reached from the standard scenario IP-1 where the waste form degrades faster than waste package internal structures. In this configuration class, the neutron absorber is not released from its carrier before the waste form degrades and the fissionable material degrades in place.

Configuration class IP-1a has potential for criticality only if there is sufficient moderator to permit criticality of the fissile material.

Configuration class IP-1b: This configuration class considers the mobilization of the degraded waste form and its separation from the neutron absorber. The mobilized fissionable material accumulates at the bottom of the waste package. A mechanism to mobilize the degraded waste form is needed. Configuration class IP-1b has potential for criticality only if there is sufficient water present with separation of fissile material from neutron absorber material to permit criticality of the fissile material accumulated at the bottom of the waste package.

Configuration Class IP-2a: Both basket and waste form have degraded to be in this configuration class. The corrosion product composition is a mixture of fissile material and degradation products from internal structures. It is more complex than for degradation scenario IP-3, and is characterized by geochemistry calculations. This configuration class is most directly reached from the standard degradation scenario IP-2, in which all the waste package components degrade at the same time. However, eventually the standard scenarios IP-1 and IP-3, in which the waste form degrades before or after the other components, respectively, can lead to this configuration class when the latter scenario catches up with the former.

The configuration class IP-2a has potential for criticality if the soluble neutron absorber is flushed from the waste package. Solubility of a substance depends on pH, Eh (the electrode potential [in volts] with respect to the standard hydrogen electrode), dissolved species levels, and ionic strength. The quantity of degradation products and the remaining soluble neutron absorber inside the waste package barrier is evaluated as a function of time using the EQ6 software package (EQ6 7.2bLV, STN: 10075-7.2bLV-02). The configuration class has potential for criticality only if there is sufficient moderating water with loss of absorber material to permit criticality of the fissile material accumulated at the waste package bottom.

Configuration Class IP-3a: This configuration class has the waste package internal basket degrading but waste form remains relatively intact at the bottom of the waste package surrounded by, and/or beneath, the basket corrosion products. This configuration class has potential for criticality only if the basket structural supports mechanically collapse due to degradation, while the absorber plates and the waste form remain intact. The mechanical collapse of the basket structural support permits geometric rearrangement of the waste form reducing the neutron leakage.

Configuration Class IP-3b: This configuration class has the waste package internal basket structures collapsing with the waste form and degradation corrosion products stratified. Neutron absorbers are flushed from the waste package. This configuration class has potential for criticality only by complete basket structure support degradation and partial neutron absorber degradation.

Configuration Class IP-3c: This configuration is characterized by the complete degradation of the basket structure support and neutron absorber plates. The soluble neutron absorber is flushed from the waste package. Two sequences that lead to this configuration class apply to the waste package design in which either the basket structural support degrades prior to the neutron absorber plates or the neutron absorber plates degrade prior to the waste package internal structures.

Configuration Class IP-3d: The neutron absorbing structure degrades significantly before structural collapse occurs. The absorber separates from the waste form and remains inside the waste package. The waste form and waste package internal structures maintain their integrity.

Configuration Class IP-4a: Fissile material degrades in place faster than the waste package internal structures in a flow through geometry and moves away from the neutron absorber, which remains in the waste package. In this configuration class, the waste form degrades prior to the neutron absorber being released from its carrier. The degraded material hydrates and collects in its initial location. Configuration class IP-4a has potential for criticality only if there is sufficient hydration of the degradation products to permit criticality of the fissile material.

Configuration Class IP-4b: This configuration class considers the mobilization of the degraded waste form and its separation from the neutron absorber. The mobilized fissionable material hydrates and collects with other hydrated corrosion products and most likely accumulates at the waste package bottom. A mechanism to mobilize the degraded waste form is needed. Configuration class IP-4b has potential for criticality only if the hydrated waste form mobilizes in order for it to separate from the neutron absorbing material.

Configuration Class IP-5a: In this configuration class, both the waste package basket and waste form have degraded at similar rates. This configuration class can also be obtained from degradation scenarios IP-1 or IP-3. IP-1 has the waste form degrading faster than basket and IP–3 has the basket degrading faster than waste form, but ultimately both waste form and other internal components degrade and accumulate on the bottom of the waste package. This configuration class can be reached from the IP-5 standard scenarios (i.e., flow-through geometry occurring either prior to or after both waste form and basket degrade and hydrated products collect on the bottom of waste package).

Configuration class IP-5a has potential for criticality if the soluble neutron absorber is flushed from the waste package and there is sufficient hydration of the degradation products to permit criticality of the fissile material. Solubility of a substance depends on pH, Eh (the electrode potential [in volts] with respect to the standard hydrogen electrode), dissolved species levels, and ionic strength.

Configuration Class IP-6a: In this configuration class, the waste package internal basket degrades faster than the waste form. The waste form is relatively intact and sitting at the bottom of the waste package surrounded by, and/or beneath, the basket corrosion products. This configuration class is also obtained from degradation scenario IP-3 where the neutron absorber and waste package basket structure have significantly degraded before the waste package bottom failure. This configuration has potential for criticality only if the basket structural supports mechanically collapse due to degradation, the neutron absorber is flushed from waste package, and there is sufficient hydration of the insoluble degradation products to permit criticality of the fissile material.

6.2.4 Parameters Associated with Potential Critical Configurations

The k_{eff} of a nuclear system is a complex function of neutron production, moderation, absorption, and leakage for the system being analyzed. The contents inside a degraded waste package and the relative positioning of those contents continuously change under the degrading factors of drift environments; therefore, there are a large number of possible configurations. However, based on the features of the repository and the characteristics of waste package contents, a finite number of configuration classes have been deemed to have potential for criticality (YMP 2003, Section 3.3). These configuration classes have been presented in Subsection 6.2.3. The configuration classes identify states of a degraded waste package that could attain criticality, thus reducing the range for some of the parameters associated with criticality.

Variables that affect k_{eff} for a degraded waste package are the isotopic and elemental contents, volume of moderator, and geometry of the system components. These parameters are based on the waste form and waste package internal structure and materials and are discussed in the next subsections.

6.2.4.1 Parameters Associated with Waste Packages

The different waste package types are identified as (BSC 2002c)

- 21-PWR with Absorber Plates
- 21-PWR with Control Rods
- 12-PWR
- 44-BWR
- 24-BWR
- 5 DHLW/DOE SNF-SHORT
- 5 DHLW/DOE SNF-LONG
- 2-MCO/2-DHLW
- NAVAL LONG[3]
- NAVAL SHORT[3].

The different variants on the waste package design (excluding the Naval Nuclear Propulsion Program) can be classified into two main groups, CSNF and DOE, based on the type of waste form to be placed in the waste package. However, these variants of the waste package design have the same characteristics with respect to the outer barrier. The waste package barrier design features two shells, an inner shell of stainless steel for structural strength and an outer shell of Alloy 22 for corrosion resistance. The differences among the waste packages, aside from the contained waste forms, are the different variants on the design of the inner basket structure.

The CSNF waste package group is comprised of the following: 21-PWR with Absorber Plates, 21-PWR with Control Rods, 12-PWR, 44-BWR, and 24-BWR. An isometric view representative of the 21-PWR with Absorber Plates Waste Package (with internal basket) is shown in Figure 6-2 and of the 44-BWR in Figure 6-3. The 12-PWR and 24-BWR variants are similar to their respective larger counterparts. Although the waste package nomenclature is being revised, the individual components as shown in Figures 6-2 through 6-3 sufficiently illustrate the major variants on the waste package design .

[3] The Naval Nuclear Propulsion Program waste packages are discussed in *Transmittal of the Naval Nuclear Propulsion Program Addendum to the* Yucca *Mountain Site Characterization Office "Disposal Criticality Analysis Methodology Topical Report."* (Mowbray 1999). Therefore, Naval Nuclear Propulsion Program information is not included in this report.

The waste package inner basket structure for the CSNF contains interlocking plates that delimit the locations for assembly loading. There are three types of plates in the intact waste package design for CSNF, each having a different function (CRWMS M&O 2000g, Section 6.1). Plates made of carbon steel serve as structural support for assemblies. A second type of plate made of aluminum alloy serves as a thermal conductive medium from the assemblies to the waste package outer barrier in design variants for high thermal output. The third type of plate made of Neutronit A978 is used for criticality control in the 21-PWR with Absorber Plates Waste Packages. The 21-PWR with Control Rods Waste Package design variant for PWR CSNF having a high assembly k_∞ uses zirconium clad boron carbide (B_4C) control rods for reactivity control in place of the absorber plates (CRWMS M&O 1997, Subsection 7.3.2). The waste package internal structure for this latter design variant also contains fuel basket tubes and side guide plates made of carbon steel that are similar to the 21-PWR with Absorber Plates Waste Package.

The DOE waste package group is comprised of the following: 5 DHLW/DOE SNF-SHORT, 5 DHLW/DOE SNF-LONG, and 2-MCO/2-DHLW waste packages. The basket structure for the 5 DHLW/DOE SNF-SHORT and 5 DHLW/DOE SNF-LONG waste packages is a web device to be constructed of carbon steel (CRWMS M&O 2000l, Section 6.1) and divided into six separate compartments, five on the periphery and one in the center. The five compartments on the periphery are intended to contain the HLW canisters while the center tube is for the DOE SNF waste form canister. An isometric view representative of a 5 DHLW/DOE SNF waste package with six compartments is shown in Figure 6-4. The long and short design variants are similar except for their length. Another variant on the design of the DOE waste packages, designated as 2-MCO/2-DHLW, has the basket structure divided into four separate compartments. The 2–MCO/2-DHLW waste package is intended to contain two multi-canister overpacks and two defense high-level radioactive waste glass canisters.

6.2.4.2 Parameters Associated with Waste Form Design and Criticality

The parameters for the different variants of the waste package design and the parameters associated with criticality for the different waste forms can be obtained from many YMP sources. Various YMP reports define the physical characteristics of the waste form along with how the waste form is loaded into its respective waste package type. One such report, *Generic Degraded Configuration Probability Analysis for DOE Codisposal Waste Package* (BSC 2001d), provides information and references about DOE waste form types. That report discusses the probability analysis for potential critical configurations using waste form specific information. The physical characteristics and parameters of the specific waste form can be obtained from the references listed in *Generic Degraded Configuration Probability Analysis for DOE Codisposal Waste Package* (BSC 2001d).

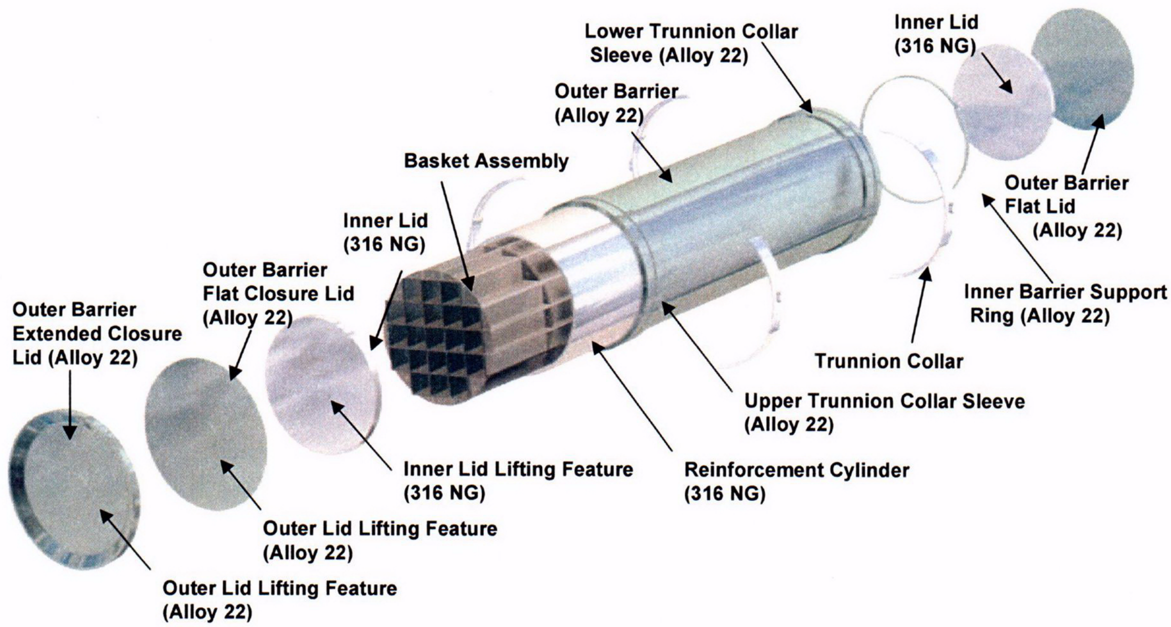


Figure 6-2. 21-PWR With Absorber Plates Waste Package

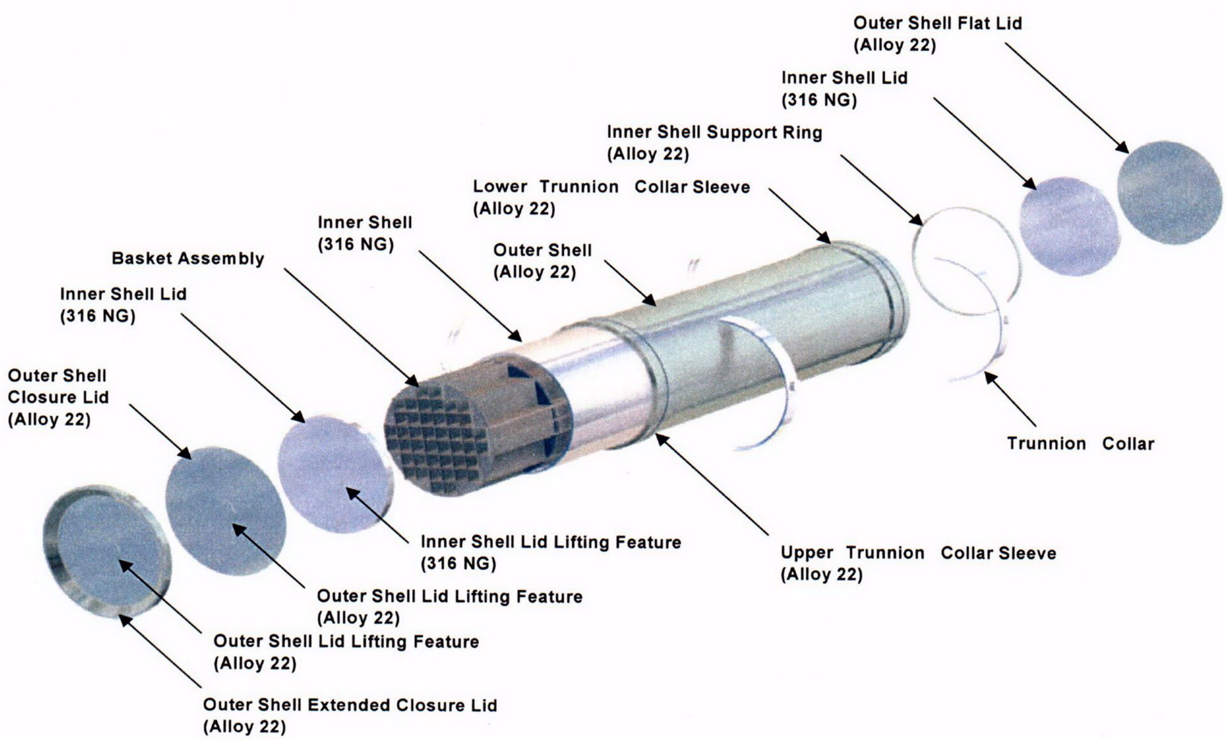


Figure 6-3. 44-BWR Waste Package

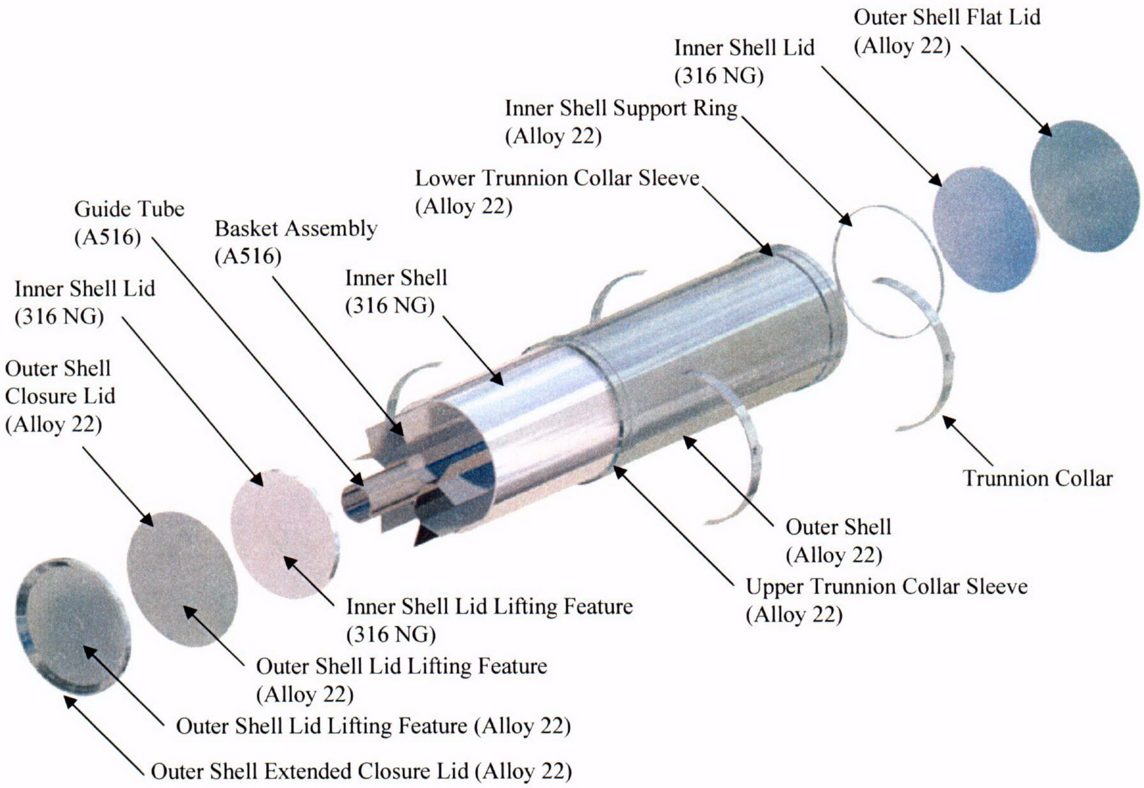


Figure 6-4. 5 DHLW/DOE SNF Waste Package

A number of reports provide information and references about characteristics and parameters associated with CSNF (e.g., CRWMS M&O 1998b). The CSNF waste form has also been evaluated for both criticality potential and probability of criticality in *Probability of a PWR Uncanistered Fuel Waste Package Postclosure Criticality* (CRWMS M&O 1998b). Cladding is one characteristic that is used to separate CSNF into two categories (i.e., Zircaloy-clad CSNF comprising 96.5 percent of CSNF and stainless steel-clad CSNF comprising 3.5 percent of CSNF) (CRWMS M&O 2000b, p. 4-5). In addition, each fuel assembly contains spacers made of Zircaloy or Inconel that define the pitch for the intact fuel rod lattice.

A generic list of the important parameters required for criticality can be found in Table 6-1. Table 6-1 lists the parameters associated with CSNF together with drift environment and waste package variables. Although the parameters listed in Table 6-1 are for CSNF, the same or similar type of information is required for the other waste forms.

C04

Table 6-1. Parameters Associated with In-Package Criticality

Neutronic Process	Parameter	Drift Environment and Waste Package Variable[a]
Neutron production	Fissile amount	Initial fuel enrichment
		Fuel burnup level
		Burnup axial and radial profile
		Time since fuel discharged from the reactor
		Fraction of misloaded fuel rods
		Fraction of damaged fuel rods
		Water flux rate[d]
		In-package chemistry (pH)[d]
Neutron absorption[b]	Boron amount[c]	Stainless steel corrosion rate
		Water flux rate
	Fission product amount	Initial fuel enrichment
		Fuel burnup level
		Burnup axial and radial profile
		Time since fuel discharged from the reactor
		Fraction of damaged fuel rods
		Water flux rate[d]
		In-package chemistry (pH)[d]
Neutron moderation	Water volume	Water flux rate
		Non-hydrogenous moderators
		Insoluble degradation products in the waste package
	Fuel rod pitch	Intensity and frequency of disruptive events
Neutron leakage	Amount of neutron reflector materials; spatial distribution of fissile and reflector materials	Insoluble degradation products and non-hydrogenous moderators in the waste package
		Relative positioning of waste package intact components and degraded insoluble products
		Burnup axial and radial profile
		Frequency and intensity of disruptive events

NOTES: [a] A functional relationship can be established between parameter and variables listed.
[b] The neutron absorber consists of materials containing radionuclides with high absorption cross sections.
[c] EQ6 geochemistry calculations have shown that boron is effectively removed as a soluble corrosion product from the waste package as the borated stainless steel plates degrade (CRWMS M&O 1998a, Section 6).
[d] Some of the actinides and fission products released from the degraded CSNF matrix have a limited solubility and can be removed from the waste package by the egress of fluid that contains dissolved species.

6.3 MATHEMATICAL CONCEPTS AND NOTATION USAGE

The notations used for deriving various distribution functions are the following:

- 'P' a probability
- 'F' a cumulative distribution function
- 'f' a probability density function for a continuous random variable.

A subscript on a parameter indicates that the parameter is used with the probability functions f and F.

If X is a continuous random variable, the cumulative distribution function, F, of the random variable X (Walpole et al. 1998, Section 3.3), is defined for all real numbers $x \in \{-\infty < x < \infty\}$ by

$$F_X(x) = P\{X \leq x\} \quad \text{(Eq. 1)}$$

The cumulative distribution function is a continuous, monotonically increasing function defined on the interval $x \in [0,1]$.

The probability density function, f, of the continuous random variable X (Walpole et al. 1998, Section 3.3) is defined by:

$$f_X(x) = \frac{dF_X(x)}{dx} \quad \text{(Eq. 2)}$$

If the probability density function, f, of a random variable is known, then the distribution function F is obtained as follows (Walpole et al. 1998, Section 3.3)

$$F_X(x) = \int_{-\infty}^{x} f_X(x')dx' \quad \text{(Eq. 3)}$$

For any two random variables X and Y, the joint cumulative distribution function of X and Y is defined for all real numbers a and $b \in \{-\infty < (a, b) < \infty\}$ by

$$F(a,b) = P\{X \leq a, Y \leq b\} \quad \text{(Eq. 4)}$$

Two random variables, X and Y, are independent if the joint distribution function $F(x,y)$ can be given by

$$F(x,y) = F_X(x) \cdot F_Y(y) \quad \text{(Eq. 5)}$$

Likewise, when X and Y are independent, the joint density function of X and Y is given by Equation 6 (Walpole et al. 1998, Section 3.5)

$$f(x,y) = f_X(x) \cdot f_Y(y) \quad \text{(Eq. 6)}$$

6.4 CONFIGURATION GENERATOR MODEL FOR IN-PACKAGE CRITICALITY

Information on the overall methodology that the CGM must address is given in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Section 3.1). The Master Scenario List shown in Figures 3-2a, 3-2b, 3-3a, and 3-3b (YMP 2003) represent three general degradation configurations in the monitored geologic repository having criticality potential. The three general configurations are based on locations inside the waste package (IP), outside the waste package in the near-field environment (emplacement drift outside the waste package), and outside the waste package in the far-field environment (region outside the emplacement drift). These three different locations are broken down into specific scenarios (i.e., six IP degradation scenarios (Section 6.2.2), five near-field environment degradation scenarios, and three far-field environment degradation scenarios).

The following is a discussion of how the CGM is used with the Master Scenario List. For the probabilistic analysis part, the CGM discussed in this report is concerned only with the six IP degradation scenarios. The model uses event tree methodology to express the degradation processes and sequences that lead to the different configuration classes. Note that a configuration class may possess multiple end states. The construction of the event tree captures all of the configuration classes discussed in the Master Scenario List (YMP 2003, Figures 3-2a and 3-2b).

The event tree (illustrated in Figures I-1 through I-32) starts with the different waste forms expected for disposal in the monitored geologic repository. Listing the different waste forms in the event tree provides a bookkeeping mechanism. However, in an analysis, a specific waste form must be specified in order to quantify the degradation parameters for both the waste form and waste package. The event tree then lists in sequential order the degradation processes required to reach each of the six IP degradation scenarios. The top events on the event tree are the specific processes required for degradation. The branching under the top events (degradation processes) provides a traceable sequence to each configuration class. The different configuration classes are noted on the event tree with their respective end states.

The degradation processes listed as top events are developed into fault tree logic submodels. The majority of the fault trees contain single inputs; however, some processes (e.g., drip shield failure) contain multiple inputs. The fault tree inputs need to consider many variables, the most important of which is the time dependency. The complete degradation processes and achievement of the configurations are based on time, beginning with the time of closure of the repository.

The second part of the CGM addresses the calculation of the criticality potential for a given configuration class and ties the criticality analysis together with the probability analysis. The CGM generates the different configuration classes based on the Master Scenario List following the sequences through the event tree to generate the different waste form and waste package configuration classes. Once an end state in a configuration class has been generated, the probability of that state is compared with the screening criterion (Section 6). If the screening criterion is exceeded, the potential for criticality of the state is evaluated (Figure 6-1). A detailed evaluation using the criticality model (BSC 2003a) is performed for those configurations to evaluate their potential for criticality. Then, if the criticality potential criterion for the waste form is not satisfied, a probability analysis of the critical configuration is performed (YMP 2003, Subsection 3.2.1). Since the configuration classes are mutually exclusive entities, the probabilities for a configuration class are summed over the various end states.

In order to perform the probabilistic analysis, probability density functions for the independent variables associated with the potential critical configurations need to be defined. These probability density functions are derived from the functional relationships between drift environment, waste form variables, and waste package variables and are obtained from various sources. The density functions for some of the parameters are developed in and are obtainable from the (current) TSPA model. Other density functions are developed from abstractions as in the demonstration analysis that is part of this CGM report. The probability analysis uses the range of parameters determined from the criticality analysis. Methods for the criticality analyses are discussed in *Criticality Model Report* (BSC 2003a). Methods for the probability analysis are discussed in the following subsections.

The potential for criticality of a waste form configuration class in the waste package is determined by the material composition and the physical arrangement (or geometry) of this material composition. For a waste package containing CSNF, the initial configuration is the waste package as-loaded with commercial light water reactor fuel assemblies. The fuel assemblies in this initial configuration are intact; thus, the fuel rods within the fuel assembly are expected to have the same geometry as during their operation in the commercial reactor. The fuel rod geometry in the fuel assembly is a square pin matrix optimized with respect to maximizing reactivity in the reactor core (i.e., results in a potentially high k_{eff}). This initial configuration in the waste package is subcritical since a correctly loaded waste package is designed to ensure that condition, even in a flooded state, through inclusion of neutron absorbing materials. Any potential criticality thus can only occur for degraded configurations.

6.4.1 CGM Event Tree

The CGM event tree represents the degradation processes and sequences that lead to the different configurations classes discussed in the Master Scenario List shown in Figures 3-2a and 3-2b (YMP 2003, Section 3.3). The event tree is developed in a comprehensive manner in order to capture all of the processes and sequences that lead to one of the six in-package degradation scenarios associated with internal waste package processes. Only these six related degradation scenarios are constructed in the CGM event tree using the SAPHIRE software V7.18 (SAPHIRE V7.18, STN: 10325-7.18-00), a state-of-the-art computer code for performing probabilistic risk assessment evaluations. The CGM event tree, shown in Attachment I, is used to evaluate all of the in-package configuration classes resulting from the scenarios to identify those having potential for criticality and thus require a detailed criticality analysis to determine if the k_{eff} is greater than the critical limit for the waste form.

The CGM event tree starts with the different waste forms expected to be stored in the monitored geologic repository. The sequences for the various waste forms then transfer, respectively, to their specific configuration generating event trees. These event trees identify the specific waste form along with the degradation processes listed in sequential order, in order to provide the start to finish sequences for the degradation process. The top events on the event tree are the specific processes required for degradation. Branching under the top events (degradation processes) provides a traceable sequence to each configuration class. The different configuration classes are noted on the CGM event tree with their respective end states. Note that to reach a specific end state, the degradation-related processes in that sequence must occur. Thus, the probability of reaching that end state is evaluated in a reverse manner (i.e., determine first what parameter values are required to allow the end state conditions to occur within the given time period, then evaluate the probability of occurrence for these particular values). This process will normally require an iterative approach to maximize the overall probability.

The various end states of a configuration class are evaluated for their potential for criticality without necessarily quantifying the probability of achieving such a state. End states of a configuration class are marked as having potential for criticality if their essential parameters have values in the range that can support criticality. The sequences to those particular end states are then backtracked to assess the probabilities that the parameters can actually have the requisite values. Summing these probabilities is the method for estimating the probability of occurrence of a configuration class (Figure 6-1). The parameter values essential for criticality are correlated, but the probability distributions for the random variables in the set are independent. Thus, an iterative approach may be necessary to maximize the probability of occurrence based upon the correlated variables. The process is time-dependent so that the assigned probabilities include the additional requirement that the parameter values must be realized within a given time period. The probability of criticality is set to zero for all end states of configuration classes that are not marked as having potential for criticality.

The following example is provided to show how the CGM event tree is used to generate the different configuration classes. This example, using configuration class IP-3c, is representative of how all of the configuration classes are obtained, stepping through the CGM event tree and provides the degradation processes required to reach the end state. The example starts with the event tree shown in Figure I-2 and ends with the event tree shown in Figure I-16.

The configuration class is generated by starting with the CGM event tree shown on Figure I-2, using the branching logic where down represents the occurrence of the degradation process, and up represents the non-occurrence of the degradation process. Note that one of the decision branches must occur, independent of their respective probabilities (e.g., for a two-way branch an event either happens or does not happen). The first top event on Figure I-2 is MS-IC-1, which specifies whether or not water reaches the drift. If water reaches the drift, then top event (MS-IC-2) is queried. However, if water does not reach the drift (i.e., the branching goes up) then the analysis ends at this point since there is no water to fill the waste package and provide neutron moderation. The questioning of the next three top events proceeds in the same manner. If any of the first three top events branch upward, the analysis stops because they do not meet the requirements for criticality. The fourth top event (MS-IC-4) determines if the waste package is in a bathtub configuration and, if true, then degradation scenarios IP-1 through IP-3 are generated. If the waste package is not in a bathtub configuration, then degradation scenarios IP-4 through IP-6 are generated. The last top event determines what degradation scenario will be generated. For this example, degradation scenario IP-3 will be generated by transferring from Figure I-2 (event tree) to the event tree noted in the END-STATE column. This event tree is shown on Figure I-10.

The event tree shown on Figure I-10 is used to generate the four different configuration classes of degradation scenario IP-3 denoted by 3a, 3b, 3c, and 3d (Subsection 6.2.2). For configuration class IP-3c to be generated, top event IP3-CON-CLASS will transfer to event tree C-IP3C listed in the END-STATE column. Event tree C-IP3C shown in Figure I-15 contains the remaining degradation processes required to achieve configuration class IP-3c. These functions are performed as part of the SAPHIRE process.

The first top event listed on event tree C-IP3C is a repeat of the top event that determines if the configuration can be classified as a bathtub configuration. This top event is forced to branch downward because of the event tree shown in Figure I-2. The next top event (MS-IC-8) deals with the degradation process of the waste form and waste package internals. This top event states that the waste package internals degrade faster than the waste form. Given that the waste package internals degrade faster than the waste form, two separate sequences end up with the same configuration class identifier. The first sequence has significant neutron absorber degradation prior to the waste package internal structures collapsing (MS-IC-22). Top event MS-IC-23 has the internal structures collapse and degrade followed by the soluble neutron absorber flushed from the waste package (top event MS-IC-19). The sequence discussed above leads to end state IP-3C-T, which is associated with the configuration class IP-3c.

The second sequence leading to configuration class IP-3c has the basket structure collapsing (top event MS-IC-16) given that top event MS-IC-8 has occurred. This sequence continues with full degradation of the waste package internal structures containing the neutron absorber (MS-IC-17). The final degradation process along this sequence has the soluble neutron absorber completely flushed from the waste package (MS-IC-19). Both sequences transfer to event tree IP-3C-T shown in Figure I-16, which details whether or not further evaluation is required. Further evaluation depends upon whether top events WF-TYPE or CRIT-POT-FUEL can occur. Both of these top events must occur (i.e., downward branching) for further evaluation. If further evaluation is required, an analysis of the criticality potential for a misload and/or nominal configuration is performed and the event tree IP-3C-T provides the time steps.

The two degradation processes that lead to configuration class IP-3c as defined by the event tree are shown in Table 6-2. The top events that are required to occur (i.e., branch downward) in order for configuration class IP-3c to be obtained are listed in sequential order. Table 6-2 also provides the description of each top event.

6.4.2 Fault Tree Model

The processes listed as top events in the event tree are managed by fault trees that contain either single or multiple inputs depending on the process being evaluated. Attachment II provides a representative example set of these fault trees where Figures II-1 through II-10 identify the processes required to produce sequence 2 of configuration class IP-3c. Table 6-3 lists the top events for sequence 2 and their associated fault tree inputs.

Table 6-2. Degradation Processes for Configuration Class IP-3c Based on CGM Event Tree

Top Event	Description
Sequence 1	
MS-IC-1	Water reaches Drift
MS-IC-2	Water drips on waste package
MS-IC-3	Waste package penetration at top surface
MS-IC-4	Liquid accumulates in waste package
MS-IC-8	Waste package internal structures degrade faster than waste form
MS-IC-22	Significant neutron absorber degradation before structural collapse
MS-IC-23	Waste package internal structures mechanically collapse and degrade
MS-IC-19	Soluble neutron absorber flushed from waste package
WF-TYPE	Waste form degrades according to configuration class
CRIT-POT-FUEL	Criticality potential of waste form (i.e., does the waste form have the potential to become critical given the configuration)
MISLOAD	Waste package misload evaluation
TIME-STEP	Time after waste package loaded into the monitored geologic repository, used to evaluate probability of other events
Sequence 2	
MS-IC-1	Water Reaches Drift
MS-IC-2	Water Drips on waste package
MS-IC-3	Waste package penetration at top surface
MS-IC-4	Liquid accumulates in waste package
MS-IC-8	Waste package internal structures degrade faster than waste form
MS-IC-16	Basket structural supports mechanically collapse
MS-IC-17	Structures containing neutron absorbers fully degrade
MS-IC-19	Soluble neutron absorber flushed from waste package
WF-TYPE	Waste form degrades according to configuration class
CRIT-POT-FUEL	Criticality potential of waste form (i.e., does the waste form have the potential to become critical given the configuration)
MISLOAD	Waste package misload evaluation
TIME-STEP	Time after waste package loaded into the repository, used to evaluate probability of other events

Table 6-3. Fault Tree Inputs for Configuration Class IP-3c Event Tree (Sequence 2)

Event Tree Top Event	Description	Fault Tree Inputs	Description
MS-IC-1	Sufficient water reaches drift to achieve configuration class (timestep)	BE-SEEPAGE	Water reaches drift
		BE-SEEP FRACT	Fraction of waste packages that can have seepage
		BE-SEISMIC	Seepage enhancement from seismic event
MS-IC-2	Static drip shield failure Water Drips on waste package	BE-DS EMPLACEMENT	Drip shield improperly installed
		BE-DS FLOOR HEAVE	Drip shield failure due to floor heave
		BE-DS THERM-EXPAN	Drip shield failure due to thermal expansion
		BE-DS FABRICATION	Drip shield failure due to fabrication error
		BE-DS ROCK-FALL	Drip shield failure due to rock fall
		BE-DS-SEISMIC	Drip shield failure due to seismic event
	Time dependent drip shield failure Water Drips on waste package	BE-DS-GENCOR	Drip shield failure due to general corrosion
		BE-DS-SCC	Drip shield failure due to stress corrosion cracking
		BE-DS-CREVICE	Drip shield failure due to localized crevice corrosion
		BE-DS-PITTING	Drip shield failure due to localized pitting corrosion
MS-IC-3	Static waste package failure top surface penetration allows bathtub geometry	BE-WP-SEISMIC	Waste package failure due to seismic event
		BE-WP-EARLY-F	Waste package early failure event
	Time dependent waste package failure top surface penetration allows bathtub geometry	BE-WP-GENCOR	Waste package failure due to general corrosion
		BE-WP-SCC	Waste package failure due to stress corrosion cracking
		BE-WP-CREVICE	Waste package failure due to localized crevice corrosion
		BE-WP-PITTING	Waste package failure due to localized pitting corrosion
	Advective flow path through drip shield and waste package	BE-WP-DS-ALIGN	Waste package failure location aligned with drip shield failure location

Table 6-3. Fault Tree Inputs for Configuration Class IP-3c Event Tree (Sequence 2) (Continued)

Event Tree Top Event	Description	Fault Tree Inputs	Description
MS-IC-4	Liquid accumulates in waste package	BE-BATHTUB-xxK-EF[a]	Bathtub geometry in place at 'xxK' years resulting from early failure mode
		BE-BATHTUB-xxK-GC	Bathtub geometry in place at 'xxK' years resulting from time dependent corrosion
MS-IC-8	Waste package internal structures degrade faster than waste form	BE-MS-IC-8	Waste package internal structures degrade faster than waste form
MS-IC-16	Basket structural supports mechanically collapse	BE-MS-IC-16	Basket structural supports mechanically collapse
MS-IC-17	Structures containing neutron absorbers fully degrade	BE-MS-IC-17	Structures containing neutron absorbers fully degrade
MS-IC-19	Soluble neutron absorber flushed from waste package	BE-MS-IC-19-xxK-EF	Soluble neutron absorber flushed from degraded portion of basket at 'xxK' years resulting from early failure mode
		BE-MS-IC-19-xxK-GC	Soluble neutron absorber flossed from degraded portion of basket at 'xxK' years resulting from time dependent corrosion

[a] xx - Place holder for time step information.

The fault trees have their logic broken into different gates that represent the probability of the process occurring at each time step. The time steps represent the time in years after closure of the repository. These time steps are variable and can be adjusted in the analysis. For example, the time steps in the demonstration analysis documented in this report (Section 6.7) start at 10,000 years, based upon the estimated time of initial waste package breach, and end at 50,000 years. By breaking the fault tree up into these specific time steps, only the (cumulative) probability of the process at that particular time step is included in the final probability result for the time step. The fault trees are structured with true/false gates (house events) to allow only the probabilities for a specific time step to propagate from the fault tree. Note that all initiating events are included in the fault tree construction but can be disabled for particular analyses. The fault trees may appear complicated but in actuality, they contain only a single input for each time step. The fault trees are developed in this manner to account for the different time dependent probabilities of the processes.

The fault trees that contain multiple inputs are those required to represent both time dependent and time independent probabilities. An example of this type of fault tree is the one representing the drip shield failure mechanisms as shown in Figure II-2 for the top event MS-IC-2. The drip shield has two major failure mechanisms, the first is due to static failures (i.e., time independent) and the second is due to corrosion activity, which is time dependent. Static failures are those that can happen randomly at any time during emplacement or during the life of the drip shield (e.g., failure due to rockfall or a seismic event). These static failures contain a single failure probability that is constant over time. Various corrosion mechanisms acting on the drip shields progress over time and affect the number of patches on the drip shields and the fraction of drip shields that have failed at any particular time. The number of drip shield failures due to corrosion thus changes over time and is addressed by structuring the fault tree with these time dependent inputs that are separate events in the fault tree. These time dependent events contain the drip shield failure information at the time steps shown on the CGM event tree (Figures I-1 through I-32).

6.4.3 Design Modifications of the SAPHIRE CGM

The CGM event tree model created in SAPHIRE requires some modifications in order for it to be used to evaluate each configuration class. These modifications are changes to some of the top events listed on the event tree, creation of end states for grouping the final results, and removal of mutually exclusive process combinations. These modifications are discussed in the following subsections.

6.4.3.1 Top Event Modifications to SAPHIRE CGM

The CGM event tree requires certain top events to be changed from their default (i.e., top event listed on the event tree) to a new top event. This top event modification is required for SAPHIRE to correctly perform the probability analysis. By making the referenced substitutions, the generic top events listed on the event tree are changed to specific top events. These specific top events contain the waste form and waste package specific probabilities for the analysis. Another reason for making this top event change is to set up the creation of time specific end states. The time specific end states are used to group all of the configuration class events together based on the time step (i.e., years after closure of the repository).

To make the top event changes, substitution rules are created and implemented. Substitution rules are simple structures that allow for the searching of a specific top event and replacing it with a new top event. The substitution rules are provided in Attachment III. An example of a substitution rule follows.

```
if MS-IC-4*CONFIG-SCEN[1]*MS-IC-9 then
    /WF-TYPE = WF-TYPE-IP1A;
    WF-TYPE = WF-TYPE-IP1A;
    /CRIT-POT-FUEL = CRIT-POT-FUEL-IP1A;
    CRIT-POT-FUEL = CRIT-POT-FUEL-IP1A;
endif
```

The rule structure above causes SAPHIRE to substitute a more specific top event for the default top event whenever the three top events occur in any given sequence. As shown above, whenever SAPHIRE finds top events MS-IC-4, CONFIG-SCEN, and MS-IC-9 in a sequence, it exchanges the default top event WF-TYPE with the more specific top event WF-TYPE-IP1A. This instructs the SAPHIRE CGM to change the generic top event listed on the CGM event tree to the configuration class specific top event.

6.4.3.2 Time Specific End States of the SAPHIRE CGM Model

The CGM event tree shows the configuration classes and associated end states on the event tree. These end states gather all of the process combinations together regardless of the specific time step being evaluated. Therefore, new end states are created to allow each time step process combination to be gathered together for viewing and summing. The new end states are based on the configuration class and the specific time step. The new end states are created by the use of SAPHIRE logic rules similar to the substitution rules discussed above. The logic rules that are used for the creation of time specific end states are provided in Attachment III. An example of this rule structure is given as follows:

```
if SYSTEM(CONFIG-SCEN1) * SYSTEM(MS-IC-9) * SYSTEM(TIME-STEP-10K)
then
   partition ="IP-1A-10k";
endif
```

The rule structure above tells SAPHIRE that if the three top events are together along a sequence, then create an end state called IP-1A-10k. This end state gathers all process combinations together that contain these three top events. Thus, the results for this end state contain only those process combinations for configuration class IP-1a and time step 10K (years). Similar rules listed in SAPHIRE are used to create the remaining configuration class and time specific end states.

6.4.3.3 Removal of Mutually Exclusive Process Combinations

The interaction of fault trees linked to event tree degradation sequences can cause combinations of basic events that are mutually exclusive. The process of removing sequences with these mutually exclusive combinations is common in probabilistic risk analyses. When event tree sequences are analyzed, all possible combinations are generated and some of these combinations are mutually exclusive. Because the SAPHIRE CGM model is an event tree model with fault trees linked to the sequences, it also creates mutually exclusive process combinations. In order to remove sequences with these mutually exclusive process combinations, specific rules are created in the SAPHIRE CGM and applied to all possible process combinations.

The mutually exclusive process combinations that are generated in the SAPHIRE CGM deal with the products of different waste package failure mechanisms and water accumulation inside the waste package. The specific rules to remove all mutually exclusive process combinations in the SAPHIRE CGM are provided in Attachment III. An example of these rules follows.

```
if BE-WP-EARLY-F * BE-BATHTUB-50K-GC then
   DeleteRoot;
endif
```

The rule structure above instructs SAPHIRE that if the specified combination of basic events exists in a sequence, then that sequence is to be removed from the final results because of the conflicting failure processes. Basic event BE-WP-EARLY-F is a failure mechanism that is due to early waste package failure and not due to general corrosion. Basic event BE-BATHTUB-50K-GC is an event that represents the probability that the waste package has been in a bathtub configuration since the waste package failed due to general corrosion. Since the early failure mechanism of the waste package does not depend on a bathtub duration, this combination of basic events is mutually exclusive. Therefore, the rule listed above removes the sequences containing this combination from all of the possible combinations generated by SAPHIRE. Similar rules to the one listed above are created and used by the SAPHIRE CGM to effect the removal of sequences with mutually exclusive combinations.

6.5 INFORMATION REQUIRED TO PERFORM ANALYSES USING THE CGM

Use of the CGM is illustrated by a demonstration analysis documented in Sections 6.5 through 6.7 of this report.

6.5.1 Steps Required for Analyses

The required steps to use the CGM for analysis are described in the following discussion. The CGM requires considerable information to be obtained and formulated in a manner that allows for its evaluation. All of the important steps required for evaluation are listed below along with the information on how to perform the steps. The steps discussed in the following paragraphs are independent of the waste form being analyzed.

Step 1. The first step is to generate all of the potential in-package critical configuration classes. Subsection 6.2.3 discusses all of the configuration classes for in-package criticality. For each configuration class, there are specific degradation sequences. The CGM event tree (Subsection 6.4.1) is used to obtain these specific degradation sequences for each configuration class as identified in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003). The CGM event tree not only generates the sequence of events required for the waste form to reach a specific configuration class, it also provides a time frame for the analysis. The end states in the analysis may be subdivided into major time intervals that are required for the evaluation. The time steps provided on the event tree are very important for the probabilistic calculation since they govern what the probability is for most of the degradation processes.

Step 2. For each waste form, all of the in-package critical configuration classes need to be evaluated. Therefore, the analyst starts with configuration IP-1a and works all the way through to IP-6a. For each configuration class there are two questions that need to be answered as either TRUE (i.e., yes) or FALSE (i.e., no). These questions are

(1) Can the waste form in the particular configuration class degrade?
(2) Does the configuration class have potential for becoming critical?

and can be answered using engineering judgment or simple calculations. If the answer to either question based on engineering judgment or simple calculations is FALSE, further evaluation of the waste form for that particular configuration class is not required. The engineering judgment or simple calculation requires documentation on why the waste form can not degrade according to the configuration class or the waste form does not have the potential of becoming critical. This process must also take into account each time step listed on the event tree since certain processes may or may not be able to occur within the period being evaluated.

Step 3. If the answer to both of the questions in Step 2 (i.e., waste form degradation and criticality potential) is TRUE, then an estimation of the probability of occurrence for the configuration class is performed. This estimated probability is tested against the probability screening criterion stated in Section 6. If the estimated probability is less than the criterion, then the analysis for the configuration class is complete at this point of the analysis and the analyst moves to Step 5.

If the estimated probability is greater than the criterion, the configuration class has potential for criticality and a more detailed analysis is required. A detailed criticality calculation is performed using the criticality model (BSC 2003a) with the waste form and waste package parameters from the configuration class to determine the k_{eff}. These waste form and waste package parameters have probabilities that are based on degradation and time and, if the k_{eff} goes above the critical limit, a more detailed probability calculation is performed for the configuration class to estimate the probability of criticality. However, if k_{eff} is less than the critical limit over the entire parameter range, then the configuration class can be screened from further consideration for this waste form.

Step 4. The detailed criticality probability calculation performed for the configuration class of interest uses the range of waste form and waste package parameters that caused k_{eff} to be greater than the critical limit. In order to perform the probability calculation, the probability density functions such as listed in Section 6.6 for the waste form and waste package are extracted. The only probability density functions extracted in Section 6.6 are those specific to the configuration class being analyzed. The probability calculation takes into account the time after waste package emplacement as noted on the event tree and the probability that the waste form and waste package take on the parameters required for criticality. The calculated probability is added to the probability of the other configuration classes to obtain an overall probability of criticality for the waste form. Note: Probability values for configuration classes are additive since the classes are mutually exclusive.

Step 5. All of the configuration classes need to be evaluated; therefore, the next configuration class (i.e., IP-1b) needs to be evaluated for the same waste form. Steps 1 through 4 are performed until all of the configuration classes generated by the event tree have been analyzed. Once all of the configuration classes have been analyzed, the probabilities from individual configuration classes are then summed together to obtain an overall probability of criticality for the waste form. This overall probability determines if consequence analyses need to be performed. If the total probability of all configuration classes is less than a defined screening probability, e.g., a factor of ten lower than the 10 CFR Part 63 criterion, then no further analysis is required. However, if the total probability of all configuration classes is greater than the defined screening probability, then consequence analyses are required for all configuration classes that contribute to the overall probability (i.e., non-zero probability configuration classes).

6.5.2 Analysis Input Data and Parameters

The parameters that are required as input to analyses using the CGM consist of waste package design parameters, generic degradation scenarios, and parameters that characterize the emplacement drift environment. The waste form parameters are dependent upon the particular waste form being analyzed. These input parameters are used for two separate but joint evaluations: (1) to determine the potential for criticality, and (2) to determine the probability of those configuration parameters that have the potential for causing criticality.

Input data used for the demonstration analysis discussed in this report were obtained from the then current information available. This included information from License Application analysis and model reports as available; otherwise, information was obtained from the Site Recommendation analysis and model reports. The analysis documented in this report is a demonstration of the CGM and it is not anticipated that any impact of superceded data on this analysis will be evaluated.

Input to a CGM analysis consists of generic parameters identified by Event Tree Top Events that characterize the degradation sequences applicable multiple waste forms. These input parameters and information sources are listed in Table 6-4. While the input abstractions and sources provided with this CGM demonstration analysis are applicable generally to analyses with the CGM, alternate and/or updated abstractions can replace those provided in this report.

Table 6-4. Top Event and Configuration Class Input Sources

Scenarios and Top Events	Input	Reference Document	Section
Sufficient water reaches drift MS-IC-1	Seepage fraction	*Total System Performance Assessment (TSPA) Model for Site Recommendation* (CRWMS M&O 2000a); *Abstraction of Drift Seepage* (CRWMS M&O 2001a)	6.6.3
	Seepage flux rate		
Water drips on waste packages MS-IC-2	Evaporative flux from the invert	*Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000b); *Abstraction of NFE Drift Thermodynamic Environment and Percolation Flux* (CRWMS M&O 2001b)	
	Drip shield penetration due to general corrosion	*WAPDEG Analysis of Waste Package and Drip Shield Degradation* (CRWMS M&O 2000c); DTN: MO0010MWDWAP01.009	6.6.3
	Drip shield early failure	*Analysis of Mechanisms for Early Waste Package Failure* (CRWMS M&O 2000d)	
	Rockfall on drip shield	*Analysis of Preclosure Design Basis Rock Fall onto Waste Package* (BSC 2001a); *Rock Fall on Drip Shield* (CRWMS M&O 2000e)	
	Seepage flux location conceptualization	*EBS Radionuclide Transport Abstraction* (BSC 2001b)	
	Waste package first stress corrosion crack penetration	*WAPDEG Analysis of Waste Package and Drip Shield Degradation* (CRWMS M&O 2000c); DTN: MO0010MWDWAP01.009	
Waste package barrier penetration MS-IC-3	Waste package first general corrosion patch penetration	*FY01 Supplemental Science and Performance Analyses, Volume 1: Scientific Bases and Analyses* (BSC 2001c)	6.6.5
	Waste package juvenile failure		
	WAPDEG[a] first time top and first time bottom breach	*WAPDEG Analysis of Waste Package and Drip Shield Degradation* (CRWMS M&O 2000c); DTN: MO0010MWDWAP01.009; *WAPDEG and Analysis of Bathtub Delays Using the WAPDEG Output Data* (Case 2001)	

Table 6-4. Scenario and Configuration Class Input Sources (Continued)

Scenarios and Top Events	Input	Reference Document	Section
Water accumulation in waste package MS-IC-4	Waste package water evaporation	*Water Pooling-Evaporation in a Waste Package* (CRWMS M&O 2000f)	6.6.6
	Waste package bottom breaches before top or sometime after top creating a flow through process.	*WAPDEG Analysis of Waste Package and Drip Shield Degradation* (CRWMS M&O 2000c); DTN: MO0010MWDWAP01.009	
Waste package bottom breaches allowing liquid to flow through MS-IC-28	Waste package internal component materials and characteristics	*Design Analysis for UCF Waste Packages* (CRWMS M&O 2000g)	6.6.7
Degradation process of waste package internals i.e., Waste form degrades faster than waste package internals MS-IC-6 MS-IC-29 Waste form degrades the same as waste package internals MS-IC-7 MS-IC-30 Waste form degrades slower than waste package internals MS-IC-8 MS-IC-31	CSNF grouping based on cladding material	*Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000b)	6.6.8
	Degradation processes for waste forms (CSNF, DOE-owned spent nuclear fuel, and HLW)	*Waste Form Degradation Process Model Report* (CRWMS M&O 2000h)	
	Degradation processes for DOE waste form and HLW glass	*Generic Degradation Scenario and Configuration Analysis for DOE Codisposal Waste Package* (CRWMS M&O 1999a); *Generic Degraded Configuration Probability Analysis for DOE Codisposal Waste Package* (BSC 2001d)	
	Waste form degradation rate	*Waste Form Degradation Process Model Report* (CRWMS M&O 2000h)	
Waste form degrades in place MS-IC-9	Carbon steel corrosion rate distribution function	(DTN: MO0303SPAMCRAQ.000)[c]	6.6.9
Waste package internal structure degrades MS-IC-10 MS-IC-33	Stainless steel 304 corrosion rate distribution function	(DTN: MO0303SPAMCRAQ.000)	6.6.10
	Neutronit A978 corrosion rate distribution function	(DTN: MO0303SPAMCRAQ.000)	
	Neutronit A978 corrosion rate distribution function	(DTN: MO0303SPAMCRAQ.000)	

Table 6-4. Scenario and Configuration Class Input Sources (Continued)

Scenarios and Top Events	Input	Reference Document	Section
Degradation of neutron absorber carrier MS-IC-10 MS-IC-33	Carbon steel corrosion rate distribution function	(DTN: MO0303SPAMCRAQ.000)	6.6.10
Degraded waste form and waste package collect at bottom of waste package MS-IC-11 MS-IC-20	Stainless steel 304L corrosion rate distribution function	(DTN: MO0303SPAMCRAQ.000)	6.6.11, 6.6.12, and 6.6.15
	Neutronit A978 corrosion rate distribution function		
	Degradation processes for waste forms (CSNF, DOE-owned spent nuclear fuel, and HLW)	*Waste Form Degradation Process Model Report* (CRWMS M&O 2000h)	
	Neutronit A978 corrosion rate versus carbon steel corrosion rate	(DTN: MO0303SPAMCRAQ.000)	
Significant neutron absorber degradation before structural collapse	Fraction of rods that have failed before emplacement	*Clad Degradation – Summary and Abstraction* (CRWMS M&O 2001c)	6.6.10 and 6.6.15
Waste form degrades mobilizing fissionable materials MS-IC-20	Fraction of rods failed from creep strain	*In-Package Chemistry for Waste Forms* (BSC 2001e)	6.6.11
	Fraction of rods failed from stress corrosion cracking (SCC)		
	Localized corrosion		
	Parameters that affect the removal rate for soluble absorber	*EQ6 Calculations for Chemical Degradation of PWR LEU and PWR MOX Spent Fuel Waste Packages* (CRWMS M&O 1998a)	
	Water mixing and solubility of waste form	*In-Package Chemistry for Waste Forms* (BSC 2001e); *EQ6 Calculations for Chemical Degradation of PWR LEU and PWR MOX Spent Fuel Waste Packages* (CRWMS M&O 1998a)	
Degraded waste form mobilized, separating from intact neutron absorber MS-IC-11	Parameters that affect the removal rate for soluble absorber	*EQ6 Calculations for Chemical Degradation of PWR LEU and PWR MOX Spent Fuel Waste Packages* (CRWMS M&O 1998a); *Geochemistry Model Abstraction and Sensitivity Studies for the 21 PWR CSNF Waste Packages* (BSC 2002b)	6.6.11
Soluble neutron absorber flushed from waste package MS-IC-14 MS-IC-18 MS-IC-19	Carbon steel corrosion rate distribution function	(DTN: MO0303SPAMCRAQ.000)	6.6.13

Table 6-4. Scenario and Configuration Class Input Sources (Continued)

Scenarios and Top Events	Input	Reference Document	Section
Degradation of basket structural support (mechanically collapses) MS-IC-16 MS-IC-23	Parameters affecting waste form final condition	*No available information at this time. This parameter is contained here as a placeholder and is not used in this report.*[b]	6.6.14
Waste form degradation products hydrate in initial location MS-IC-32	Parameters affecting waste form final condition, solubility	*No available information at this time. This parameter is contained here as a placeholder and is not used in this report.*[b]	6.6.16
Degraded waste form is mobilized, separating from neutron absorbers and hydrating MS-IC-34 MS-IC-39	Parameters affecting solubility, chemical reactions	*No available information at this time. This parameter is contained here as a placeholder and is not used in this report.*[b]	6.6.17
Hydrated waste form and internal component degradation products collect in bottom of waste package MS-IC-35	Parameters affecting solubility of neutron absorber	*EQ6 Calculations for Chemical Degradation of PWR LEU and PWR MOX Spent Fuel Waste Packages* (CRWMS M&O 1998a); *Geochemistry Model Abstraction and Sensitivity Studies for the 21 PWR CSNF Waste Packages* (BSC 2002b)	6.6.18
Flow-through flushing removes soluble neutron absorbers MS-IC-36 MS-IC-38	Parameters affecting waste form final condition, solubility, chemical reactions	*No available information at this time. This parameter is contained here as a placeholder and is not used in this report.*[b]	6.6.19
Intact waste form settles in bottom of waste package, mixed with hydrated corrosion products from waste package internal components MS-IC-37	Frequencies and consequences of disruptive events	*Features, Events, and Processes: Disruptive Events* (CRWMS M&O 2000i); *Characterize Framework for Seismicity and Structural Deformation at Yucca Mountain, Nevada* (CRWMS M&O 2000j); DTN: SN0006T0502900.002	6.6.20
Disruptive events	Probability of fuel misload	*Waste Package Misload Probability* (BSC 2001f)	6.6.21
Fuel misload	Probability of fuel misload	*Waste Package Misload Probability* (BSC 2001f)	6.6.22

NOTES: [a] WAste Package DEGradation.

[b] These parameters are not used in the demonstration analysis documented in this report, but when they are required as input to CGM analyses, geochemistry calculations will be necessary along with abstractions of related analysis and model reports to acquire these parameters.

[c] DTN: MO0303SPAMCRAQ.000 supercedes DTN: MO0211SPASDR01.004 that was used for generating the steel corrosion rate probability functions. An impact analysis determined that there was no effect on results from this model report due to the revised data set.

6.6 CONFIGURATION PARAMETERS FOR WASTE FORM AND WASTE PACKAGE

6.6.1 Assumptions for Parameter Development

Fault tree inputs to the CGM top events that are configuration parameters as discussed in Subsection 6.5.2. Several of simplifying assumptions, listed in this subsection, have been utilized in developing the probability functions and values for these parameters for use in the demonstration analysis (Section 6.7). The bases for these assumptions are experimental measurements, calculations, or conservatism.

6.6.1.1 Seepage Flow Into Drifts

Assumption: It is assumed that the seepage flow into drifts falls from a point source located at the crown of the drift.

Rational: The bases for this assumption are: (1) the experimental data from the ATLAS Test Facility that have shown that drips occur preferentially from the region of the crown (BSC 2001b, p. 24) and (2) the conservatism that results from this assumption.

Confirmation Status: No further confirmation is required for this assumption.

Use in the Analysis: The assumption results in the entire seepage flux dripping on waste packages provided the axial locations of seepage and drip shield penetrations coincide. The higher seepage flux rates resulting from this assumption are more effective in flooding the waste package cavity and removing soluble absorbers, which increase the chance of criticality. This assumption is used in Subsections 6.6.4.1 and 6.6.6.1.

6.6.1.2 Evaporative Flow Rate

Assumption: It is assumed that the evaporative flow rate from a 21-PWR with Absorber Plates Waste Package, $Q_{evaporate}$, in cubic meters per year, can be expressed as a function of waste package heat generation rate and time from emplacement, t, in years, as shown in Equation 7.

$$Q_{evaporate} = 2.4224\times10^{+4} \times t^{-1.5752} \qquad \text{(Eq. 7)}$$

Rational: The bases for this assumption are the results of calculations for the evaporation rate in a waste package based upon median CSNF thermal loading (CRWMS M&O 2000f, Figure 9). Equation 7 was derived for evaporation internal to a breached waste package. Other thermal loading percentiles were represented by similar functional relationships. Effects of adjacent waste packages were included implicitly through the repository temperature history without explicitly considering thermal interactions with the adjacent waste packages.

Confirmation Status: No further confirmation is required for this assumption.

Use in the Analysis: This relationship has been obtained using the repository thermal loading and waste package surface temperature time histories from the Viability Assessment studies of CSNF. It is anticipated, although not demonstrated, that a similar relationship will apply to evaporation rates based upon the CSNF design-basis repository thermal loading. This assumption is used in Subsections 6.6.4.2, 6.6.6.3 and 6.7.2.6.1.

6.6.1.3 Water Accumulation in the Waste Package

Assumption: It is assumed that the void space available for water accumulation inside a degraded 21-PWR with Absorber Plates Waste Package decreases linearly with time.

Rational: The basis for this assumption is the calculations for chemical degradation of a 21-PWR with Absorber Plates Waste Package (CRWMS M&O 1998a, Figure 5.3.1-1). This calculation shows that the volume occupied by insoluble products increases linearly with time for given values of water influx rates and material corrosion rates. Figure 5.3.1-1 (CRWMS M&O 1998a) is based on the degradation of the basket material only. Therefore, all waste packages that are expected to be constructed with this basket structure material can use this assumption. This variation with time results from a constant surface area for corrosion and a rate that is not diffusion limited.

Confirmation Status: No further confirmation is required for this assumption.

Use in the Analysis: This assumption is used in Subsection 6.6.6.4.

6.6.1.4 Corrosion Rate of Neutronit A978

Assumption: It is assumed that the corrosion rate of Neutronit A978 is 2.5 times the rate of Stainless Steel Type 316.

Rational: The basis for this assumption is from *Probability of PWR UCF WP Postclosure Criticality for Enhanced Design Alternatives* (CRWMS M&O 1999b, Sections 3.4 and 5.1.4) and manufacturer's data. That latter report indicates that, while the chemical performance of Neutronit A978 has not been evaluated for conditions relevant to the repository, data indicate that the degradation rate of stainless steel increases with increasing boron content. The manufacturer's information (Kügler 1997), while not providing values, states that although the corrosion resistance of Neutronit A976 is satisfactory, it is diminished somewhat from expectations but still similar to the resistance of Stainless Steel Type 321. In addition, Kügler (1997) states that Neutronit A978, which contains molybdenum, has more corrosion resistance than Neutronit A976. Thus, the available information indicates that the degradation rate of Neutronit A978 is likely to be somewhat greater than, but within an order of magnitude of, stainless steel degradation rates.

The composition of Stainless Steel Type 321 is very similar to Stainless Steel Type 316 (ASTM A 240/A 240M-02a, 2002, Table 1) which implies that both stainless steel types have a similar response to corrosion attack. The 2.5 multiplier of the Stainless Steel Type 316 as an estimator for the Neutronit A978 corrosion rate is reasonable, providing an enhanced boron loss rate from the waste package while remaining within the range of the stainless steel corrosion rate data (DTN: MO0303SPAMCRAQ.000).

Confirmation Status: No further confirmation is required for this assumption.

Use in the Analysis: This assumption is used in Subsections 6.6.10.2 and 6.7.2.6.1.

The following standard was used as collaborating information in support of the Neutronit A978 degradation rate:

> ASTM A 240/A 240M-02a 2002. *Standard Specification for Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels and for General Applications.*

6.6.1.5 Ingress of Water Into Waste Packages

Assumption: It is assumed that the ingress rate of water into a waste package is the same as the seepage rate through the drip shield breaches.

Rational: The basis for this assumption is that it is conservative, maximizing the quantity of water available for internal waste package degradation and neutron moderation.

Confirmation Status: No further confirmation is required for this assumption.

Use in the Analysis: This assumption is used in Subsections 6.6.6, 6.6.7, and 6.6.13.

6.6.1.6 Creation of an Advective Pathway

Assumption: It is assumed that cracks in the drip shield generated by rockfall will create an advective pathway allowing seepage to flow through the drip shield.

Rational: The basis for this assumption is that it is conservative, maximizing the number of available pathways for water to contact waste packages.

Confirmation Status: No further confirmation is required for this assumption.

Use in the Analysis: This assumption is used in Subsections 6.6.4.1 and 6.7.2.6.2.

6.6.1.7 First Breaches of the Drip Shield

Assumption: It is assumed that the first breaches of the drip shield and waste package occur on co-located units.

Rational: The basis for this assumption is that it is conservative because it increases the probability of water entering the waste package.

Confirmation Status: No further confirmation is required for this assumption.

Use in the Analysis: The probability of a breach in these units obtained from WAPDEG analyses is not individualized but averaged over the WAPDEG analysis suite. This assumption is used in Subsections 6.6.4.1, 6.6.5, and 6.6.7.

6.6.1.8 Gap Between Drip Shields

Assumption: The gap between two drip shields caused by any drip shield emplacement error is assumed to be 30 cm.

Rational: This assumed gap is created when operators are installing the drip shields and fail to correctly emplace one drip shield over a previously installed drip shield. In order for advective flow to occur through the drip shield, there must be a reasonably sized pathway (on the order of waste package patch sizes). This pathway was assumed to be one-half the overlap between two drip shields which is 595 mm (CRWMS M&O 2000k, Attachment II). The gap between the two drip shields was rounded to 30 cm. The basis for this assumption is that it provides a bounding gap size. A 30-cm gap is sufficiently large to allow advective flow onto the waste package without additional assumptions concerning the gap size distribution.

Confirmation Status: No further confirmation is required for this assumption.

Use in the Analysis: This assumption is used in Subsections 6.6.4.1 and 6.7.2.6.2.

6.6.1.9 Size of Gap Created by Stress Corrosion Cracking

Assumption: It is assumed that the gap size created in the waste package caused by corrosion is correlated with the length of a stress corrosion crack (BSC 2001b, pp. 51 to 54 for idealized relationship). The gap is required in order to allow advective flow to penetrate the waste package.

Rational: The basis for this assumption is that it is conservative since the total length of the gap is available for advective flow to penetrate the waste package.

Confirmation Status: No further confirmation is required for this assumption.

Use in the Analysis: This assumption is used in Subsection 6.7.2.6.3.

6.6.2 Configuration Parameter Development

This subsection presents a discussion of the configuration parameters identified as top events in the event tree leading to potential critical configurations. These parameters are associated with degradation sequences that have been identified in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Section 3.3). Many of the parameters input to an analysis using the CGM are generic to all waste package/waste form combinations and the process is generally applicable to all such combinations. The parameters that characterize these configuration classes, particularly those associated with potentially critical configuration classes are also presented in the following subsections. These parameters consist of (1) a set of independent variables and (2) a set of functional relationships abstracted, in part, from established models. The independent variables have associated probability distributions that are discussed. The uncertainty associated with these probability distributions is normally characterized by bounding distributions and can be incorporated into analyses through sensitivity evaluations. Correlations, on the other hand, may be in a functional or tabular form with associated uncertainties that can be quantified. The waste form specific information addressed in Section 6.2 is combined with information in the following subsections, which provide guidance on the specific information required for all of the top events on the event tree in order to perform the probability analysis, given that the waste form became critical. This latter subsection defines all of the top events along with the parameters required for an evaluation.

The top event fault tree inputs that are required for a probability evaluation of critical configurations are discussed in the following subsections. The discussion includes formulation of the probability density functions required for probabilistic evaluations. The density functions are abstracted from TSPA-SR information or formulated based on data obtained from other sources. While these configuration parameters are considered valid for analyses using the CGM, they can be updated or replaced with revised information as available (Subsection 6.5.2).

6.6.3 Sufficient Water Reaches Drift

Water reaching the drift is an important factor in waste package degradation and criticality and is associated with top event MS-IC-1 of the CGM event tree (Figure I-2) and its associated fault tree inputs (Figure II-1). Processes that determine the location and quantity of water entering the drift are infiltration, seepage, and flow focusing. These processes are independent of both the waste form and waste package. The temperature effects of decay heat generated by the different waste forms are accounted for in Subsections 6.6.4.2 and 6.6.6.3. Therefore, abstractions related to these processes can be used for all waste forms being analyzed. The cumulative distribution function for the seepage rate developed in this subsection is applicable for all of the configuration classes. However, the probability values assigned to various classes will differ since the values are determined from the requirement that seepage rates be sufficient to permit the particular configuration class to develop within a specified time.

Net infiltration is the amount of water that has penetrated through the ground surface to a depth where it can no longer be withdrawn by evaporation or transpiration by plants. Three climate states spanning 10,000 years were considered in the TSPA-SR labeled as “Present Day,” “Monsoonal,” and “Glacial-Transition.” The duration of the first two states together span 2000 years and the “Glacial-Transition” state spans the remaining years of the simulation (≥10,000 years) (CRWMS M&O 2000a, pp. 118 and 119). Three infiltration scenarios were considered in the TSPA for each of the climate states, termed low-, medium-, and high-infiltration cases, with probabilities of occurrence, 0.17, 0.48, and 0.35, respectively (CRWMS M&O 2000a, Table 6-2).

Flow focusing accounts for the heterogeneous nature of the flow paths that channel flow into discrete fractures or fracture sets. It may result in higher percolation fluxes (percolation refers to the flow of liquid water through the unsaturated zone) in some locations, thereby increasing the local percolation flux in those areas.

Previous TSPA analyses have shown that water does not impinge on all waste package locations in the repository since the fracture network provides a channeling and focusing mechanism for the seepage flux. Seepage into emplacement drifts is characterized by a seepage fraction, SF_D, and a seepage flux rate, Q_{seep}, both of which have temporal and spatial variations. The seepage fraction is defined as the fraction of waste package locations that have seepage, while the seepage flux rate is the volumetric flow rate of seepage in a drift segment. The seepage flux rate is a variable on which parameters that are associated with potential critical configurations depend. Some examples of critical configuration parameters are water volume, hydration, and the quantity of soluble absorber inside a waste package.

Temporal and spatial variations of seepage fractions and seepage flow rates are considered in the stochastic simulations of engineered and geologic processes in a repository at Yucca Mountain using GoldSim (GoldSim V6.04.007, STN: 10344-6.04.007-00). Climate, infiltration, mountain-scale unsaturated zone flow, and seepage into emplacement drifts are the component models that provide the unsaturated zone flow results. The implementation of component models in the Performance Assessment Model is described in *Total System Performance Assessment (TSPA) Model for Site Recommendation* (CRWMS M&O 2000a, Subsection 6.3.1) and *FY01 Supplemental Science and Performance Analyses, Volume 1: Scientific Bases and Analyses* (BSC 2001c, Section 4), and is summarized in the following paragraphs.

Seepage is a random process that can be treated probabilistically (CRWMS M&O 2001a, Section 5). The seepage fraction and seepage flux rate probability functions, F_{SF_D} and $F_{Q_{seep}}$, respectively, can be extracted from the TSPA model (CRWMS M&O 2001a, Section 6.5). These functions depend on the three climatic regimes (CRWMS M&O 2000b, p. 3-29) identified according to infiltration rate as Modern (low), Monsoon (medium), and Glacial-Transition (high). A flow-focusing factor having a log-uniform distribution is used to scale the percolation (infiltration) flux and seepage fraction. A triangle distribution is used for the seepage uncertainty probability and a Beta distribution for the seepage rate probability. The cumulative distribution function (probability that the value is less than a specified value) for the glacial transition infiltration flux is shown in Figure 6-5 as an example of the seepage abstraction. The corresponding cumulative distribution functions for the seepage fraction and seepage rate are shown in Figures 6-6 and 6-7, respectively. The complete seepage abstraction is documented in Attachment IV.

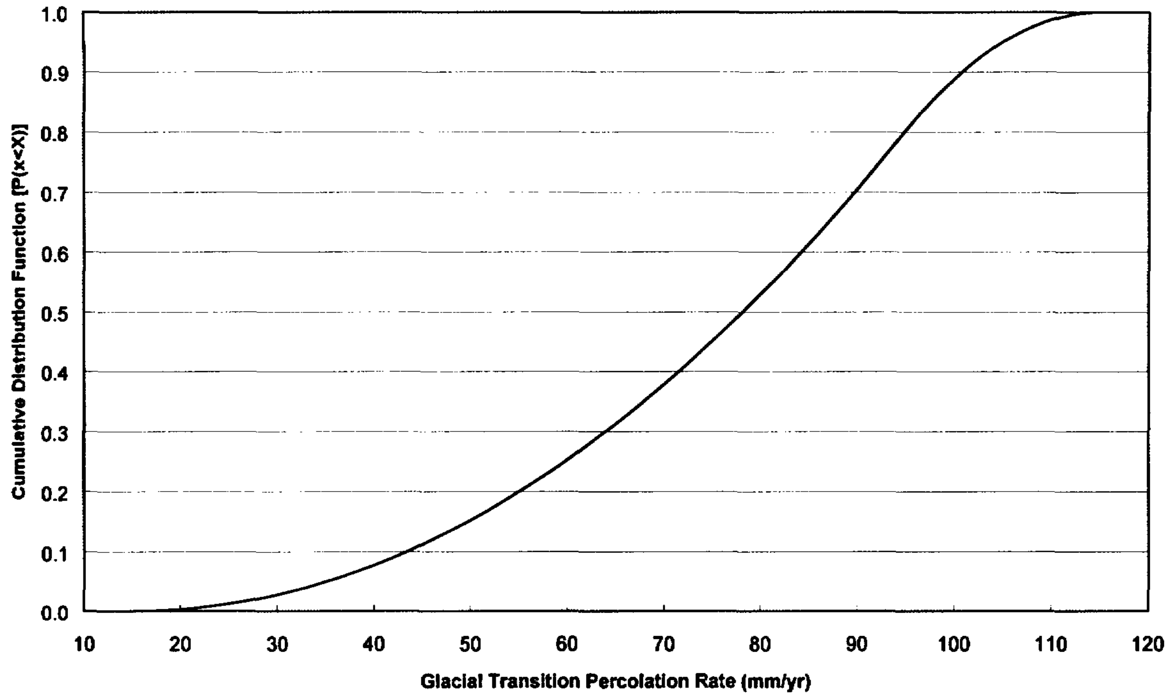


Figure 6-5. Cumulative Distribution Function for Percolation Flux During Glacial Transition Climate

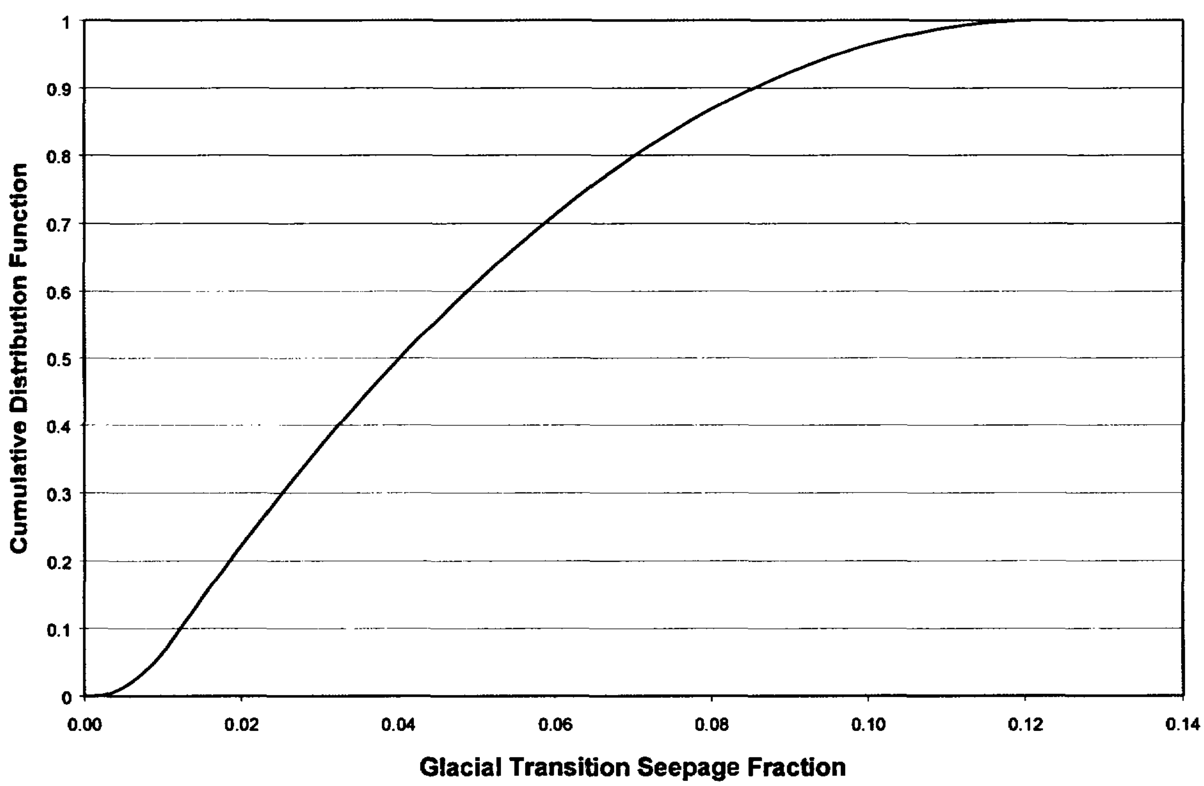


Figure 6-6. Cumulative Distribution Function for Seepage Fraction During Glacial Transition Climate

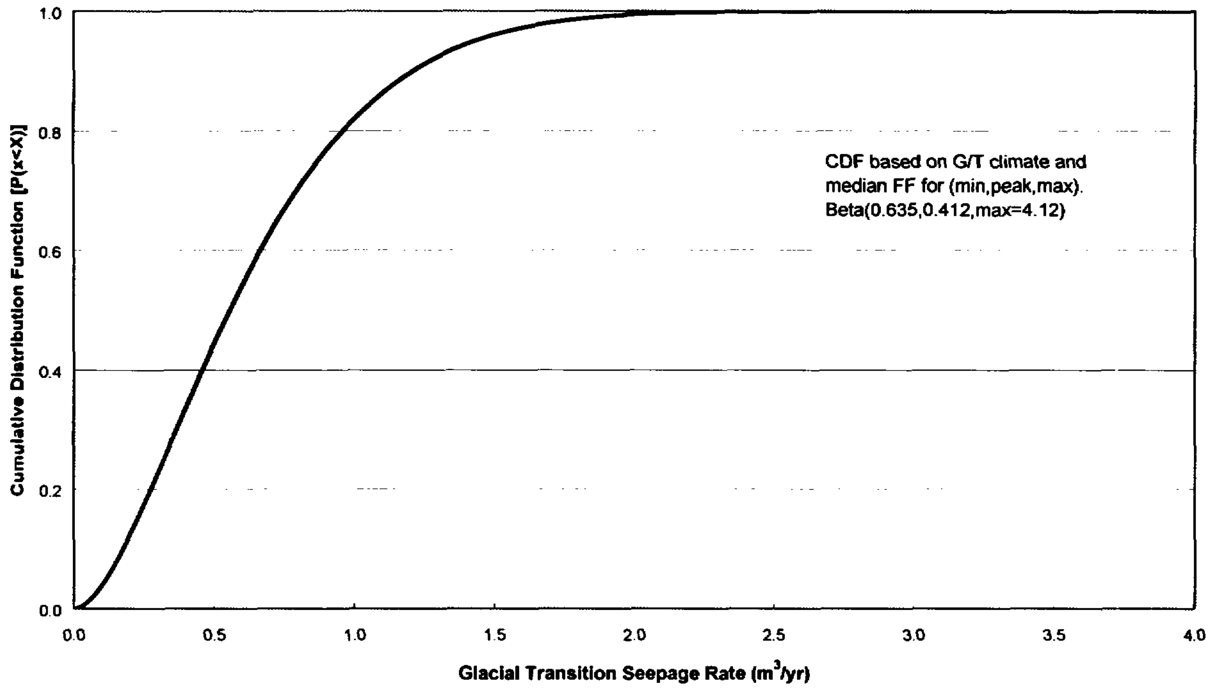


Figure 6-7. Cumulative Distribution Function for Seepage Rate During Glacial Transition Climate

6.6.4 Water Drips on Waste Packages

Water dripping on the waste package is associated with top event MS-IC-2 of the CGM event tree (Figure I-2) and its associated fault tree inputs (Figure II-2). Water can reach the waste packages along two primary pathways (i.e., water dripping from the drift crown through the drip shield and water dripping from the drip shield due to evaporative/condensation). The first pathway can occur if the drip shield fails to divert dripping water from the drift crown because of drip shield failure. The second pathway can occur if water vapor condenses on the underside of the drip shield. Both of these pathways are discussed in the following subsection. This parameter is independent of both the waste form and waste package; therefore, it can be used for analyses of all waste form and waste package combinations.

6.6.4.1 Seepage Flow through Drip Shield

The water-flow through the drip shield is dependent upon the presence of pathways (holes). These pathways can be created by corrosion and/or gaps caused by the drip shield response to events such as seismic activity and emplacement errors (Figure II-2). WAPDEG calculations concerning general corrosion (discussed in Subsection 6.6.5) provide information about patches created in the drip shield due to general corrosion. The WAPDEG output provides, among other things, cumulative probability curves for drip shield failures due to general corrosion as a function of time. Localized corrosion (pitting and crevice corrosion) of the drip shield was not modeled in the WAPDEG analysis. The probability data for drip shield failure due to alignment gaps are obtained from seismic and loading error analyses.

The possible mechanisms that can create advective pathways and allow water seepage through the drip shield are the various types of corrosion listed in Table 6-3 categorized as either static or time-dependent failure mechanisms. These mechanisms are captured in the fault tree evaluations for the drip shield failure modes (Figure II-2). Each of these failure mechanisms may be in an active or inactive mode, subject to their availability in abstraction information and their likelihood of significantly effecting the criticality potential of the configuration classes. An example of the latter is stress corrosion cracks that may develop in weld areas. With the potential in-growth of corrosion products and the calcite deposition due to water evaporation, little, if any, water is expected to flow through stress corrosion cracks (CRWMS M&O 2000m, Subsection 6.5.5; BSC 2001g, Subsection 6.4.8). However, it is assumed for conservatism that any stress corrosion crack penetrations due to a rockfall will generate an advective pathway for water through drip shield (Assumption 6.6.1.6).

The identified drip shield static failures for this report are emplacement errors, fabrication errors (BSC 2003b, Section 6), thermal expansion, seismic response, rock fall, and floor heave (BSC 2001b, Subsection 6.1.3). These failure mechanisms are classified as independent of time since they can occur randomly from initial emplacement (Figure II-2). In certain cases (fabrication errors and rock fall) the failure mechanism is an initiator that exacerbates corrosive action that is a time dependent mechanism. An emplacement error is assumed to form a gap between adjacent drip shield sections (Assumption 6.6.1.8) allowing dripping water to contact the waste package as soon as seepage occurs at that location. For this demonstration analysis, the only drip shield failure mechanisms activated are emplacement errors, rock fall, and general corrosion.

For the current repository design (no backfill), a source of water flow onto the drip shield is the seepage flux that drips from the crown of the emplacement drift assumed to originate from a point source (Assumption 6.6.1.1). It is highly unlikely that a vertical plane exists that intersects the apex point loci of both the emplacement drift and drip shield since it would require an exact positioning of the drip shield relative to the emplacement drift. Therefore, the dripping water from the region of the crown most likely forms a film on either the left or the right section of the drip shield top. Thus, for coincident axial locations of the seepage and barrier penetration, part of the film of water that forms on the surface of the drip shield flows through the penetrations.

Consider a drip shield patch whose center coordinates are x_i and φ_i, as shown in Figure 6-8. The maximum number of patches per drip shield (considered as complete degradation) is 500 in the WAPDEG analysis (CRWMS M&O 2000c, p. 36) where the patch area is given as 7.214×10^4 mm^2.

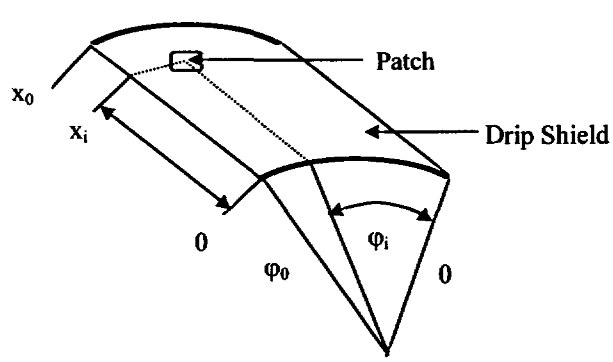


Figure 6-8. Axial and Radial Coordinates of a Drip Shield Patch

This patch area is calculated by dividing the total surface area of a drip shield by the total number of patches (i.e., drip shield patch area = 3.607×10^7 mm^2 (drip shield surface area)/500 patches = 7.214×10^4 mm^2). The location of patches on the surface of a drip shield is modeled as a uniform distribution because a number of uncorrelated mechanisms can cause patch formation. Patches from general corrosion can result from other situations besides dripping water such as aqueous films. Secondly, seepage may be intermittent and/or be repositioned from the original location. Rockfall on the drip shield can also cause patch failure through SCC action in the high stress area of the impact region. Allowance for the distribution of possible patch initiators results in a random alignment between a seepage location and a potential advective flow path. Thus, the probabilities of axial and azimuthal patch coordinates are independent. The maximum number of patches in the axial direction is L_{DS}/L_{DS_Patch}, where L_{DS} is the length of the drip shield section and L_{DS_Patch} is the patch length or diameter. [The maximum number of patches in the azimuthal direction, φ, for any x where ($0 \le x \le \varphi_0$), is $500 \cdot L_{DS\_Patch}/L_{DS}$]. The probability that the location of dripping water and one axial penetration opening coincide is the ratio of the patch length to the drip shield length (Assumption 6.6.1.7). Likewise, the probability that the location of the water drip and the azimuthal location of the penetration opening coincide is the ratio of the patch length to the drip shield arc length. Thus, the total probability that a drip location coincides with a patch is given by the product of these probabilities shown in Equation 8.

$$P\{Drip\ location \equiv DS\ \ patch\ location\} = \frac{L_{DS\_Patch}}{L_{DS}} * \frac{L_{DS\_Patch}}{\varphi_0\ R} \qquad \text{(Eq. 8)}$$

where R is the effective drip shield radius and $\varphi_0 \times R$ is the drip shield arc length accessible to water drips.

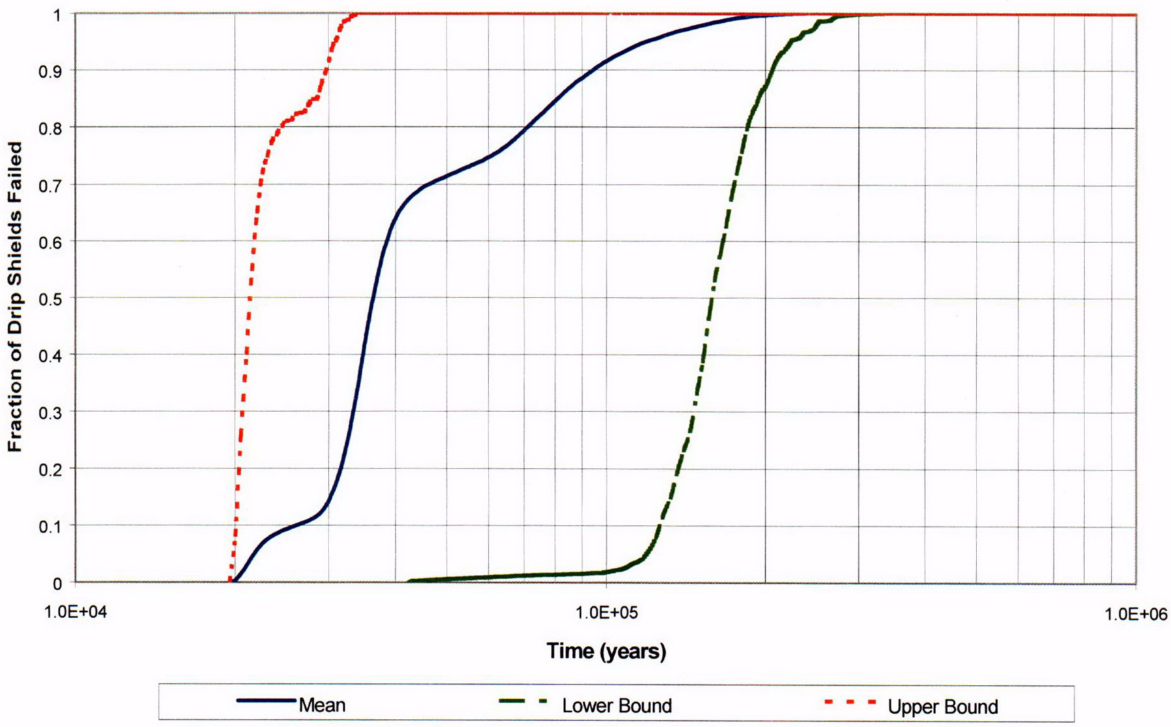
Applying the logic discussed previously (i.e., that a water drip from the drift crown that is axially but not azimuthally coincident with a patch will form a film on the drip shield surface and flow into the patch penetration), the second term in Equation 8 reduces to 0.5 since a water drip is equally likely to occur on either side of the drip shield crown.

To calculate the probability that water can penetrate the drip shield and impinge on the waste package, the term P_{FTDS} is defined as the ratio of drip shield penetration openings to the drip shield length [(BE-WP-DS-ALIGN, Figure II-4) Assumption 6.6.1.7]. The penetration openings, L_{DS_PO}, are defined as all penetration openings (i.e., emplacement gap and advective gap caused by rockfall) in the drip shield. The total probability of all gaps that can lead to seepage flux impinging on the waste package is defined by Equation 9.

$$P_{FTDS} = \frac{L_{DS\_PO}}{L_{DS}} + \frac{L_{DS\_Patch}}{L_{DS}} \qquad \text{(Eq. 9)}$$

The probability of occurrence for the failure mechanisms is used in the probabilistic analysis. An example of such "probability of occurrence" for one of the failure mechanisms (i.e., the drip shield emplacement error probability) was determined to be 9.0×10^{-5} (CRWMS M&O 2000d,

p. 62)[4]. Another example of "probability of occurrence" is the probability of drip shield failure due to general corrosion as shown in Figure 6-9. Figure 6-10 shows the number of patch failures per failed drip shield. Data for Figures 6-9 and 6-10 are listed in the spreadsheets "DSFail.xls" and "DSAvgPat.xls" (Attachment XII), respectively. All of these failure mechanisms are mutually independent; therefore, their probabilities can be added together.

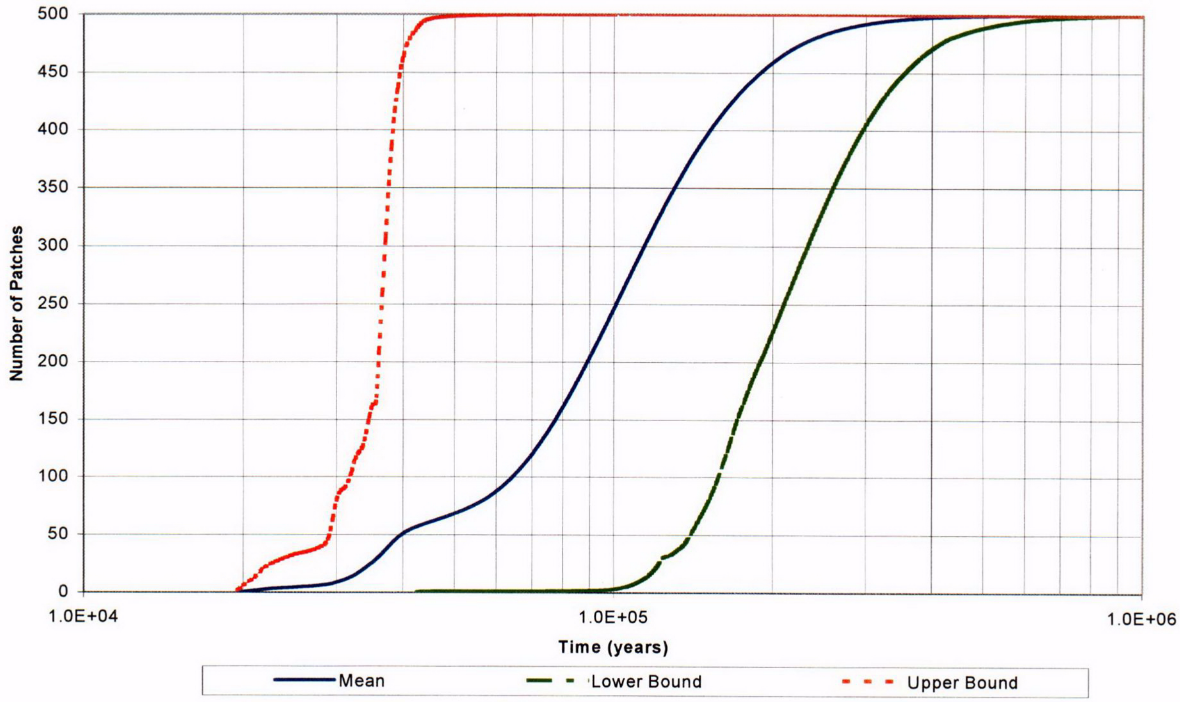


Source: CRWMS M&O 2000c, Figure 19

Figure 6-9. Cumulative Distribution Function for First Patch Failure in Drip Shield

[4] A re-evaluation of the probability of drip shield emplacement errors in *Analysis of Mechanisms for Early Waste Package/Drip Shield Failure* (BSC 2003b) concluded that the possibility of such errors leaving sufficiently large gaps between drip shield segments to admit advective flow is not credible. This affects the first term in Equation 9 which impacts the evaluation of the minimum seepage flux required to realize configuration classes. The likely net effect of eliminating the contribution of drip shield emplacement errors to the scenario evaluation is a reduction in the probability of achieving the end state of the configuration classes.

C05



Source: CRWMS M&O 2000c, Figure 20

Figure 6-10. Cumulative Distribution Function for Number of Patch Failures in Drip Shield

6.6.4.2 Condensation from the Invert

An evaporation and condensation process under the drip shield is another pathway that would potentially enable water to impinge on the waste package provided the drip shield temperature is below the invert temperature (CRWMS M&O 2000b, p. 3-136). Condensation under the drip shield can occur as a result of water vapor in the invert evaporating due to the thermal output of the waste package and moving upward towards the drip shield. As the water vapor moves away from the heat source (i.e., thermal output from waste package), condensation may start on the under surface of the drip shield depending upon the relative humidity and temperature gradient.

To model the evaporation/condensation process in the CGM, the conceptual model discussed in *Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000b, p. 3-136) is used. The TSPA model assumes that if condensation can occur, the water flux due to condensation is equal to the evaporation rate. The TSPA model also assumes that the resulting water flux drips onto the waste package. The abstracted evaporative flux rate, discussed in *Abstraction of NFE Drift Thermodynamic Environment and Percolation Flux* (CRWMS M&O 2001b, Subsection 6.3.6), is used to determine the water flux due to evaporation. The average flux for the invert near a CSNF waste package is shown in Figure 6-11 and is based upon the mean infiltration map and the TSPA-SR base case (CRWMS M&O 2001b, Section 6.3). After 10,000 years, the evaporation rates have all dropped to below 0.00146 1m^3/year/m-drift (4 ml/day/m-drift). The averaged drip shield temperatures from the abstraction were very similar to the averaged invert temperatures making it unlikely that water evaporated from the invert re-condenses at the peak of the drip shield underside. This water flux calculated using the evaporation from Equation 7 (Assumption 6.6.1.2) is conservatively added to the

COC

seepage flux discussed in Subsection 6.6.3 in order to obtain the total amount of water that may be available to flow into the waste package.

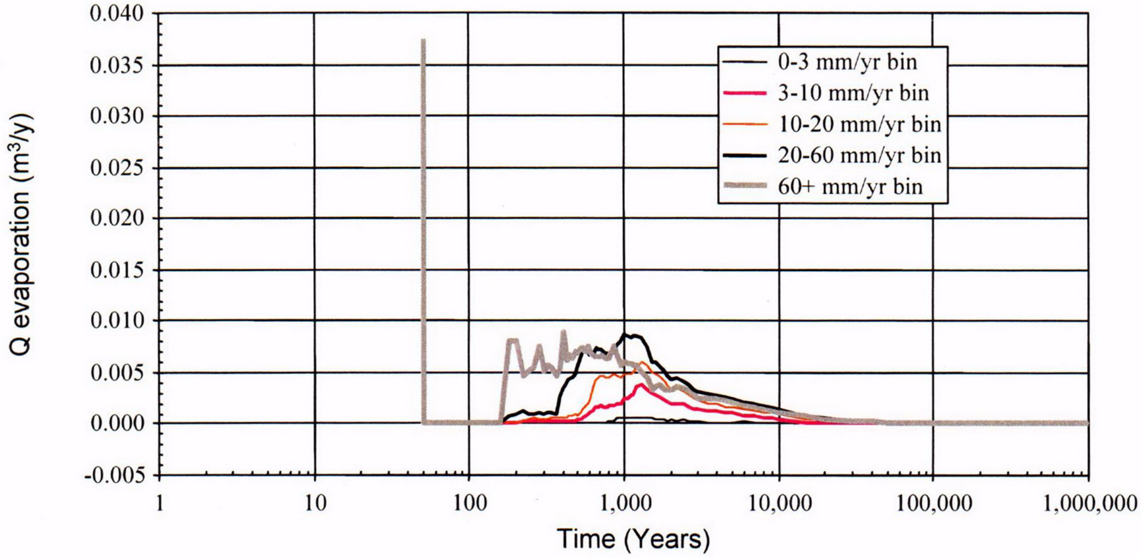


Figure 6-11. Average Evaporation Rate from the Invert Near a CSNF Waste Package

6.6.5 Waste Package Penetration

Waste package penetration is associated with top event MS-IC-3 of the CGM event tree (Figure I-2) and its associated fault tree inputs (Figure II-3). Waste package penetration is required in order for waste package internal components to start degrading. This parameter is independent of both waste form and waste package because all variants of the waste package design have the same outer barrier material; therefore, it can be used for all waste forms being analyzed.

The possible mechanisms that can create advective pathways and allow water seepage through the waste package outer barriers are the various types of corrosion listed in Table 6-3 categorized as either static or time-dependent failure mechanisms. These mechanisms are captured in the fault tree evaluations for the waste package failure modes (Figure II-3).

The identified waste package static failures for this report are fabrication errors (BSC 2003b, Section 6) and seismic response, rock fall, floor heave, and emplacement pallet failure (BSC 2001b, Subsection 6.1.3). These failure mechanisms are classified as independent of time since they can occur randomly from initial emplacement. In certain cases (fabrication errors and rock fall), the failure mechanism is an initiator that exacerbates corrosive action that is a time dependent mechanism. For this demonstration analysis, the only waste package failure mechanisms activated are fabrication errors, rock fall, and general corrosion.

The WAPDEG analysis that determines the time to penetration and provides time dependent penetration (i.e., failure) curves for the waste package was used to generate waste package penetration probabilities in *Total System Performance Assessment (TSPA) Model for Site Recommendation* (CRWMS M&O 2000a, Subsection 6.3.3). The WAPDEG analysis

C07

incorporates model abstractions for degradation processes of the waste package in the repository as well as the drift environment parameters used for the degradation processes. A description of the component models used in the WAPDEG analysis is provided in *WAPDEG Analysis of Waste Package and Drip Shield Degradation* (CRWMS M&O 2000c, Section 6.2). The corrosion models used in the WAPDEG analysis consider three types of penetration modes:

- Crack penetration by SCC (in the weld regions of Alloy 22 waste package outer barrier closure lid only)
- Pit penetration by pitting and crevice corrosion (localized corrosion)
- Large (or patch) opening by general corrosion.

The WAPDEG failure mechanism of localized corrosion is not considered possible in the TSPA-SR analyses under potential repository conditions (CRWMS M&O 2000b, p. 3-85), however the three types of failure modes are part of the WAPDEG analysis. The WAPDEG output provides the cumulative probability of failure by one of the three penetration modes as a function of time. However, penetrations of the waste package outer barrier due to localized corrosion or stress corrosion cracking are not expected to occur under repository conditions (CRWMS M&O 2000c, Section 7). Thus, only two of the various failure mechanisms allow sufficient water to penetrate the waste package to be of concern for criticality evaluations. These two failure mechanisms are early waste package failure due to improper heat treatment and general corrosion, modeled in the fault tree representing top event MS-IC-3. The time to waste package penetration due to general corrosion is uncertain because of variability in both the drift environment and waste package parameters. Both of these failure mechanisms (improper heat treatment and general corrosion) are discussed in this subsection.

The WAPDEG analysis is normally run until complete degradation of waste packages and drip shields occur. The WAPDEG analysis uses a maximum of 1000 patches per waste package to represent complete degradation of the waste package where the total patch area is 2.346×10^4 mm^2 (CRWMS M&O 2000c, p. 36). This patch area is likewise calculated by dividing the total surface area of the waste package by the total number of patches. The WAPDEG analysis also assumes that the waste package inner cylinder material does not delay the waste package barrier failure process (CRWMS M&O 2000c, p. 37).

Once the WAPDEG analysis is complete, a set of profiles for the failure (i.e., initial breach) and the subsequent number of penetration openings (i.e., patches) in the waste package as a function of time are provided. *WAPDEG Analysis of Waste Package and Drip Shield Degradation* (CRWMS M&O 2000c) presents the results for both the nominal-case and sensitivity case studies. The WAPDEG analysis output files, tracked by DTN: MO0010MWDWAP01.009, provide the upper and lower bounds, mean, and the 95th, 75th, 25th, and 5th percentiles as a function of time for the following output parameters:

- Waste package first failure
- Drip shield first failure
- Waste package first crack penetration
- Waste package first patch penetration

- Waste package crack penetration numbers per failed waste package
- Waste package patch penetration numbers per failed waste package
- Drip shield patch penetration numbers per failed drip shield.

The cumulative distribution for time to waste package failure (SCC or general corrosion) is fitted to regression equations using values obtained from the graphical representation of waste packages failed as a function of time (file case18-20.jnb, DTN: MO0010MWDWAP01.009). Early failure of the waste package has not been considered in the WAPDEG analysis model that generated the data tracked by DTN: MO0010MWDWAP01.009.

The second failure mechanism modeled is the only early failure mechanism for waste package considered in Subsection 7.3.6 of *FY01 Supplemental Science and Performance Analyses, Volume 1: Scientific Bases and Analyses* (BSC 2001c) and that is improper heat treatment of waste packages. The improper heat treatment resulted in a failure probability of 2.23×10^{-5} per waste package (CRWMS M&O 2000d, Subsection 6.2.3). Subsection 7.3.6 of *FY01 Supplemental Science and Performance Analyses, Volume 1: Scientific Bases and Analyses* (BSC 2001c) assumed the probability function followed a Poisson distribution and calculated the probability for the number of waste packages improperly treated. This same approach is used in this report to calculate the probability of having one or more waste packages fail due to improper heat treatment. This probability is constant and independent of the general corrosion failure probability so that the probabilities are additive.

6.6.5.1 First Waste Package Penetration at Top Surface

Generic degradation scenarios IP-1, IP-2, and IP-3 are contingent upon the waste package being in a bathtub configuration where water can accumulate in the waste package. The fraction of waste packages that have the first penetration opening at the top surface defines the probability that a waste package has the bathtub geometry (i.e., allows water to accumulate inside). Subsection 8.3.4.3 of *FY01 Supplemental Science and Performance Analyses, Volume 1: Scientific Bases and Analyses* (BSC 2001c) also discusses the probability of waste packages with a top penetration prior to a bottom penetration. The probability of waste package patch failure for the baseline waste package design is shown in Figure 6-12 and the number of patch failures per failed waste package in Figure 6-13 (CRWMS M&O 2000c, Figures 22 and 24). Data for Figures 6-12 and 6-13 are listed in the spreadsheets "WPFailPat.xls" and "WPAvgPat.xls" (Attachment XII), respectively. As shown in Figure 6-12, at the upper bound confidence level, the first patch failure necessary for a bathtub criticality configuration, occurs beyond 10,000 years.

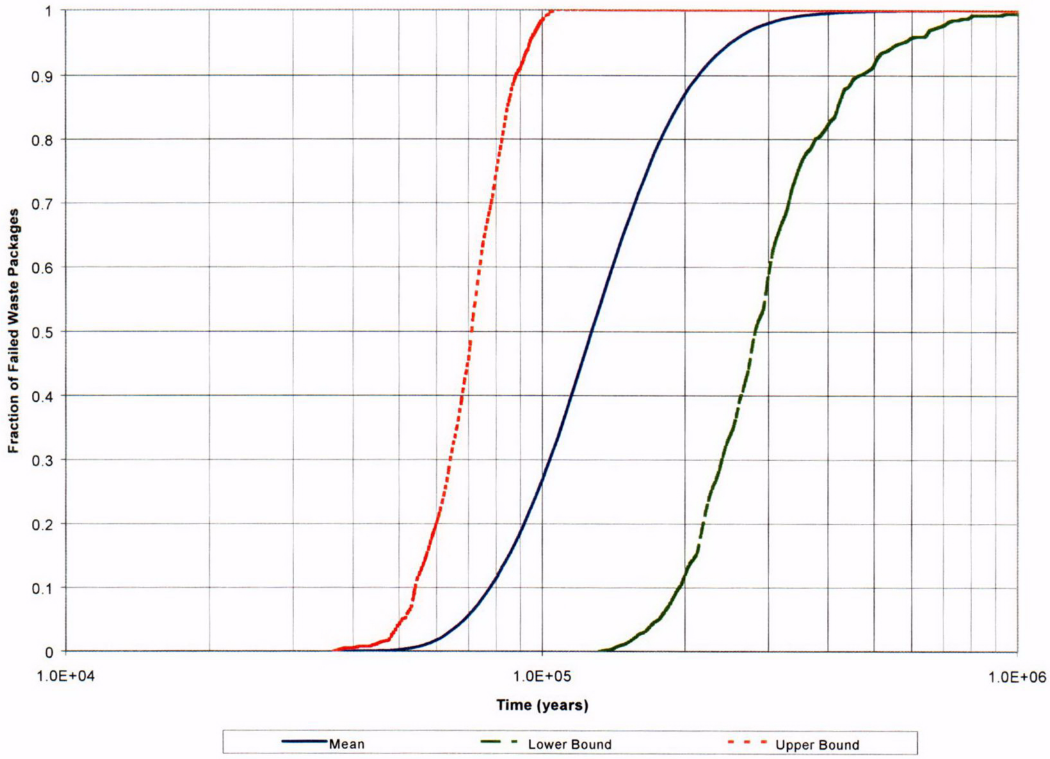


Figure 6-12. Cumulative Distribution Function for First Patch Failure in Waste Package

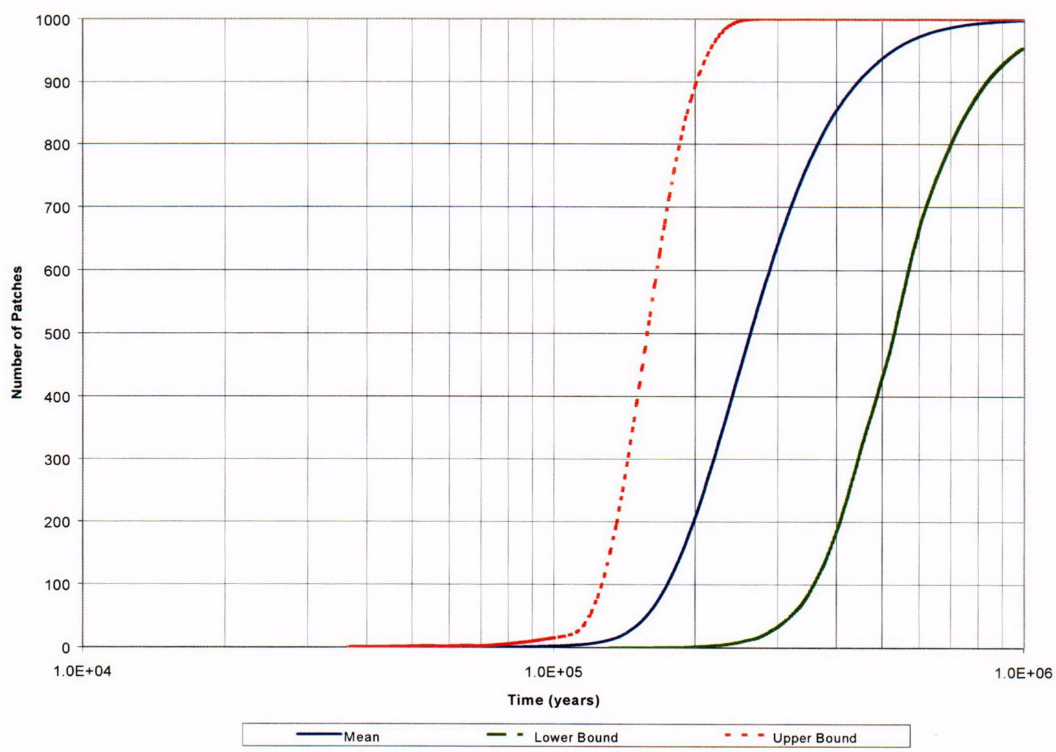


Figure 6-13. Cumulative Distribution Function for Number of Patch Failures in Waste Package

6.6.5.2 First Waste Package Penetration at Bottom Surface

Generic degradation scenarios IP-4, IP-5, and IP-6 are based on a flow-through geometry. The flow-through geometry can occur from one of two sequences. The first sequence is having the bottom of the waste package breach prior to the breach of the waste package top. The second sequence is to have the top of the waste package breach first and then at some latter time, the bottom of the waste package breaches. The probability of having flow-through geometry is the complement of the probability of having a bathtub geometry. The degradation scenarios IP-4, IP-5, and IP-6 associated with flow-through geometry are excluded from analyses of the PWR waste form since the configuration classes for these scenarios can not become critical because of insufficient neutron moderator present in the waste package.

6.6.6 Water Accumulates in Waste Package

Water accumulating in a waste package is associated with top event MS-IC-4 of the CGM event tree (Attachment I). The rate at which the water flows into a waste package is assumed to be the same as the seepage rate through the drip shield and waste package gaps (Assumption 6.6.1.5). The probability that water accumulates in a waste package depends on many parameters discussed in the following subsections. The probability for water flowing through a waste package is discussed in Subsection 6.6.7. This parameter is independent of the waste form and waste package parameters; therefore, it can be used for all waste forms being analyzed.

6.6.6.1 Flux Into a Waste Package

The angular location of the water flux through the drip shield is where the drip shield patch intercepts the water film formed on the surface of the drip shield. The spatial distribution of patches is uniform since there is no mechanism that would create a non-uniform distribution. Thus, a large number of patches on the drip shield assure that a patch forms at any axial location. This also assures that a patch occurs at or near the apex point locus of the drip shield. The WAPDEG results (CRWMS M&O 2000c, Figures 19, 20, 22, and 24) show that the drip shield surface degrades extensively before the waste package failure. A drip shield starts to fail by general corrosion at approximately 20,000 years, while a waste package starts to fail by general corrosion at approximately 36,000 years. By the time of the first patch failure on the waste package, a drip shield has, on average, about 50 patches. The continued growth of patches on the waste package is very slow, amounting to only a few patches at 100,000 years. By this time, a drip shield on average, has developed about 250 patches (CRWMS M&O 2000c, Figure 20) (i.e., half of a drip shield surface has failed). This means it is almost certain that a patch formation would exist at any axial location on the apex, or close to the apex, of a drip shield to intercept a water film. The analysis demonstrates that the conceptualization of water flux incident to the apex of a waste package is adequate in the case of water transport by advection, due to the delay of patch formation on the waste package surface relative to the drip shield failure.

The probability of water flow through the outer barrier of a failed waste package, P_{FTWP}, has two components; the probability of water flow through patches due to general corrosion, P_{WP_Patch}, and the probability of water flow through stress corrosion cracks, P_{WP_SCC}. The WAPDEG analysis shows that the waste package first failure is due to stress corrosion cracking. The flow through pits due to localized corrosion is neglected since it would have a negligible contribution to the total probability (BSC 2001g, Subsection 6.3.2). Since dripping water onto a waste package is assumed to fall from a point source at the crown of the drift (Assumption 6.6.1.1), the derivation of P_{WP_Patch} can be performed similarly to that of P_{FTDS} presented in Subsection 6.6.4.1. Thus, P_{WP_Patch} is the ratio of waste package patch length to the length of the waste package, L_{WP}, as shown in Equation 10.

$$P_{WP\_Patch} = \frac{L_{WP\_Patch}}{L_{WP}} \quad \text{(Eq. 10)}$$

The length of a patch on the waste package outer surface is the square root of the patch surface area considered in the WAPDEG analysis (Subsection 6.6.4.1, CRWMS M&O 2000c, Subsection 6.4.3) (i.e., $\sqrt{2.346 \times 10^2}$ cm, which is approximately 15.3 cm). The length of the waste package is dependent upon the type of waste package being analyzed where the length of a CSNF waste package is 5.17 m for a 21-PWR with Absorber Plates Waste Package and 3.59 m for a 5 DHLW/DOE SNF-SHORT Waste Package (BSC 2002c).

The probability of dripping water onto the waste package surface having a pathway through a stress corrosion crack is proportional to the length of the crack, L_{WP_SCC}, and inversely proportional to the pathway length, as shown in Equation 11.

$$P_{WP\_SCC} = \frac{L_{WP\_SCC}}{L_{WP} + L_{WP\_SCC}} \quad \text{(Eq. 11)}$$

The length of a stress corrosion crack is obtained as follows (BSC 2001b, p. 54)

$$L_{WP\_SCC} = \lambda_{LID} \sin(\alpha) \quad \text{(Eq. 12)}$$

where:

λ_{LID} = the diameter of the lid within the waste package skirt (cm)
α = the maximum tilt angle of the waste package (degrees).

The model assumes that the waste package is tilted at an early time after closure in order to make possible an advective flow in the waste package. The maximum tilt angles are 8.8 degrees and 5.01 degrees for the 21-PWR with Absorber Plates Waste Package and the 5-DHLW/DOE SNF-SHORT Waste Package, respectively (BSC 2001b, Table 6).

The probability of water flow through the outer barrier of a failed waste package is defined by Equation 13 as the sum of the probability of water flow through a patch and the probability of water flow through a stress corrosion crack.

$$P_{FTWP} = P_{WP\_Patch} + P_{WP\_SCC} \quad \text{(Eq. 13)}$$

6.6.6.2 Duration of Bathtub Configuration

A bathtub configuration is one where a breach or failure on the top part of the waste package occurs prior to a breach or failure on the bottom part. From the information given in Figures 8.3.4-2 and 8.3.4-3 of *FY01 Supplemental Science and Performance Analyses, Volume 1: Scientific Bases and Analyses* (BSC 2001c), about 50 percent of the waste packages can sustain a bathtub configuration for some time. 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:

- The start time for accumulating water = Max {First failure time (top of drip shield); First failure time (top of outer barrier)}
- The start time for flow through geometry = Max {First failure time (top of outer barrier); First failure time (bottom of outer barrier)}
- The 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 (Figure 6-13). The cumulative probability for the duration of the waste package bathtub configuration, shown in Figure 6-14, has been abstracted from the WAPDEG analysis (Case 2001) for realizations that have a non-zero probability (Excel spreadsheet "freqhist_bathtub.xls," Attachment XII). The first waste package failure was as likely to occur in the lower part of the waste package as in the upper part resulting in approximately half of the realizations in the WAPDEG analysis having a zero duration time.

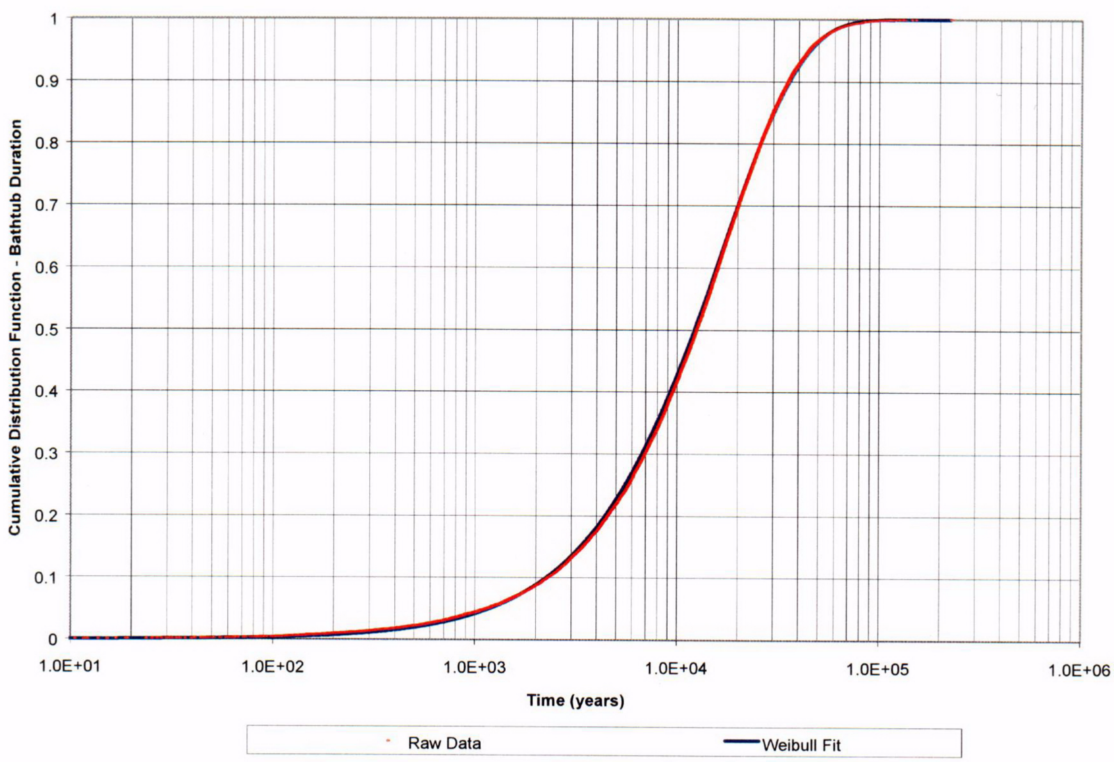


Figure 6-14. Cumulative Distribution Function for Waste Package Bathtub Duration

6.6.6.3 Water Evaporation in Waste Package for the Case of Juvenile Failure

Water evaporation in most cases can conservatively be neglected. Water evaporation is very low at the time when patches and stress corrosion cracks start to form on the waste package surface (i.e., after approximately 30,000 years from closure of repository). However, in the case of juvenile failure of the waste package, evaporation cannot be neglected as juvenile failures are assumed to occur prior to general corrosion of the emplaced waste package. Since the juvenile failure of a waste package is assumed to occur during the first few thousand years (BSC 2001c, Subsection 7.3.6), the decay heat has a significant affect on the seepage into the waste package. The decay heat evaporates some of the incoming seepage flux; therefore, in order to fill the waste package the amount of seepage flux must account for the loss due to evaporation. The significant decay heat during the first few thousand years after waste package emplacement is demonstrated in *Water Pooling-Evaporation in a Waste Package* (CRWMS M&O 2000f, Section 6). Equation 7 is assumed (Assumption 6.6.1.2) to represent the functional relationship for water vaporization rate from a waste package due to decay heat and time since waste package emplacement. The water vaporization rate coefficient will vary depending upon the waste form.

Water accumulates in the waste package if the seepage flux rate, Q_{seep}, exceeds the evaporation rate of the waste package, $Q_{evaporate}$. Based on *Water Pooling-Evaporation in a Waste Package* (CRWMS M&O 2000f, Section 6), the decay heat can cause evaporation. Equation 14 is used to account for CSNF waste package evaporation rate. This equation (see Assumption 6.6.1.2) is used to determine the amount of seepage flux required to fill a waste package and flush out the neutron absorbing materials. Equation 14 does not represent a probability density function, but rather a mathematical equation to calculate the amount of seepage flux lost due to decay heat.

$$Q_{evaporate} = 2.422x10^{+4} t^{-1.5752} \quad \text{(Eq. 14)}$$

where t represents the time, in years, since closure of repository.

6.6.6.4 Water Volume in a Degraded Waste Package

After waste package failure due to general corrosion or SCC, water and air accumulate inside the waste package and initiate degradation of the internal components. The degree of degradation depends on the corrosion rates of waste package internal structures and waste form dissolution rates. The initial void space inside the waste package changes as degradation progresses because new chemical species are being formed that have lower material densities than the intact materials they are replacing. The change in the waste package void space is a function of the corrosion rates of the waste package internal structures, the fraction of degraded waste form, and seepage flux rate. Since the void space decreases as degradation progresses, and because the amount of insoluble degradation products is proportional to the elapsed time since waste package failure, there is an inverse proportionality between void space and time (Assumption 6.6.1.3). However, the constant of proportionality changes after the structural components have fully degraded, as shown in Figure 5.3.1-1 of *EQ6 Calculations for Chemical Degradation of PWR LEU and PWR MOX Spent Fuel Waste Packages* (CRWMS M&O 1998a).

The change in void space is one of the parameters used to determine the criticality potential of the waste package configuration classes. The insoluble degradation products (i.e., iron oxide) can either collect directly on the bottom or mix within the waste form matrix. The insoluble degradation products have a negative effect on the criticality potential of the waste package. The insoluble degradation products take up void space within the waste package, which allows less water to accumulate inside the waste package. Water is important for neutron moderation, which is required for a waste package loaded with CSNF to become critical. Another effect on the waste package criticality potential from the insoluble degradation products is the way these products settle (or do not settle) within the waste package. The products may either settle on the bottom of the waste package or remain uniformly mixed with the waste form. Therefore, the void space volume plays an important part in the final configuration class parameters for criticality analysis.

The composition of the degradation products and the void volume are determined by the geochemistry analysis using the EQ3/6 and EQ6 software. The void volume available for moderator materials (water and/or silica) varies over time since the degradation products from the waste package internal structures, in general, have a lower density and thus occupy a larger volume than the initial structures.

6.6.7 Water Flows through the Waste Package

The fraction of seepage flux available to impinge on a waste package is based on the gap size of the drip shield. The seepage rate at which the water flows into a waste package is assumed to be the seepage rate into the emplacement drift multiplied by the fraction of failed drip shields and waste packages. The seepage rate that can enter the waste package is based on the flow path through the drip shield and the waste package (Assumptions 6.6.1.5 and 6.6.1.7). In order for water to flow through a waste package, there must be a penetration in both the top and bottom of a waste package. The results from WAPDEG provide the information about waste package penetrations. The probability of a flow-through configuration is the complement of the waste package accumulating water (due to bathtub configuration) since the waste package can only accumulate water or have a flow through path.

Water flowing through a waste package is stated as top event MS-IC-28 (Attachment I). This process can occur by different processes as indicated by the CGM event tree. The waste package bottom breach can occur prior to breach of the top of the waste package. The waste package bottom can breach at some time after the top of the waste package. This process would allow some water to accumulate depending on the temporal difference between the top and bottom breaches of the waste package. This process is stated as different top events on the CGM event tree (Attachment I) depending upon the degradation sequences. The flow through process is dependent upon the failure of the waste package and is independent of the waste form; therefore, it can be used for all waste forms being analyzed.

6.6.8 Waste Package Internal Structures and Waste Form Degradation

Waste form degradation is dependent upon many factors, including in-package water chemistry. Degradation processes and rates vary for each waste form. Information about the processes and degradation rates are discussed in *Waste Form Degradation Process Model Report* (CRWMS M&O 2000h) or their specific degradation report. These waste form specific degradation rates and processes determine how the waste form degrades with respect to the waste package internal structures. The degradation rate functions for both the specific waste form and waste package internal structure can be used in calculating the probability for this process. Waste package internal structure degradation depends on the corrosion rates of the internal structure materials. These corrosion rates are used in the EQ6 calculations. Cumulative distribution functions for these corrosion rates have been developed (Attachment VI) and are used in the CGM.

6.6.8.1 Waste Package Internal Structures Degrade Slower than Waste Form

The waste package internal structures degrading more slowly the waste form is associated with top events MS-IC-6 and MS-IC-29 of the CGM event tree (Attachment I). This degradation scenario has the waste form degrading faster than the waste package internal structure. The waste form degradation process and rate can be obtained from its specific degradation report. Once the degradation rate has been abstracted and converted into a probability density function, the degradation rate is used in conjunction with the waste package internal structure corrosion rate to calculate the probability that the waste form degrades faster than the waste package internal structure. The probability for this process can be viewed as the overlap of the density function for the waste form degradation rate and waste package internal structure corrosion rate. Therefore, for the waste form to degrade faster than the waste package internal structure, some part of the waste form degradation rate density function must be larger than some part of the waste package internal structure corrosion rate density function. If there is no overlap between the two density functions (i.e., degradation rate of waste form smaller than corrosion rate of waste package internal structure) then the probability is set to zero.

6.6.8.2 Waste Package Internal Structures Degrade at the Same Rate as the Waste Form

The waste package internal structures degrading at the same rate as the waste form is associated is associated with top events MS-IC-7 and MS-IC-30 of the CGM event tree (Attachment I). The waste form degradation process and rate can be obtained from its specific degradation report. Once the degradation rate has been abstracted and converted into a probability density function, the degradation rate is used in conjunction with the waste package internal structure corrosion rate to calculate the probability that both the waste form and the waste package internal structure degrade at the same rate. The probability for this process can be viewed as the overlap of the density functions for the waste form degradation rate and waste package internal structure corrosion rate. Therefore, for the waste form to degrade at the same rate as the waste package internal structure, the waste form degradation rate density function must overlap the majority of the waste package internal structure corrosion rate density function. If there is no overlap between the two density functions (i.e., degradation rate of waste form is smaller than the corrosion rate of waste package internal structure), then the probability is set to zero.

6.6.8.3 Waste Package Internal Structures Degrade Faster than Waste Form

This degradation scenario has the waste form degrading slower than the waste package internal structure and is associated with top events MS-IC-8 and MS-IC-31 of the CGM event tree (Attachment I). The waste form degradation process and rate can be obtained from its specific degradation report. Once the degradation rate has been abstracted and converted into a probability density function, the degradation rate is used in conjunction with the waste package internal structure corrosion rate to calculate the probability that both the waste form and the waste package internal structure degrade at the same rate. The probability for this process can be viewed as the overlap of the density function for the waste form degradation rate and waste package internal structure corrosion rate. Therefore, for the waste form to degrade slower than the waste package internal structure, the waste form degradation rate density function must not overlap the waste package internal structure corrosion rate density function. If there is no overlap between the two density functions (i.e., degradation rate of waste form is much smaller than the corrosion rate of waste package internal structure), then the probability is one.

6.6.9 Waste Form Degradation in Place

This process has the waste form degrading in place and is stated on the CGM event tree as top event MS-IC-9 (Attachment I). This process is dependent upon the waste form degradation with respect to the waste package internal structure degradation. The waste form degrades in such a way that the waste package internal structure remains intact. Each waste form has its own degradation process and rate dependency on in-package chemistry that can be obtained from *Waste Form Degradation Process Model Report* (CRWMS M&O 2000h) or the specific waste form degradation report. This process relates the degradation of the waste form to the degradation of the waste package internal structures, which is dependent on the waste form degrading prior to the waste form internal structures. If the waste package internal structures degrade faster than the waste form then this process can not occur. There is no probability assigned to this process since it is used to define the configuration class used for criticality analysis.

6.6.10 Waste Package Internal Structure Degradation

This subsection discusses the degradation rates of the waste package internal structures. The waste package internal structures are comprised of carbon steel and stainless steel. All of the waste packages, regardless of the waste form, have similar internal structures. The degradation rates for the different waste package internal structure materials are discussed in the following subsections. Degradation of the waste package internal structures is associated with top events MS-IC-10 and MS-IC-33 of the CGM event tree (Attachment I).

6.6.10.1 Waste Package Basket Structure Degradation

All of the waste packages use structural Carbon Steel Type A516 for part of the basket structure. A distribution of the corrosion rate for Carbon Steel Type A516 has been developed for data from DTN: MO0303SPAMCRAQ.000. Using this data, the corrosion rate was fitted to a lognormal distribution with a lognormal mean of 4.204 and lognormal standard deviation of 0.386. An Anderson-Darling Test (D'Agostino and Stephens 1986) was used to verify the data fits a lognormal distribution. The cumulative distribution function for structural Carbon Steel Type A516 is shown in Figure 6-15. The complete abstraction on how the density function was evaluated along with the statistical test is given in Attachment VI. Equation 15 is the lognormal distribution (Ang and Tang 1975, Subsection 3.2.2) representing the corrosion rate for Carbon Steel Type A516.

$$f_{CR_{CS}}(x) = \frac{1}{\sqrt{2\pi}\zeta x} \exp\left[-\frac{1}{2}\left(\frac{\ln x - \lambda}{\zeta}\right)^2\right] \quad \text{(Eq. 15)}$$

where

λ = the lognormal mean of 4.204
ζ = the lognormal standard deviation of 0.386
x = the Carbon Steel Type A516 corrosion rate (μm/yr).

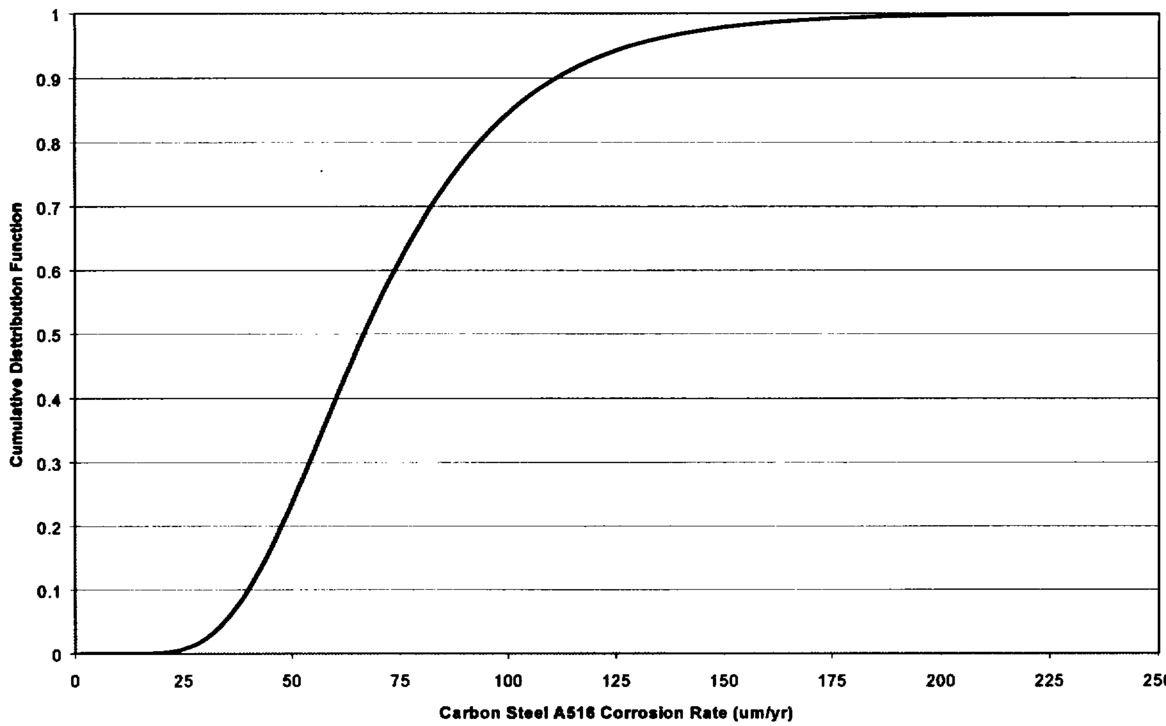


Figure 6-15. Cumulative Distribution Function for Carbon Steel (A516) Corrosion Rate

The internal structure of certain waste packages, namely, defense high-level radioactive waste canisters, is designed to be partly constructed of Stainless Steel Type 304. A distribution of the corrosion rate for Stainless Steel Type 304 has been developed from DTN: MO0303SPAMCRAQ.000. Using this data, the corrosion rate was fit to a lognormal distribution with a lognormal mean of -2.213 and lognormal standard deviation of 0.752. An Anderson-Darling Test (D'Agostino and Stephens 1986) was used to verify the data fits a lognormal distribution. The cumulative distribution function for Stainless Steel Type 304 is shown in Figure 6-16. The complete abstraction on how the density function was evaluated along with the statistical test is given in Attachment VI. Equation 16 is the lognormal distribution (Ang and Tang 1975, Subsection 3.2.2) representing the corrosion rate for Stainless Steel Type 304.

$$f_{CR_{SS}}(x) = \frac{1}{\sqrt{2\pi}\zeta x}\exp\left[-\frac{1}{2}\left(\frac{\ln x - \lambda}{\zeta}\right)^2\right] \quad \text{(Eq. 16)}$$

where

λ = the lognormal mean of -2.213
ζ = the lognormal standard deviation of 0.752
x = the Stainless Steel Type 304 corrosion rate (µm/yr).

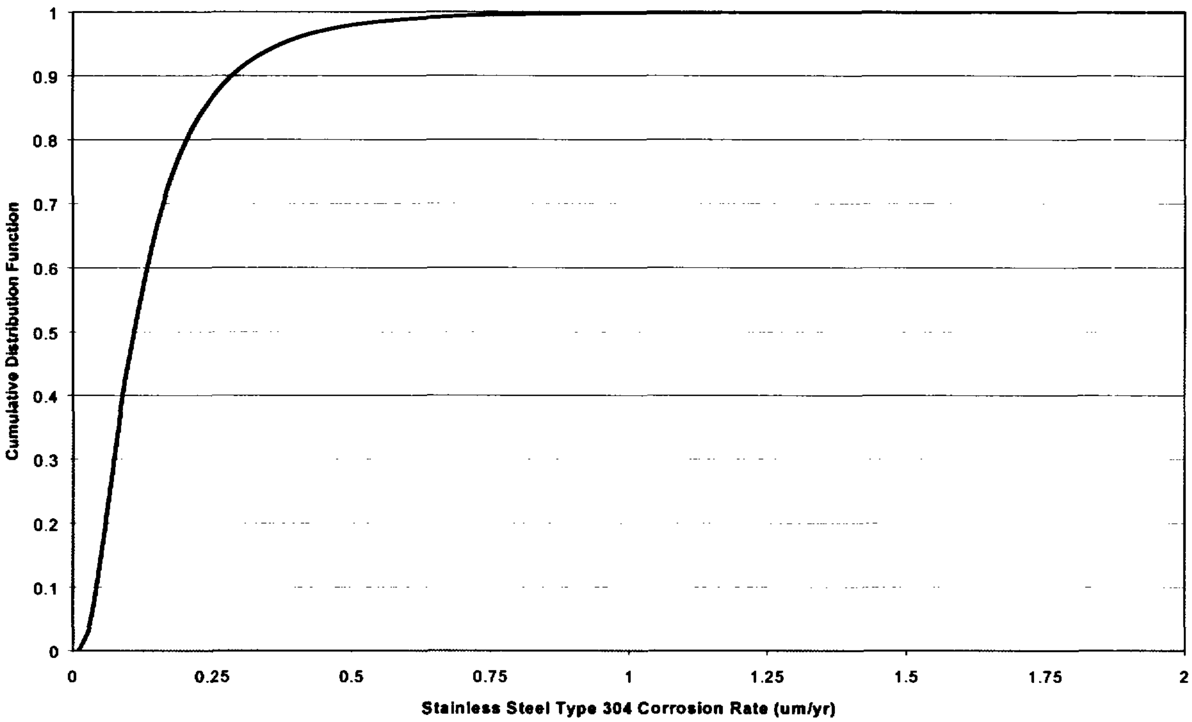


Figure 6-16. Cumulative Distribution Function for Stainless Steel Type 304 Corrosion Rate

6.6.10.2 Waste Package Absorber Plate Degradation

A subset of the CSNF waste packages (i.e., 21-PWR with Absorber Plates, 44-BWR, and 24-BWR design variants) contain absorber plates made of Neutronit A978 that can degrade over time. For those waste package design variants that do not contain absorber plates as part of the basket structure, this parameter will be null since this degradation process cannot occur.

A distribution of the corrosion rate for Neutronit A978 has been developed (Attachment VI) from Stainless Steel Type 316 data (DTN: MO0303SPAMCRAQ.000). It is assumed that Neutronit A978 has a corrosion rate that is 2.5 times that of Stainless Steel Type 316 in an aqueous environment (Assumption 6.6.1.4). The calculated corrosion rate for Neutronit A978 was fitted to a normal distribution with a normal mean of 0.468 and standard deviation of 0.175 using the data from DTN: MO0303SPAMCRAQ.000 and multiplying it by 2.5. An Anderson-Darling Test (D'Agostino and Stephens 1986) was used to verify the data fits a normal distribution. The cumulative distribution function for borated stainless steel (Neutronit) is shown in Figure 6-17. The complete abstraction on how the density function was evaluated along with the statistical test is given in Attachment VI. Equation 17 is the normal distribution (Ang and Tang 1975, Subsection 3.2.1) representing the corrosion rate for Neutronit A978.

$$f_{CR_{NT}}(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2 \right] \quad \text{(Eq. 17)}$$

where

μ = the normal mean of 0.468
σ = the normal standard deviation of 0.175
x = the Neutronit A978 corrosion rate (μm/yr).

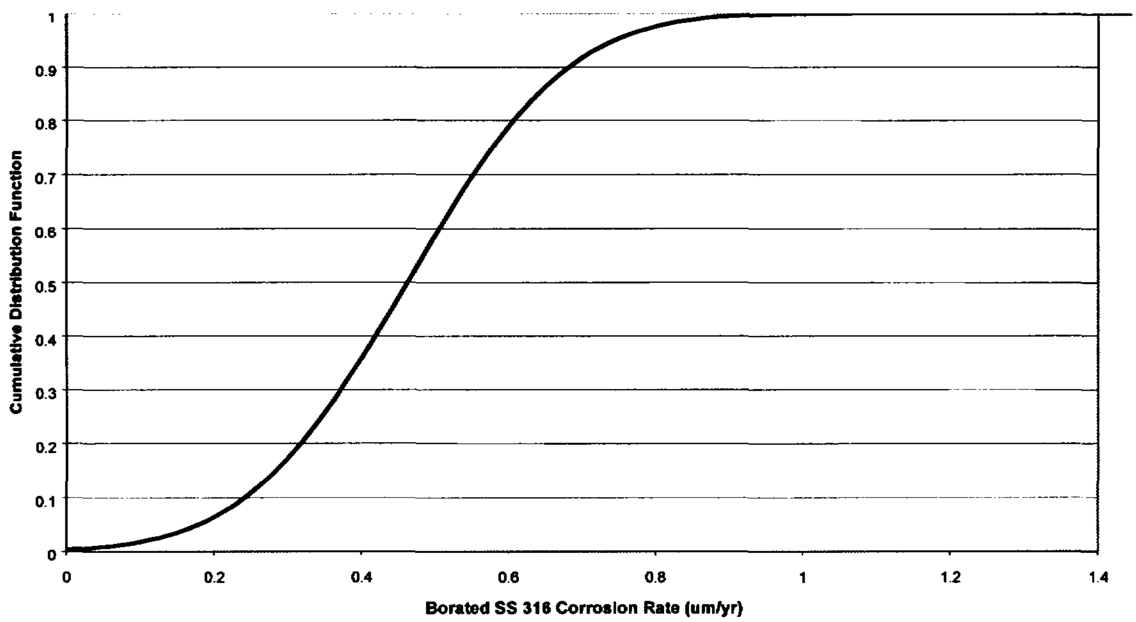


Figure 6-17. Cumulative Distribution Function for Borated Stainless Steel Corrosion Rate

6.6.10.3 Control Rod Degradation

A subset of the CSNF waste packages (i.e., the 21-PWR with Control Rods Waste Package) contain control rods rather than absorber plates that also degrade over time. For those waste packages that do not contain control rods as part of the waste package internal, this parameter will be null since this degradation process can not occur.

For the process where the neutron absorber is in the form of control rods, the probability calculation is based on the corrosion rate of the neutron absorbing material [zirconium clad boron carbide (CRWMS M&O 1997, Subsection 7.3.2)] placed into the waste package. The corrosion rate distribution for the control rod material is used to calculate the probability that the control rod material can have the required corrosion rate in order for it to degrade at the time of evaluation. Likewise, the probability of the control material having a corrosion rate equal to or greater than that required for all of the neutron absorber to be degraded and removed from the waste package at the time of evaluation is also based on the corrosion rate distribution data.

6.6.10.4 Department of Energy Waste Form Neutron Absorber Degradation

The following discussion concerns DOE waste packages that contain neutron-absorbing materials as part of the waste package internal structures. For those DOE waste packages that do not contain neutron-absorbing materials as part of the basket structure, this parameter will be null since this process can not occur.

For the process where the neutron absorber is part of the waste package internal structure, the probability calculation is based on the degradation of the waste package internals and the separation and removal of the neutron absorbing material. The corrosion rate distribution for the waste package internal structure and the separation of the neutron absorbing material is used to calculate the probability that the neutron absorbing material can separate from the fissile material and be removed from the waste package during the evaluation period.

The probability analysis for this event is expected to be similar to the calculation discussed in Subsection 6.6.10.2 (see also BSC 2001d). The main difference between the DOE absorber plates and the CSNF absorber plates is in the neutron absorbing material. The DOE absorber plates contain gadolinium (BSC 2001d) whereas the CSNF absorber plates contain boron. The solubility, and thus transport potential, of the respective degradation products differ significantly.

6.6.11 Degraded Waste Form Mobilized, Separating from Intact Neutron Absorber

In this process, the degraded waste form separates from the neutron absorber material in the waste package and is associated to top events MS-IC-11 and MS-IC-20 of the CGM event tree (Attachment I). The separated waste form mobilizes and moves away from the neutron absorber while settling within the waste package. This process can occur when the waste form has degraded either prior to or after the waste package internal structures. When the waste form has degraded prior to the degradation of the waste package basket, the waste form can only collect within each basket cell since the structure is essentially intact. When the waste form degrades after degradation of the waste package basket, the waste form can settle almost anywhere depending upon water flux, waste package temperature, and natural circulation patterns.

This process of having the waste form degrade, mobilize, and then separate from the neutron absorber is dependent upon waste form degradation rates with respect to the waste package internal structure degradation rates. This process is also dependent upon in-package circulation of water, which can cause separation of the absorber material and the waste form. Each waste form has its own degradation process and rate, dependent on in-package chemistry, that can be obtained from *Waste Form Degradation Process Model Report* (CRWMS M&O 2000h) or their specific degradation reports. *Generic Degraded Configuration Probability Analysis for DOE Codisposal Waste Package* (BSC 2001d, Subsection 6.1.3.1) contains information about the separation of fissile material from neutron absorbing material. This process is used to define a configuration class for criticality analysis rather than developing a probability distribution for the likelihood of such a material separation occurring.

6.6.12 Degraded Waste Form and Waste Package Components Collect at Bottom of Waste Package

This process has the degraded waste form and degraded waste package internals settling on the bottom of the waste package and is associated with top event MS-IC-13 (Attachment I). In order for this process to occur, both the waste form and waste package internals have degraded. There are three options in this degradation process: (a) the waste form degrades first, followed by the waste package internals; or (b) both waste form and waste package internals degrade at the same rate; or (c) the waste package internals degrade first, followed by the degradation of the waste form.

This process is dependent upon the degradation of the waste form and waste package internals along with the settling of the waste form and waste package internal degradation products. The settling of the waste form and waste package internal degradation products for this event depends upon natural circulation within the waste package and the density of the degradation products. *Generic Degraded Configuration Probability Analysis for DOE Codisposal Waste Package* (BSC 2001d, Subsection 6.1.3.1) contains information about the settling of degradation products within a waste package. The settling of the waste form and waste package internal degradation products is used for defining the configuration class. Depending upon the degradation process, the stratification of the waste form and waste package internals can be different. These different possibilities define the configuration classes that are evaluated for criticality analysis. There is no probability assigned to this process.

6.6.13 Soluble Absorber Flushed from Waste Package

Soluble absorber being flushed from the waste package is associated with top events MS-IC-14, MS-IC-18, and MS-IC-19 of the CGM event tree (Attachment I). This process is limited to those waste packages that contain neutron absorber material. For those waste packages that do not contain neutron absorber material, this process will be bypassed since this degradation process cannot occur.

The degradation and flushing of the neutron absorber is based on the corrosion rate of the neutron absorber and the seepage flux into the waste package (see Assumption 6.6.1.5). The flushing of the neutron absorber from the waste package depends upon its solubility. For absorber plate waste packages containing Neutronit A978, the following equations can be used to determine the amount of boron in a waste package based on time, corrosion rate, and seepage flux. Using these equations, the amount of boron still inside a waste package can be determined using a defined corrosion rate, seepage flux, and time. The boron loss equations are used in the geochemistry abstraction (BSC 2002b, Section 6.2). These equations are developed specifically for boron loss from Neutronit A978; however, similar type equations can be developed for other neutron absorbing materials provided they are soluble and do not form insoluble minerals with other waste package internal degradation products.

While Neutronit A978 is still degrading ($t < t_f$):

$$N_B(t < t_f) = \frac{V_R D}{v}\left(1 - \exp^{\frac{tv}{V_R}}\right) + B_i - Dt \qquad \text{(Eq. 18)}$$

After Neutronit A978 has degraded ($t > t_f$):

$$N_B(t > t_f) = \frac{V_R D}{v}\exp^{\frac{-v(t-t_f)}{V_R}}\left(1 - \exp^{\frac{t_f v}{V_R}}\right) \qquad \text{(Eq. 19)}$$

where

N_B	=	moles B (boron) in waste package = moles B in liquid + in undegraded Neutronit (no B goes into minerals)
t	=	time
t_f	=	time when the Neutronit has fully degraded
V_R	=	reactor volume (chemical)
D	=	moles of B added from Neutronit/year
v	=	volumetric flow rate (liter/t)
B_i	=	initial moles of B in Neutronit.

The boron loss equations are used to determine the corrosion rate and seepage flux required to degrade and flush out some or all of the boron at a specified time. These equations are not used directly for the probabilistic analysis but are used to obtain specific corrosion rates and seepage fluxes at specified times, which are random variable and have probabilities associated with them.

6.6.14 Basket Structure Supports Mechanically Collapse

Basket structure degradation and mechanical collapse is associated with top events MS-IC-16 and MS-IC-23 of the CGM event tree (Attachment I). This process addresses the scenario that occurs when the basket structure supports lose their strength as the material degrades and mechanically collapse due to the weight of the waste form. The degradation process that causes the basket to mechanically collapse is discussed in Subsection 6.6.10.1.

6.6.15 Complete Degradation of Structures Containing Neutron Absorbers

Neutron absorber material degrading is associated with top events MS-IC-17 and MS-IC-22 of the CGM event tree (Attachment I). The degradation of the neutron absorber material for this event occurs before the basket structure has degraded and collapsed. Subsection 6.6.10.2 discusses the degradation process for waste packages that contain neutron absorber plates in the basket structure. However, there are other types of neutron absorber materials used in the waste packages (see Subsections 6.6.10.3 and 6.6.10.4).

The corrosion rate cumulative distribution functions listed in Subsection 6.6.10 are used for the degradation process of these top events. The probability calculation will use the corrosion rate cumulative distribution functions along with the boron loss equation to calculate the amount of boron remaining in the waste package at specified times. The boron loss equation and Neutronit A978 corrosion rate is used for the absorber plate waste packages. Similar corrosion rate and absorber loss equations are expected to be developed for the waste packages that use control rods or other types of neutron absorbing material.

6.6.16 Waste Form Degradation Products Hydrate in Initial Location

This process has the waste form degrading faster than the waste package internal structures and is associated with top event MS-IC-32 of the CGM event tree (Attachment I). The waste package is in a flow through geometry. The degraded waste form hydrates within the waste package and settles in its initial location.

The degradation process leading to this event is discussed in Subsection 6.6.8.1. The hydration of the waste form is dependent upon the seepage flux through the waste package and the chemical reaction properties of the degraded waste form products. The parameters required for the waste form to hydrate need to be abstracted from geochemistry calculations, related analysis reports, and model reports. The required parameters are waste form composition and chemical interaction of the waste form with the incoming seepage flux. These parameters are not used in the demonstration analysis documented in this report. However, when they are required as input into the CGM, geochemistry calculations will need to be performed together with abstractions from related analysis reports and model reports to acquire these parameters, as necessary, for CGM analyses.

6.6.17 Degraded Waste Form is Mobilized Separating from Neutron Absorbers and Hydrating

The mobilization, separation, and hydration of the waste form are associated with top events MS-IC-34 and MS-IC-39 of the CGM event tree (Attachment I). In this process, the degraded waste form hydrates and separates from the neutron absorber material. It is necessary that the waste package have water flowing through it allowing hydration of the waste form.

The degradation process leading to this event has been discussed in Subsections 6.6.8.1 and 6.6.8.3. The hydration of the waste form for this event is dependent upon the seepage flux through the waste package and the chemical reaction properties of the degraded waste form products. The separation of waste form from neutron absorber material is dependent on waste form parameters associated with density, mass, and waste package heating rate, which can cause natural circulation. These waste form parameters need to be abstracted from geochemistry calculations, related analysis reports, and model reports. These parameters are not used in the demonstration analysis documented in this report. However, when they are required as input into the CGM, geochemistry calculations will need to be performed together with abstractions from related analysis reports and model reports to acquire these parameters as necessary for CGM analyses.

6.6.18 Hydrated Waste Form and Internal Component Degradation Products Collect in Bottom of Waste Package

The hydration of the waste form and collecting on the bottom of the waste package is associated with top event MS-IC-35 of the CGM event tree (Attachment I). In this process, the waste form degrades, hydrates, and collects on the bottom of the waste package along with the waste package internal components. It is necessary that the waste package have water flowing through it allowing hydration of the waste form.

The degradation process leading to this event has been discussed in Subsection 6.6.8.2. The hydration of the waste form and waste package internals for this event is dependent upon seepage flux through the waste package and the chemical reaction properties of the degraded waste form and waste package internal products. The settling of the waste form and waste package internals for this event is dependent upon natural circulation within the waste package and the density of the degradation products. These waste package internal components and waste form parameters need to be abstracted from geochemistry calculations, related analysis reports, and model reports. These parameters are not used in the demonstration analysis documented in this report. However, when they are required as input into the CGM, geochemistry calculations will need to be performed together with abstractions from related analysis reports and model reports to acquire these parameters as necessary for CGM analyses.

6.6.19 Flow-Through Flushing Removes Soluble Neutron Absorber

Soluble neutron absorber being flushed from the waste package due to a flow-through process is associated with top events MS-IC-36 and MS-IC-38 of the CGM event tree (Attachment I). This process is applicable only for waste packages that contain neutron absorber material. For those waste packages that do not contain neutron absorber material, this process is bypassed since degradation cannot occur.

The degradation and flushing of the neutron absorber is based on the corrosion rate of the neutron absorber and the seepage flux through the waste package. The flushing of the neutron absorber from the waste package depends upon its solubility. The solubility and corrosion rate for Neutronit A978 has been discussed in Subsection 6.6.13. The properties of the other neutron absorbing materials will need to be abstracted as necessary from geochemistry abstractions, related analysis reports, and model reports. These parameters are not used in the demonstration analysis documented in this report. However, when they are required, as input into the CGM, geochemistry calculations will need to be performed together with abstractions from related analysis reports and model reports to acquire these parameters as necessary for CGM analyses.

The flushing of neutron absorbing materials from the waste package is expected to follow similar equations as listed in Subsection 6.6.13. These equations do not calculate the probability of flushing the neutron absorbing material from the waste package but are used to determine values of the random variables that have probabilities associated with them (i.e., corrosion rate and seepage flux).

6.6.20 Intact Waste Form Settles in Bottom of Waste Package, Mixed with Hydrated Corrosion Products from Waste Package Internal Components

The hydration of the waste package internals, mixing with the intact waste form, and collecting on the bottom of the waste package are associated with top event MS-IC-37 of the CGM event tree (Attachment I). In this process, the degraded waste package internals hydrate and mix with the intact waste form. The intact waste form and hydrated waste package internals collect on the bottom of the waste package. It is necessary that the waste package have water flowing through it allowing hydration of the waste package internals.

The degradation process leading to this event has been discussed in Subsection 6.6.8.3. The hydration of the waste package internals for this event is dependent upon seepage flux through the waste package and the chemical reaction properties of the degraded waste package internal products. The settling of the waste form and waste package internals for this event is dependent upon the seepage flux through the waste package and the density of the degradation products. These waste package internal component parameters need to be abstracted from geochemistry calculations, related analysis reports, and model reports. These parameters are not used in the demonstration analysis documented in this report. However, when they are required as input into the CGM, geochemistry calculations will need to be performed together with abstractions from related analysis reports and model reports to acquire these parameters as necessary for CGM analyses.

6.6.21 Disruptive Events

The disruptive events are treated on the CGM event tree as initiating events. When analyzing a disruptive event, the frequency of occurrence is placed as the initiating event and the probability of the processes that are affected by the disruptive event are adjusted accordingly. The result from the CGM event tree is a frequency of criticality due to the disruptive event. Using the frequency of criticality, the probability of criticality can be obtained assuming the frequency is constant over time and it follows the Poisson process.

The probability of the first criticality occurring at time, t (in years), after waste package emplacement is a random variable having a Poisson distribution with constant mean value λ (per year), where λ is the criticality frequency result from the CGM event tree. The probability of the first criticality occurring at time, t, from closure of repository is defined by Equation 20.

$$F(t) = 1 - \exp(-\lambda t) \qquad \text{(Eq. 20)}$$

The initiating event frequencies are provided in the analysis reports and model reports supporting the TSPA-SR that analyze disruptive events at the monitored geologic repository. These disruptive events are summarized in the following subsections.

6.6.21.1 Tectonic Activity

Large-scale tectonic activities include regional uplift, subsidence, folding, mountain building, and other processes related to plate movements. These tectonic events are characterized by insignificant rates and they do not affect repository performance. Tectonic activity is an on-going process in the Yucca Mountain region, resulting in regional compression or extension characterized by local slip rates in the range of 0.001-0.03 mm/yr (CRWMS M&O 2000i, p. 37). Based on the present extensional-tectonic regime of the Yucca Mountain region, tectonic subsidence is a more likely scenario than uplift at the Yucca Mountain site. Any uplift of significance to the repository is very unlikely to develop within the next few million years (CRWMS M&O 2000i, p. 37). The rate of subsidence has diminished consistently over the last several million years and any subsidence-related effects will be minimal due to the very low local slip rates in the Yucca Mountain region (CRWMS M&O 2000i, p. 37). Folding at Yucca Mountain is estimated to result in a dip-steepening of about 2 degrees in one million years (CRWMS M&O 2000i, p. 42). Tectonic activities such as uplift, subsidence, folding, and mountain building processes are characterized by insignificant rates that cannot change the physical state of a waste package. However, deformational processes associated with tectonism can be perturbed by local disruptive events such as seismic and igneous activities.

6.6.21.2 Seismicity

Ground motions may affect the integrity of drifts, drip shields, and waste packages (CRWMS M&O 2000n). A fault displacement comparable to those at Bow Ridge and Solitario Canyon faults can induce significant shear stress at the emplacement drift location if the fault is close to the drift. The effects on drip shields may include bending and twisting. Fault displacement induced by seismic activities could cause rotation, bending, and tilting of a waste package provided an existing fracture intersects the emplacement drift or is located within a set-back distance from the emplacement drift.

Fault displacement can occur perpendicular to the fractured walls (extension) or parallel to the fractured surface (shear). Fault displacement hazard curves for the existing faults at the site, which show an annual exceedance probability for values of the displacement, are provided in *Characterize Framework for Seismicity and Structural Deformation at Yucca Mountain, Nevada* (CRWMS M&O 2000j). The annual exceedance probability is the probability that a specified value (such as for ground motion or fault displacement) will be exceeded during one year (CRWMS M&O 2000j, p. I-2). A movement (i.e., minimal displacement) developing in intact rock has less than a 10^{-8} annual-exceedance probability (CRWMS M&O 2000i, p. 48). This represents that the fault displacement in intact rock (defined in CRWMS M&O 2000i, p. 60) within the repository will be less than 0.1 cm for a 10^{-8} annual-exceedance probability (CRWMS M&O 2000i, p. 62).

The majority (>98%) of CSNF fuel assemblies are composed of Zircaloy clad fuel pins (CRWMS M&O 2001c, Section 6.7) with the remainder consisting of stainless steel clad fuel pins. Under normal conditions, Zircaloy assemblies will be intact for a very long time (CRWMS M&O 2001c, Figures 19-20) because Zircaloy cladding is very resistant to corrosion. Similarly, the assembly spacers will be intact for a very long time maintaining the initial lattice pitch. However, the horizontal and vertical motions of the rock bed during an earthquake transfer momentum to the fuel assemblies inside a waste package. The assemblies can undergo a limited displacement in the axial and radial directions, thus changing the geometry and, consequently, k_{eff}. The effect that seismic activities with different spectral accelerations have on the integrity of waste package components has not been analyzed and, thus, such data are currently not available. Therefore, it is assumed that any ground acceleration has the potential to induce a change of the initial fuel assembly geometry. Additionally, rockfall associated with seismic activities also has the potential to change the fuel assembly geometry. Hazard curves for parameters that characterize ground motion (peak ground and spectral accelerations and velocities) are provided in *Characterize Framework for Seismicity and Structural Deformation at Yucca Mountain, Nevada* (CRWMS M&O 2000j, pp. 77 to 83).

The stainless steel cladding in the remaining CSNF assemblies is assumed in *Clad Degradation – Summary and Abstraction* (CRWMS M&O 2001c, Section 6.7) to be perforated when the waste package fails and to be immediately available for unzipping. The fissile material from stainless steel clad fuel pins is conservatively assumed to be exposed and dispersed in the waste package. Thus, seismic activity will not significantly alter the contribution from this fissile material to the waste package reactivity.

6.6.21.3 Igneous Activity

Igneous activity concerns eruptive/extrusive and intrusive events. During an extrusive igneous event a dike may rise to the repository level and possibly intersect one or more drifts in the repository. For the intrusive event, an igneous dike is assumed to intersect a section of the repository and partially or completely engulf the intersected waste packages in magma. The number of waste packages intersected by an igneous intrusion and the waste package response to this intrusion is modeled in *Igneous Consequence Modeling for the TSPA-SR* (BSC 2001h). This reference also provides a conceptual model for a volcanic eruption that entrains and transports radioactive waste from the intersected waste packages. The igneous parameters that support the igneous consequence modeling for the TSPA are identified by DTN: SN0006T0502900.002 that includes probability density functions for:

- Volcanic eruption and igneous intrusion events
- Number of vents intersecting waste package
- Number of packages hit per drift per vent
- Number of packages hit by igneous groundwater intrusion.

The model for igneous intrusion considers two zones of damage within the intersected drifts. Zone 1 corresponds to waste packages in the vicinity of the dike intersection and Zone 2 corresponds to locations of the waste packages in adjacent drifts. It is assumed that three waste packages on either side of the dike in Zone 1 (intersected drift) suffer sufficient damage to provide no further protection, allowing magma to entrain the material within the waste package (BSC 2001h, Assumption 5.3.2). The basis for assuming that three waste packages on either side of the dike suffer damage is discussed in *Igneous Consequence Modeling for the TSPA-SR* (BSC 2001h, Assumption 5.3.2). The remainder of the waste packages in the intersected drift are modeled to fail due to deformation of the lid at the end of the waste package at high temperatures and high pressures, allowing magma to accumulate inside the waste package. Waste packages in Zone 2 (adjacent drifts 80 meters from Zone 1) are not expected to suffer significant damage.

In addition to the engineered barrier and fuel-rod cladding damage, magma has the potential to change the k_{eff} because it has different neutron moderating and reflective properties than the medium that had surrounded fuel rods before magma intrusion. The fuel rods of Zone 1 entrained by magma could stack up in a geometry that minimizes neutron leakage. Therefore, destruction of the waste packages in Zone 1, if such an event were to occur, may result in a near field criticality.

6.6.22 Fuel Assembly Misload

A waste package misload event occurs when one or more assemblies placed in the waste package cause a violation of the waste form loading curve criteria. The impact of a misload event is limited to waste package/waste form configuration classes that have potential for criticality. While the effect of a misload event on the criticality potential of configurations may be included in the loading curve evaluation, the methodology for developing loading curves for the various waste forms has not been finalized. Thus, the event trees for configuration classes that have potential for criticality contain both nominal and misload branches (Figures I-4, I-5, I-9, I-12, I-14, I-16, I-18, I-21, I-23, I-29, and I-32) with their respective probabilities obtained from misload probability calculations (BSC 2001f). If the loading curve methodology accounts for possible misload events, then the event tree misload branches will have a zero probability of occurrence.

6.7 CONFIGURATION PARAMETERS FOR COMMERCIAL SPENT NUCLEAR FUEL SPECIFIC WASTE FORM AND WASTE PACKAGE

The specific parameters for CSNF loaded into a 21-PWR with Absorber Plates Waste Package that can lead to potential critical configuration classes are presented in the following subsections. The parameters presented below are specific to CSNF. The parameters that deal with water influx, drip shield failure, waste package failure, and degradation of waste package internals are discussed in Section 6.6. The following subsections also provide a demonstration using the CGM process as discussed in Section 6.5 to analyze CSNF loaded into a 21-PWR with Absorber Plates Waste Package.

6.7.1 Waste Form Degrades - Mobilizing Fissionable Materials

The following subsections are specific to CSNF and are referenced directly in *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003).

6.7.1.1 Soluble Degradation Products

Disposal Criticality Analysis Methodology Topical Report (YMP 2003, Subsection 3.5.2.1.1) has selected 14 actinides and 15 fission products present in CSNF to be considered for burnup credit. Since Zircaloy cladding has a high corrosion resistance, only the fraction of CSNF with failed cladding could degrade under the action of corrosive environment. CSNF with stainless steel cladding comprise approximately 1.1 percent of the total anticipated CSNF inventory (CRWMS M&O 2001c, Section 6.7). The stainless steel cladding is assumed to be perforated in *Clad Degradation – Summary and Abstraction* (CRWMS M&O 2001c, Section 6.7) when the waste package fails and to be immediately available for unzipping.

Once released from the CSNF matrix, the fission products may form soluble chemical products that could be flushed by the egress of fluid from the waste package. The solubility of the fission products needs to be abstracted from geochemistry calculations. The loss of fission products from the CSNF is used for criticality calculations. The amount of fission products flushed from the waste package will have an effect on the criticality potential.

6.7.1.2 Fraction of Degraded Commercial Spent Nuclear Fuel

The fraction of degraded CSNF in a waste package is one of the dependent variables associated with the amount of principal isotopes for CSNF burnup credit. The fraction of degraded CSNF is directly correlated to the fraction of fuel rods that have cladding failure. The mechanisms of cladding failure stated in *Total System Performance Assessment (TSPA) Model for Site Recommendation* (CRWMS M&O 2000a) are presented in this subsection.

It should be noted that the TSPA-SR model considers that corrosion of the cladding in a localized area is not possible for a long period (CRWMS M&O 2000a, Subsection 6.3.4.3) in the case of bathtub geometry as described in Subsection 6.6.6. Therefore, for in-package criticality, the fraction of perforated Zircaloy cladding is the fraction of initially failed rods plus the fraction of those that experience creep and SCC failure. The fraction of perforated Zircaloy cladding is a random variable, FR_{WF}, comprised of the fraction of initially failed rods, FR_{WF_INI}, the fraction of rods that experience creep, FR_{WF_CREEP}, and SCC failure, FR_{WF_SCC}. The fraction of failed fuel rods due to cladding failure (Equation 21) translates into the fraction of degraded CSNF since the failed fuel rod is available to the water environment inside the waste package.

$$FR_{WF} = FR_{WF\_INI} + FR_{WF\_CREEP} + FR_{WF\_SCC} \qquad \text{(Eq. 21)}$$

For creep and stress corrosion crack cladding failure to occur, a threshold cladding temperature must be exceeded. The distribution functions for FR_{WF_CREEP} and FR_{WF_SCC} are related to the peak temperature of the waste package in the TSPA-SR model as described in Subsection 6.7.1.2.3 and Attachment VII. A threshold temperature of 227°C for the peak waste-package surface temperature is required for creep strain failure as shown in Table VII-1 (see Attachment VII). The values presented in Table VII-2 (see Attachment VII) for the waste package peak temperatures indicate that conditions for creep strain failure in the repository environment will be negligible. This is due to the triangular distribution of the peak surface temperature for the waste package having a maximum value of 186°C for the overall environments, considering the current repository design. Therefore, the fraction of waste form failure due to creep, FR_{WF_CREEP}, is not included in the overall fraction of waste form failure, FR_{WF} (see Equation 22). For stress corrosion crack cladding failure, the fraction of rods per waste package considered to fail by SCC is 0.0048 (CRWMS M&O 2001c, p. 66).

A disruptive event (seismic of high intensity or igneous intrusion) results in perforation of the entire cladding as described in Subsection 6.6.21.

Therefore, the fraction of perforated Zircaloy cladding for this model is

$$FR_{WF} = \begin{cases} 0.0048 + FR_{WF\_INI} & \text{for the nominal case} \\ 1 & \text{for a disruptive event as defined in Section 6.6.19} \end{cases} \qquad \text{(Eq. 22)}$$

where the distribution function for the FR_{WF_INI} variable is provided in Subsection 6.7.1.2.1. This results in a maximum of 1.765 percent (0.48 percent from Equation 22 plus 1.285 percent maximum of triangular distribution discussed in Subsection 6.7.1.2.1) failed fuel rod cladding in the absence of disruptive events. For a disruptive event, 100 percent of the fuel rod cladding fails as given by Equation 22.

Mechanisms for initiating cladding perforation include reactor operation and dry storage, creep and stress corrosion cracking, localized corrosion, and physical failure from mechanical and seismic loads. After the initial perforation, further cracking and splitting of the cladding (unzipping) is assumed to occur, which exposes the CSNF matrix as it progresses. Cladding unzipping due to cladding perforation accelerates the degradation of the CSNF matrix and consequently the release of soluble fission products from the CSNF matrix.

6.7.1.2.1 Cladding Condition as Received

The failure percentage for fuel rods in a waste package because of reactor operation, dry storage, and transportation is represented by a triangular distribution. The triangular distribution has a minimum value of 0.0155 percent, a mode value of 0.0948 percent, and a maximum value of 1.285 percent (CRWMS M&O 2001c, p. 20). This distribution provides the fraction of fuel rods that are perforated before emplacement in the repository and are immediately available for cladding unzipping. The probability density function for a triangular distribution is derived in Attachment VIII (Equation VIII–6).

6.7.1.2.2 Stress Corrosion Crack Failure

The conditions for SCC on the cladding inner and outer surfaces, which require the occurrence of local stress concentrations and aggressive chemicals concentrating at crack tips, have been analyzed in *Clad Degradation – Summary and Abstraction* (CRWMS M&O 2001c, Subsection 6.2.5). The fraction of fuel rod failure due to SCC on the cladding inner surface, which is presented in Table 6-5 as a function of temperature, has been assessed considering the minimum conditions required for SCC initiation. It has been concluded that 0.48 percent of the fuel rods might fail from SCC (CRWMS M&O 2001c, p. 66).

Table 6-5. Fraction of Fuel Rods that Undergo SCC

Peak Waste Package Surface Temperature (°C)	Fraction
177	0.00458
277	0.00473
327	0.00525

Source: CRWMS M&O 2001c, p. 38

6.7.1.2.3 Cladding Corrosion in a Localized Area

There is a potential for corrosion in a localized area of the cladding given that aggressive species can exist. Corrosion in these localized areas of the cladding is due to the presence of fluoride ions and processes such as radiolysis and microbial activity that lower the pH. Since Yucca Mountain groundwater contains fluoride, a model for fluoride corrosion in a localized area has been developed in Section 6.3 of *Clad Degradation – Summary and Abstraction* (CRWMS M&O 2001c), which is implemented in the TSPA-SR simulations. This model considers that cladding is subject to fluoride degradation from dripping water at the contact location, which is possible only for a flow-through geometry. In the case of a flooded waste package, the fluoride transport by diffusion through water is a slow process that affects the entire immersed cladding surface. The discussion about this model is found in Section 6.3 of *Clad Degradation – Summary and Abstraction* (CRWMS M&O 2001c).

6.7.1.2.4 Radiolysis

Radiolysis is the process in which new chemical species are created due to ionizing radiation interacting with the molecules of a medium. The processes that generate ionizing radiation are radionuclide decay and criticality. The decay radiation has high intensity levels during the preclosure period and decreases significantly with time following waste package emplacement (BSC 2002d, Figure 5). Thus, the only source of sufficient radiation intensity to possibly permit the generation and accumulation of species affecting the waste package pH and potentially the engineered barrier system corrosion rates is a criticality extending over long periods. Radiolytic effects are thus a criticality consequence phenomenon. If compliance with 10 CFR 63.114(d) is demonstrated for the criticality probability of configurations, criticality would be screened from further evaluation and no consequence evaluations would be required. If screening of criticality cannot be demonstrated in accordance with 10 CFR 63.114(d), then criticality consequence evaluations including radiolytic effects would be required.

6.7.2 Analysis of Pressurized Water Reactor Spent Nuclear Fuel

A PWR waste form loaded in the 21-PWR with Absorber Plates Waste Package was analyzed using the CGM. The analysis will follow the process steps listed in Section 6.5. This is a demonstration analysis using the CGM process steps for all of the configuration classes associated with PWR CSNF as defined by the CGM event tree. The level of analysis required for each defined configuration class is based on its potential for criticality. The first step in the evaluation is to generate the event tree for all the potential critical configuration classes (Attachment I). The second step is to evaluate the end states of these configuration classes to estimate their potential to achieve criticality. If there is a potential of criticality for an end state, an analysis is performed (step three of the evaluation) to estimate the probability of occurrence of the configuration class. Criticality calculations are performed for configuration classes whose probability of occurrence exceeds the requisite criterion and detailed probability calculations (step four) are performed for the subset of those configurations having a k_{eff} greater than the critical limit. The final step (five) is to determine the overall probability of criticality from all configuration classes for the waste form. The following subsections provide information about the analysis of each configuration class for the PWR waste form loaded into the 21-PWR with Absorber Plates Waste Package.

6.7.2.1 Configuration Class IP-1a

Configuration class IP-1a is described as the class in which the waste package is in a bathtub configuration, the PWR waste form degrades in place, and the waste form degrades faster than the waste package internal structures (Subsection 6.2.3). The processes required to obtain configuration class IP-1a, as defined by the CGM event tree (Figures I-2, I-3, and I-4), are listed in Table 6-6. Table 6-6 lists the process events, their description, and provides the probability assigned to each process. If a probability analysis is not required for the top events (i.e., the end state that has no potential for criticality resulting from the step two evaluation), then N/A is used to indicate that no probability calculation was performed for the event tree branches. The processes are listed in sequential order as they lead to configuration class IP-1a.

Table 6-6. Configuration Class IP-1a Event Tree Sequences

Event Tree Top Event	Top Event Identifier	Assigned Probability
MS-IC-1	Water reaches drift	N/A
MS-IC-2	Water drips on waste package	N/A
MS-IC-3	Waste package penetration at top surface	N/A
MS-IC-4	Liquid accumulates in waste package	N/A
MS-IC-6	Waste package internal structures degrade slower than waste form	N/A
MS-IC-9	Waste form degrades in place	N/A
WF-TYPE	Waste form degrades according to configuration class	N/A
CRIT-POT-FUEL	Criticality potential of waste form	FALSE

A PWR waste form loaded in a waste package can become critical provided certain requirements and parameters are met. The two most important parameters required for in-package criticality are moderation and loss of neutron absorbing poison. Another important parameter or feature is the geometry of the PWR waste form inside the waste package. For configuration class IP-1a, the PWR waste form has degraded and settled within its original waste package basket location. This configuration class requires the waste package to be filled with water or to have a sufficient amount to provide neutron moderation. For configuration class IP-1a with PWR CSNF, the waste package basket structure remains intact; therefore, the entire amount of neutron absorber (i.e., boron) remains in place within the waste package and the configuration class has no potential for criticality (i.e., CRIT-POT-FUEL is FALSE in the SAPHIRE model).

Configuration class IP-1a with a PWR waste form loaded into a waste package requires no probability analysis since the configuration can not become critical. By setting this top event (CRIT-POT-FUEL) to FALSE, all of configuration class IP-1a sequences are set to a zero probability; therefore, these sequences do not contribute to the overall probability.

6.7.2.2 Configuration Class IP-1b

Configuration class IP-1b is described as the class in which the PWR waste form degrades faster than the waste package internal structures and the waste package is in a bathtub configuration. This configuration also has the degraded waste form mobilizing and separating from the intact neutron absorber. The processes required to obtain configuration class IP-1b as defined by the CGM event tree (Figures I-3 and I-5) are listed in Table 6-7. Table 6-7 lists the process events, their description, and provides the probability assigned to each process. If no probability analysis is required for the top events, then N/A is used to represent that no probability was calculated. The processes are listed in sequential order as they lead to configuration class IP-1b.

Table 6-7. Configuration Class IP-1b Event Tree Sequences

Event Tree Top Event	Top Event Identifier	Assigned Probability
MS-IC-1	Water reaches drift	N/A
MS-IC-2	Water drips on waste package	N/A
MS-IC-3	Waste package penetration at top surface	N/A
MS-IC-4	Liquid accumulates in waste package	N/A
MS-IC-6	Waste package internal structures degrade slower than waste form	N/A
MS-IC-11	Degraded waste form mobilizes and separates from intact neutron absorber	N/A
WF-TYPE	Waste form degrades according to configuration class	N/A
CRIT-POT-FUEL	Criticality potential of waste form	FALSE

For a PWR waste form loaded in a waste package, certain requirements and parameters are required in order for it to become critical. The two most important parameters required for in-package criticality are moderation and loss of neutron absorbing poison. Another important parameter or requirement is the geometry of the PWR waste form inside the waste package. For configuration class IP-1b, the PWR waste form has degraded, mobilized, and separated from intact neutron absorber. This configuration class assumes the waste package is full of water or has a sufficient amount of water to provide moderation. The configuration class also has the waste package basket remaining intact; therefore, the entire amount of neutron absorbing poison (i.e., boron) remains inside the waste package. The resultant geometry of this configuration class has the PWR waste form mobilized and collecting within the basket structure.

Based on the configuration class information and parameters (i.e., the PWR waste form has degraded and all neutron absorbing poison remains), the PWR waste form loaded in the waste package can not become critical. Thus, the configuration class has no potential for criticality.

Configuration class IP-1b with a PWR waste form loaded into a waste package requires no probability analysis since the configuration class can not become critical. Top event CRIT-POT-FUEL is set to FALSE (i.e., the PWR waste form can not go critical for this particular configuration class) in the SAPHIRE model. By setting this top event to FALSE, this sets all of configuration class IP-1b sequences to a zero probability; therefore, these sequences do not contribute to the overall probability.

6.7.2.3 Configuration Class IP-2a

Configuration class IP-2a is described as the class in which both the waste package structures and the waste form have degraded and the soluble neutron absorber is flushed from the waste package. This class can be reached via four different sequences. All of the sequences end at the same configuration, both the PWR waste form and the waste package internals have degraded and are located on the bottom of the waste package. All of the sequences are expressed in Table 6-8, which lists the process events, their description, and provides the probability assigned to each process. If no probability analysis is required for the top events, then N/A is used to represent that no probability was calculated. The processes are listed in sequential order as they

Table 6-8. Configuration Class IP-2a Event Tree Sequences

Event Tree Top Event	Top Event Identifier	Assigned Probability
	Sequence 1	
MS-IC-1	Water reaches drift	N/A
MS-IC-2	Water drips on waste package	N/A
MS-IC-3	Waste package penetration at top surface	N/A
MS-IC-4	Liquid accumulates in waste package	N/A
MS-IC-6	Waste package internal structures degrade slower than waste form	N/A
MS-IC-10	Waste package internal structures degrade	N/A
MS-IC-13	Degraded waste form and waste package components collect at bottom waste package	N/A
MS-IC-14	Soluble neutron absorbers flushed from waste package	N/A
WF-TYPE	Waste form degrades according to configuration class	N/A
CRIT-POT-FUEL	Criticality potential of waste form	FALSE
	Sequence 2	
MS-IC-1	Water reaches drift	N/A
MS-IC-2	Water drips on waste package	N/A
MS-IC-3	Waste package penetration at top surface	N/A
MS-IC-4	Liquid accumulates in waste package	N/A
MS-IC-7	Waste package internal structures degrade at the same rate as waste form	N/A
MS-IC-13	Degraded waste form and waste package components collect at bottom waste package	N/A
MS-IC-14	Soluble neutron absorbers flushed from waste package	N/A
WF-TYPE	Waste form degrades according to configuration class	N/A
CRIT-POT-FUEL	Criticality potential of waste form	FALSE
	Sequence 3	
MS-IC-1	Water reaches Drift	N/A
MS-IC-2	Water drips on waste package	N/A
MS-IC-3	Waste package penetration at top surface	N/A
MS-IC-4	Liquid accumulates in waste package	N/A
MS-IC-8	Waste package internal structures degrade faster than waste form	N/A
MS-IC-16	Basket structural supports mechanically collapse	N/A
MS-IC-17	Structures containing neutron absorbers fully degrade	N/A
MS-IC-20	Waste form degrades mobilizing fissionable material	N/A
MS-IC-13	Degraded waste form and waste package components collect at bottom waste package	N/A
MS-IC-14	Soluble neutron absorbers flushed from waste package	N/A
WF-TYPE	Waste form degrades according to configuration class	N/A
CRIT-POT-FUEL	Criticality potential of waste form	FALSE
	Sequence 4	
MS-IC-1	Water reaches drift	N/A
MS-IC-2	Water drips on waste package	N/A
MS-IC-3	Waste package penetration at top surface	N/A
MS-IC-4	Liquid accumulates in waste package	N/A
MS-IC-8	Waste package internal structures degrade faster than waste form	N/A
MS-IC-22	Significant neutron absorber degradation before structural collapse	N/A
MS-IC-23	Waste package internal structures mechanically collapse and degrade	N/A
MS-IC-20	Waste form degrades mobilizing fissionable material	N/A
MS-IC-13	Degraded waste form and waste package components collect at bottom waste package	N/A
MS-IC-14	Soluble neutron absorbers flushed from waste package	N/A
WF-TYPE	Waste form degrades according to configuration class	N/A
CRIT-POT-FUEL	Criticality potential of waste form	FALSE

lead to configuration class IP-2a. The table is separated into parts based on the different sequences required to achieve configuration class IP-2a.

The different processes and sequences listed in Table 6-8 ultimately end in the same configuration class. This final configuration class, designated as IP-2a, has both the PWR waste form and waste package internals fully degraded and settled on the bottom of the waste package. The different sequences have either the PWR waste form degrading first then the waste package internals degrade, both waste package internals and PWR waste form degrade at the same rate, or waste package internal structures degrade first, followed by the PWR waste form. The intermediate configurations where just the PWR waste form degrades are discussed in degradation scenario IP-1. The intermediate configurations where just the waste package internals degrade are discussed in degradation scenario IP-3.

Configuration class IP-2a with a PWR waste form loaded into a waste package requires no probability analysis since the configuration class cannot become critical. The PWR waste form can not go critical in this configuration class since the fissionable materials have been removed from the fuel assemblies and are mixed with the waste package internal structure degradation products. Soluble materials, both fissile and absorbers, have separated and been flushed from the waste package. Since this configuration class has both the waste package internal structure and the PWR waste form in a degraded state and settled onto the bottom of the waste package, the k_{eff} will never go above the critical limit (e.g., BSC 2001i, Section 6). Therefore, no further analysis is required for this configuration class. Top event CRIT-POT-FUEL is set to FALSE (i.e., the PWR waste form can not go critical for this particular configuration class) in the SAPHIRE model. This sets configuration class IP-2a sequences to a zero probability; therefore, these sequences do not contribute to the overall probability.

6.7.2.4 Configuration Class IP-3a

Configuration class IP-3a is described as the as the class in which the waste package internals degrade faster than the PWR waste form and the waste package is in a bathtub configuration. This configuration class also has the degraded waste package basket collapsing due to the weight of the PWR waste form and none of the neutron absorber has been flushed from the waste package. The processes required to obtain configuration class IP-3a as defined by the CGM event tree (Figures I-10 through I-12) are listed in Table 6-9. Table 6-9 lists the process events, their description, and provides the probability assigned to each process. If no probability analysis is required for the top events, then N/A is used to represent that no probability was calculated. The processes are listed in sequential order as they lead to configuration class IP-3a.

A PWR waste form loaded in a waste package can become critical given that certain requirements and parameters are met. The two most important parameters required for in-package criticality are moderation and loss of neutron absorbing poison. Another important parameter or feature is the geometry of the PWR waste form inside the waste package. For configuration class IP-3a, the waste package internal structure has degraded to a point where the basket structure collapses. This configuration class assumes the waste package is full of water or has a sufficient amount of water to provide moderation. This configuration class also has the PWR waste form remaining intact with none of the neutron absorber poison (i.e., boron) flushed from the waste package.

Table 6-9. Configuration Class IP-3a Event Tree Sequences

Event Tree Top Event	Top Event Identifier	Assigned Probability
MS-IC-1	Water reaches drift	N/A
0MS-IC-2	Water drips on waste package	N/A
MS-IC-3	Waste package penetration at top surface	N/A
MS-IC-4	Liquid accumulates in waste package	N/A
MS-IC-8	Waste package internal structures degrade faster than waste form	N/A
MS-IC-16	Basket structural supports mechanically collapse	N/A
WF-TYPE	Waste form degrades according to configuration class	N/A
CRIT-POT-FUEL	Criticality potential of waste form	FALSE

Based on the configuration class information and parameters (i.e., all the neutron absorbing poison remains), the PWR waste form loaded in the waste package can not become critical. Therefore, the configuration has no potential for criticality.

Configuration class IP-3a with a PWR waste form loaded into a waste package requires no probability analysis since the configuration can not become critical. Top event CRIT-POT-FUEL is set to FALSE (i.e., the PWR waste form can not go critical for this particular configuration class) in the SAPHIRE model. By setting this top event to FALSE, this sets configuration class IP-3a sequences to a zero probability; therefore, these sequences do not contribute to the overall probability.

6.7.2.5 Configuration Class IP-3b

Configuration class IP-3b is described as the as the class in which the waste package internals degrade faster than the PWR waste form and the waste package is in a bathtub configuration. This configuration also has the degraded waste package basket collapsing due to the weight of the PWR waste form and some of the neutron absorber has been flushed from the waste package. The processes required to obtain configuration class IP-3b, as defined by the CGM event tree (Figures I-10, I-13, and I-14), are listed in Table 6-10. Table 6-10 lists the process events, their description, and provides the probability assigned to each process. If no probability analysis is required for the top events, then N/A is used to represent that no probability was calculated. The processes are listed in sequential order as they lead to configuration class IP-3b.

For configuration class IP-3b, the waste package internal structure has degraded to a point where the basket structure collapses. This configuration class assumes the waste package is full of water or has a sufficient amount of water to provide moderation. This configuration class also has the PWR waste form remaining intact with the degraded portion of neutron absorber poison (i.e., boron) flushed from the waste package.

Table 6-10. Configuration Class IP-3b Event Tree Sequences

Event Tree Top Event	Top Event Identifier	Assigned Probability
MS-IC-1	Water Reaches Drift	N/A
MS-IC-2	Water Drips on waste package	N/A
MS-IC-3	Waste package penetration at top surface	N/A
MS-IC-4	Liquid accumulates in waste package	N/A
MS-IC-8	Waste package internal structures degrade faster than waste form	N/A
MS-IC-16	Basket structural supports mechanically collapse	N/A
MS-IC-18	Soluble neutron absorbers flushed from degraded portion of waste package basket	N/A
WF-TYPE	Waste form degrades according to configuration class	N/A
CRIT-POT-FUEL	Criticality potential of waste form	FALSE

Using the information and parameters for this configuration class, the PWR waste form loaded in the waste package does not have the potential of becoming critical due to only a portion of the neutron absorber being degraded and flushed from the waste package. As the neutron absorber is being degraded and flushed from the waste package, degradation products from internal structural elements are increasing which affects reactivity through moderator exclusion and homogenization of the internal geometry, keeping the waste package in a subcritical condition. Since the part of the neutron absorbing material remains in the waste package and degradation products are increasing, there is no potential of the waste package becoming critical (see discussion for configuration class IP-2a). Thus, the configuration class has no potential for criticality.

Configuration class IP-3b with a PWR waste form loaded into a waste package requires no probability analysis since the configuration can not become critical. Top event CRIT-POT-FUEL is set to FALSE (i.e., the PWR waste form can not go critical for this particular configuration class) in the SAPHIRE model. Setting this top event to FALSE results in setting all of configuration class IP-3b sequences to a zero probability. Therefore, these sequences do not contribute to the overall probability.

6.7.2.6 Configuration Class IP-3c

Configuration class IP-3c is described as the class in which the waste package internals degrade faster than the PWR waste form and the waste package is in a bathtub configuration. This configuration class also has the waste package internals fully degraded and all of the neutron absorber flushed from the waste package. The processes required for configuration class IP-3c as defined by the CGM event tree (Figures I-10, I-15, and I-16) are listed in Table 6-11. Table 6-11 lists the process events, their description, and provides the probability assigned to each process. The processes are listed in sequential order as they lead to configuration class IP-3c. Table 6-11 provides a summary of the independent top events on the CGM event tree. The process used to calculate each of these top event probabilities is discussed in the following subsections.

Two probabilities are listed for the processes that are generated for configuration class IP-3c. The two probabilities are based on having an early waste package failure or not having an early waste package failure. The TSPA-SR baseline results assume there are no early waste package failures (CRWMS M&O 2000b, p. 3-92). The early waste package failure is a sensitivity analysis that was performed in Subsection 7.3.6 of *FY01 Supplemental Science and Performance Analyses, Volume 1: Scientific Bases and Analyses* (BSC 2001c). Since both of these cases have been discussed in previous documents, they were analyzed using the CGM.

A PWR waste form loaded in a waste package can become critical given that certain requirements and parameters are met. The two most important parameters required for in-package criticality are moderation and loss of neutron absorbing poison. Another important parameter or feature is the geometry of the PWR waste form inside the waste package. For configuration class IP-3c, the waste package internal structure has completely degraded. This configuration class assumes the waste package is full of water or has a sufficient amount of water to provide moderation. This configuration class also has the PWR waste form remaining intact with the entire amount of neutron absorber poison (i.e., boron) flushed from the waste package.

Based on the configuration class information and parameters, the PWR waste form loaded in the waste package has the potential to become critical. Because of this criticality potential, a probabilistic analysis is performed. For the probabilistic analysis, the following subsections discuss how the process probabilities listed in Table 6-11 are obtained. The probability calculations are based on the probability density functions of Section 6.6 and probabilities identified from other sources.

Table 6-11. Configuration Class IP-3c Event Tree Sequences

Event Tree Top Event	Top Event Identifier	Baseline Probability	Early Failure Sensitivity
	Sequence 1		
MS-IC-1	Water reaches drift 10,000 years 25,000 years 50,000 years	 FALSE FALSE FALSE	 7.82×10^{-7} 9.79×10^{-3} 3.92×10^{-2}
MS-IC-2	Water drips on waste package 10,000 years 25,000 years 50,000 years	 5.89×10^{-1} 6.27×10^{-1} 8.83×10^{-1}	 5.89×10^{-1} 6.28×10^{-1} 8.83×10^{-1}
MS-IC-3	Waste package penetration at top surface 10,000 years 25,000 years 50,000 years	 FALSE FALSE $2.48\times10^{-}$	 1.01×10^{-1} 1.01×10^{-1} 1.03×10^{-1}
MS-IC-4	Liquid accumulates in waste package 10,000 years 25,000 years 50,000 years	 FALSE FALSE 2.30×10^{-1}	 6.08×10^{-1} 2.27×10^{-1} 3.75×10^{-2}
MS-IC-8	Waste package internal structures degrade faster than waste form	1.0	1.0
MS-IC-16	Basket structural supports mechanically collapse	1.0	1.0
MS-IC-17	Structures containing neutron absorbers fully degrade	1.0	1.0
MS-IC-19	Soluble neutron absorbers flushed from waste package 10,000 years 25,000 years 50,000 years	 FALSE FALSE FALSE	 8.61×10^{-4} 5.27×10^{-1} 9.36×10^{-1}
WF-TYPE	Waste form degrades according to configuration class	TRUE	TRUE
MISLOAD	Waste package loading does not violate waste form loading curve	1.00	1.00
CRIT-POT-FUEL	Criticality potential of waste form 10,000 years 25,000 years 50,000 years	 2.90×10^{-2} 3.10×10^{-2} 2.90×10^{-2}	 2.90×10^{-2} 3.10×10^{-2} 2.90×10^{-2}
	Sequence 2		
MS-IC-1	Water reaches drift	N/A	N/A
MS-IC-2	Water drips on waste package	N/A	N/A
MS-IC-3	Waste package penetration at top surface	N/A	N/A
MS-IC-4	Liquid accumulates in waste package	N/A	N/A
MS-IC-8	Waste package internal structures degrade faster than waste form	1.0	1.0
MS-IC-22	Significant neutron absorber degradation before structural collapse occurs	FALSE[a]	FALSE[b]
MS-IC-23	Waste package internal structures mechanically collapse and degrade	N/A	N/A
MS-IC-19	Soluble neutron absorbers flushed from waste package		
WF-TYPE	Waste form degrades according to configuration class	N/A	N/A
CRIT-POT-FUEL	Criticality potential of waste form	N/A	N/A

NOTE: [a]For the probabilistic analysis, top event MS-IC-22 was set to FALSE since sequence 1 was chosen as the representative degradation process for this configuration class.

6.7.2.6.1 Top Event MS-IC-1 Probability

Top event MS-IC-1 is the water reaching the drift with the potential to penetrate the waste package in order to degrade the Neutronit and flush the soluble boron. This top event has two separate evaluations, one for the baseline of no early waste package failures (CRWMS M&O 2000b, p. 3-92), and the second for the sensitivity analysis of an early waste package failure due to improper heat treatment (BSC 2001c). The probability of having sufficient seepage into a waste package is based on many factors. These factors are the time step of interest, breach size of the drip shield and waste package, and evaporation rate. All of these factors play an important part in determining the probability of the seepage flux.

This top event probability is evaluated for each time step using the glacial transition climate. The glacial transition climate was chosen for all time steps since it is the representative climate after 10,000 years (CRWMS M&O 2000b, Subsection 3.2.1). In order to determine the probability at each time step, seepage flux parameters, which fit a beta distribution, need to be determined. The seepage flux parameters are determined by taking the infiltration flux of the glacial transition and multiplying this value by a focusing factor. The focusing factor is used to account for the fractures within the mountain. This process for obtaining the seepage flux used for the probabilistic calculation is discussed in Subsection 6.4.3 of *Abstraction of Drift Seepage* (CRWMS M&O 2001a) and in this subsection. The seepage flux parameters and information are also discussed in Attachment IV.

The glacial transition climate is assumed to follow a triangular distribution with a minimum, peak, and maximum infiltration rate. The cumulative distribution for the glacial transition climate is shown in Section 6.6. Each triangular distribution point has a specific focus factor that is loguniformly distributed. For this particular analysis, the median focus factor at each triangular distribution point (minimum, peak, and maximum) is selected. The selected minimum focus factor is multiplied to the minimum glacial transition infiltration rate, the peak focus factor is multiplied to the peak infiltration rate and finally, the maximum focus factor is multiplied to the maximum infiltration rate. The new minimum, peak, and maximum infiltration rates are used to calculate a mean infiltration rate. The mean infiltration rate is used to select the minimum, peak, and maximum seepage flux mean, seepage flux standard deviation, and seepage fraction from Table 16 of *Abstraction of Drift Seepage* (CRWMS M&O 2001a).

The selected minimum, peak, and maximum seepage flux mean values are used to calculate the mean seepage flux that is used to determine the seepage flux probability. The standard deviation mean value is also calculated using the minimum, peak, and maximum values. The calculated mean and standard deviation (mean of 0.635 and standard deviation of 0.412) are fit to a beta distribution. The beta distribution is shown in Section 6.6.

The seepage fraction is calculated by dividing the focus factors into the seepage fraction values obtained from Table 16 of *Abstraction of Drift Seepage* (CRWMS M&O 2001a). The minimum seepage fraction is divided by the minimum focus factor, peak seepage fraction by peak focus factor and finally, maximum seepage fraction by maximum focus factor. The mean value of the seepage fraction is calculated using the minimum, peak, and maximum values. The mean seepage fraction used in this calculation is 4.47×10^{-2}. The seepage fraction is used for all time steps.

The various end states of a configuration class (Subsection 6.4.1) are evaluated for their potential for criticality without necessarily quantifying the probability of achieving such a state. End states of a configuration class are marked as having potential for criticality if their essential parameters have values in the range that can support criticality. The sequences to those particular end states are then backtracked to assess the probabilities that the parameters can actually have the requisite values. Summing these probabilities is the method for estimating the probability of occurrence of a configuration class (Figure 6-1). The parameter values essential for criticality are correlated, but the probability distributions for the random variables in the set are independent. Thus, an iterative approach may be necessary to maximize the probability of occurrence based upon the correlated variables. The process is time-dependent so that the assigned probabilities include the additional requirement that the parameter values must be realized within a given time period. The probability of criticality is set to zero for all end states of the configuration class that are not marked as having potential for criticality.

The seepage flux required for a potential criticality is one such essential variable and is dependent upon or correlated with drip shield failure, waste package failure, degradation of Neutronit, and the flushing of the soluble boron. In order to calculate the probability of seepage flux, these additional parameters need to be determined which dictate how much seepage is required to flush the boron from the waste package in order for it to become critical. The probability distribution used for this calculation is the seepage flux beta distribution with the mean and standard deviation listed above. The probability is calculated based on the amount of seepage required at each time step. The probability equation used for the calculation (see Equation 1) is defined as

$$F_X(x) = P(x \geq X) = \int_x^{\infty} f_X(x')dx' \qquad \text{(Eq. 23)}$$

where X represents the minimum seepage flux required to allow the correlated variables essential for criticality to be within the range where criticality is possible (i.e., the required seepage flux "x" is equal to or greater than X). The function f_x represents a beta distribution with a mean of 0.635 and standard deviation of 0.412.

The probabilities calculated for the top event, MS-IC-1, at each of the time steps are listed in Table 6-12. Table 6-12 lists the smallest possible seepage flux based on the parameters to degrade the Neutronit and flush the boron from the waste package, which in turn gives the most conservative probability. The minimum seepage flux listed in Table 6-12 is obtained from solving Equation 24. Equation 24 identifies the minimum seepage flux required to generate potentially critical configurations. The equation accounts for the flow volume that can penetrate the drip shield and waste package due to penetrations. The equation also takes into account the amount of flow that can be evaporated from the decay heat of the waste package. Therefore, Q_{seep} represents the minimum seepage flux required to reach the drift in order to penetrate both the drip shield and waste package, and degrade and flush the boron from the waste package. $Q_{required}$ represents the required seepage into a waste package to degrade the Neutronit and flush the boron. $Q_{evaporated}$ represents the amount of seepage that can be evaporated due to decay heat; therefore, increasing the amount of seepage required to reach the drift. P_{FTDS} and P_{FTWP} represent the penetration openings in the drip shield and waste package that allow seepage to penetrate. The P_{FTDS} and P_{FTWP} functions are discussed in Subsections 6.6.4.1 and 6.6.6.1, respectively. The $Q_{required}$ function is defined as part of the Boron Loss Model discussed in Attachment X.

$$Q_{seep} = \frac{Q_{required}}{P_{FTDS} * P_{FTWP}} + Q_{evaporated} \quad \text{(Eq. 24)}$$

The evaporation rate ($Q_{evaoprated}$) uses Equation 7. Information about the evaporation rate is discussed in Section 6.6 and Assumption 6.6.1.2. The evaporation rates used in calculating Q_{seep} are listed in Table 6-12.

Table 6-12. Probabilities Assigned to Top Event MS-IC-1

Time Step	Baseline Seepage Flux [P(sf ≥ X)]	Sensitivity Seepage Flux [P(sf ≥ X)]	Evaporation Rate (m³/yr)	Seepage Fraction (Baseline & Sensitivity)
10,000 yrs	N/A [FALSE]	2.95 m³/yr [1.75×10^{-5}]	0.0121	4.47×10^{-2}
25,000 yrs	N/A [FALSE]	0.922 m³/yr [0.219]	0.00286	4.47×10^{-2}
50,000 yrs	>4.12 m³/yr [FALSE]	0.242 m³/yr [0.833]	0.00096	4.47×10^{-2}

6.7.2.6.2 Top Event MS-IC-2 Probability

Top event MS-IC-2 requires two separate probability evaluations to be performed. The first evaluation is the probability of failure for the top event and the second is the probability that an advective flow path coincides with the failure location. The probability evaluation for this top event is based on the mechanisms that allow seepage to penetrate the drip shield and hit the waste package. The advective flow evaluation is based on the size of the advective flow path. Both of these evaluations are discussed in this subsection.

The probability of failure for this top event has multiple events that can allow advective flow to impinge the waste package. This top event is broken down into two distinct failure mechanisms. The first mechanism is classified as static failures and the second mechanism is classified as dynamic failures. The distinction between the two failure mechanisms is how the failure probability is determined. The static failure probability remains the same for all time steps where the dynamic failure probability changes at each time step.

The static failures are defined on the MS-IC-2 fault tree (Figure II-2) listed in Attachment II. The static failure mechanisms are emplacement error, floor heave, thermal expansion, rockfall, and fabrication error. The only failure mechanisms evaluated are those that have potential to result in an advective flow. Therefore, not all of these failure mechanisms have a probability assigned to them. Another reason for only obtaining a probability for a subset of these mechanisms is due to the size of their flow paths through the drip shield since a minimum size is required to support advective flow. The failure probability calculated for these static failures remains the same for all time steps.

From the static failures on the fault tree, two are evaluated to obtain a failure probability. These two failure mechanisms are rockfall and emplacement error (see Assumptions 6.6.1.6 and

6.6.1.8). The method for calculating the drip shield failure probability due to rockfall is discussed in Attachment IX. The calculations are contained in an Excel spreadsheet file "prob of rockfall on WP-4MT.xls" (Attachment XII). The probability of a rock greater than four metric tons falling onto the drip shield is 3.13×10^{-3}. A rock of this magnitude is required to cause a crack large enough in the drip shield to allow for advective flow (see Attachment IX).

The other static failure mechanism evaluated is drip shield emplacement error. The failure probability for this mechanism is 9.0×10^{-5}/drip shield, which is listed in *Analysis of Mechanisms for Early Waste Package Failure* (CRWMS M&O 2000d, p. 62). The Binomial process is used to calculate the probability of a drip shield being incorrectly placed in the drift. Approximately 9,840 drip shields are anticipated to be placed in the repository. The 9,840 drip shields are calculated from a drip shield length of 6.1 m and 60,000-m of drift (DOE 2001b, Tables 2-2 and 2-22). The Binomial process can be approximated by the Poisson process when there are a large number of independent events and a small probability of failure (Walpole et al. 1998, Section 5.6). The probability is based on the failure by misplacement of one or more drip shields. Equation 25 was used to perform this calculation.

$$P(\text{1 or more DS failures}) = 1 - P(\text{0 DS failures}) = 1 - \frac{e^{-\mu}\mu^{x}}{x!} \qquad \text{(Eq. 25)}$$

where

x = the expected number of drip shield emplacement errors
$\mu = n*p$
n = the total number of emplacements, 9,840
p = the probability of a single drip shield emplacement error, 9.0×10^{-5}.

The probability of one or more drip shields incorrectly placed in any of the drifts within the repository is 0.588. The misplacement of a drip shield allows for an advective flow path. This calculation represents that an advective flow is created due to a misplaced drip shield. The size of the advective flow path due to the drip shield emplacement error is discussed later.

The dynamic failure represents general corrosion of the drip shield. This failure probability changes at each time step due to corrosion of the drip shield. This failure mechanism uses the fraction of drip shield failures at each time step as the failure probability. The failure probability assigned to this event uses the mean curve for the fraction of drip shield failures.

After calculating the probability for each event, the fraction of the seepage flux reaching the waste package needs to be determined. This fraction is used to determine the amount of seepage flux required for top event MS-IC-1. To calculate the fractional area of a failed drip shield allowing advective flow, the average number of patches per failed drip shield within the time step is used. For the static failure mechanisms, assumptions are used to determine the fractional area of a failed drip shield. The following paragraphs discuss how this fractional is calculated to allow advective flow.

For static failures, assumptions are necessary to estimate the size of an advective flow path that is created. From all of the static failures, two mechanisms are assumed to allow advective flow through the drip shield (i.e., emplacement error and rockfall). The emplacement error is defined as the failure of an operator installing the drip shields to interlock one drip shield to the previously installed drip shield. The gap created by this emplacement error is 30 cm (see Assumption 6.6.1.8). This gap correlates to an advective flow path of 30 cm. The advective flow path is divided by the 610-cm length of the drip shield to obtain the fraction of drip shield that allows flow to reach the waste package. The fractional length of a drip shield that allows advective flow due to emplacement error is 0.0492.

The rockfall gap is based on the crack generated from a four metric ton rock. It is estimated (CRWMS M&O 2000e, Table 6-1) that a four-metric-ton rockfall will create a crack of 13 cm in the drip shield. The orientation of the crack can be either lengthwise or crosswise of the drip shield. To account for these orientations and their variations, the crack length is weighted by the probability of proper orientation which is one-half since either orientation is equally likely. Therefore, the fractional gap length through the drip shield that allows advective flow due to rockfall is 0.0107 (i.e., 0.5 ×13 cm divided by the drip shield length [see Equation 9]).

The general corrosion gap is based on the patch growth of the drip shield. The number of patches increase over time and, therefore, increase the area of the drip shield available for advective flow. The area used for advective flow is based on the number of (failed) patches divided by the total number of patches assumed to possibly exist on the drip shield, then additionally divided by two since a patch can occur on either side of the drip shield (as discussed relative to Equation 8). The probability of an advective flow path through the drip shield due to general corrosion is assumed to be one after more than half of the drip shield has failed due to corrosion patches.

The failure probabilities used for the events at each time step are listed in Table 6-13. The emplacement failure probability and rockfall probability are discussed above. The failure probability due to general corrosion is obtained from Subsection 6.6.4.1, Figure 6-9. Table 6–13 also lists the fractional area of a drip shield that allows advective flow. The advective flow is based on the area of the penetration openings through the drip shield from emplacement error, rockfall, and general corrosion. Equation 9 in Subsection 6.6.4.1 is used to calculate the fractional area (probability) of a drip shield available for advective flow. The fractional area of a drip shield that allows advective flow, P_{FTDS}, is placed into Equation 24 and is used to obtain the seepage flux.

Table 6-13. Probability of Drip Shield Failures and Fractional Area of Drip Shield Allowing Advective Flow

Time Step	Emplacement Error	Rockfall	General Corrosion	Fractional Area of Drip Shield Allowing Advective Flow
10,000 yrs	5.88×10^{-1}	3.13×10^{-3}	0.0	5.99×10^{-2}
25,000 yrs	5.88×10^{-1}	3.13×10^{-3}	9.30×10^{-2}	6.45×10^{-2}
50,000 yrs	5.88×10^{-1}	3.13×10^{-3}	7.15×10^{-1}	1.28×10^{-1}

6.7.2.6.3 Top Event MS-IC-3 Probability

Top event MS-IC-3 deals with the failure of the waste package. This top event has two separate evaluations, one for the baseline of no early waste package failures (CRWMS M&O 2000b, p. 3–92), and the second for the sensitivity analysis of an early waste package failure due to improper heat treatment (BSC 2001c). The probability evaluation for both cases is further broken down into two separate parts. The first part is to calculate the failure probability for the top event and the second part is to calculate the fractional surface area (probability) for an advective flow path. The probability calculation for this top event is based on the mechanisms that allow seepage to penetrate the waste package. The advective flow path calculation is based on the gap size in the waste package outer shell (see Assumption 6.6.1.9), which allows seepage into the waste package. Both of these calculations are discussed in this subsection.

This top event has two failure mechanisms that allow advective flow to penetrate the waste package. These two failure mechanisms are broken down into static failures and dynamic failures. The distinction between the two failure mechanisms is how the failure probability is determined. The static failure probability remains constant for all time steps whereas the dynamic failure probability changes at each time step.

The static waste package failure on the MS-IC-3 fault tree (Figure II-3) listed in Attachment II is defined as improper heat treatment of the waste package closure lid. This failure mechanism represents the sensitivity analysis from Subsection 7.3.6 of *FY01 Supplemental Science and Performance Analyses, Volume 1: Scientific Bases and Analyses* (BSC 2001c). The TSPA-SR baseline analysis assumed no early waste package failures; therefore, this event (MS-IC-3-2) is set to a zero probability for the baseline analysis. However, for the sensitivity analysis, improper heat treatment of the waste package has a calculated failure probability. The probability of improper heat treatment causing an early failure of the waste package and allowing advective flow is 2.23×10^{-5} per waste package (BSC 2001c, p. 7-62).

The failure probability of 2.23×10^{-5}/waste package is used to calculate the probability of having one or more failed waste packages. Only the failed waste packages can allow advective flow, which is required for criticality. In order to calculate the probability, the Poisson process is used, as it is an appropriate statistical process for sample sets that have a large population but only a small probability of "success events" (Walpole et al. 1998, pp. 138 to 139). There are approximately 4,775 21-PWR with Absorber Plates Waste Packages are anticipated to be placed in the monitored geologic repository. This number is found by adjusting Table 3-8 of *Yucca Mountain Science and Engineering Report* (DOE 2001b) to 70,000 metric tons of heavy metal (MTHM). Note that nominal number of 21-PWR with Absorber Plates Waste Packages is 4,299 from the Case A Legal Limit scenario in *Waste Packages and Source Terms for the Commercial 1999 Design Basis Waste Stream* (CRWMS M&O 2000o, Table 10). The probability calculation represents the improper heat treatment of one or more waste packages. Equation 26 was used to perform this calculation.

$$P(\text{1 or more WP failures}) = 1 - P(\text{0 WP failures}) = 1 - \frac{e^{-\mu}\mu^{x}}{x!} \qquad \text{(Eq. 26)}$$

where

x = the expected number of improperly heat treated waste packages
$\mu = n*p$
n = the total number of 21-PWR with Absorber Plates Waste Packages, 4,775
p = the probability of a single improper heat treatment, 2.23×10^{-5}.

The probability that one or more 21-PWR with Absorber Plates Waste Packages are improperly heat-treated is 0.101. (The probability value for 4,299 waste packages is 0.090 that, if used, would reduce the calculated probabilities in subsequent subsections). The improperly heat treated waste package allows for an advective flow path. This is the probability that an advective flow path is created in a waste package. The size of the advective flow path due to improper heat treatment of the waste package is discussed later in this subsection.

The dynamic failure probability is based on general corrosion of the waste package. This failure probability changes at each time step due to corrosion of the waste package. This failure mechanism uses the fraction of waste package failures at each time step as discussed in Subsection 6.6.5. The failure probability assigned to the event uses the mean curve for the fraction of waste package failures.

The fraction of the seepage flux penetrating the waste package, based on the probabilities for the two events, is used to determine the amount of seepage flux required for top event MS-IC-1. To calculate the fractional area of a failed waste package allowing advective flow, the average number of patches within a time step per failed waste package is used for the dynamic failures. For the static failure mechanism, assumptions are used (see Assumption 6.6.1.9) to determine the fractional area of a failed waste package. The following discusses how the fractional area of a failed waste package is calculated to allow for advective flow.

For improper heat treatment, Equations 27 and 28 are used to calculate the fractional area (probability) of a failed waste package allowing advective flow (these equations are the same as Equations 11 and 12 listed in Subsection 6.6.6.1). The equations are listed below with their inputs.

$$P_{WP\_SCC} = \frac{L_{WP\_SCC}}{L_{WP} + L_{WP\_SCC}} \qquad \text{(Eq. 27)}$$

The length of a crack due to improper heat treatment is obtained as follows:

$$L_{WP\_SCC} = \lambda_{LID} \sin(\alpha) \qquad \text{(Eq. 28)}$$

where

λ_{LID} = the diameter of the lid within the waste package skirt (1541 mm)
α = the maximum tilt angle of the waste package (8.8 degrees [BSC 2001b, Table 6]).

The fractional waste package length that allows advective flow calculated from Equation 27 is 0.0437.

The failure probabilities used for the events at each time step are listed in Table 6-14. The early failure probability is discussed previously in Subsection 6.6.4. The failure probability due to general corrosion of the waste package is obtained from Subsection 6.6.5.1, Figure 6-12. Table 6-14 also lists the fractional area of a waste package that allows advective flow. The advective flow is based on the number of penetration openings through the waste package within a time step from general corrosion (baseline) and general corrosion with improper heat treatment (form the sensitivity analysis). Equation 13 in Subsection 6.6.6.1 is used to calculate the total fractional area of a waste package, P_{FTWP} that can allow advective flow. This fractional area is placed into Equation 24 and is used to obtain the seepage flux as discussed on Subsection 6.7.2.6.1.

Table 6-14. Probability of Waste Package Failures and Fractional Area of Waste Packages that Allow Advective Flow

Baseline Analysis			Sensitivity Analysis	
Time Step	General Corrosion Probability	Fractional Area of Waste Packages for Advective Flow	Early Failure Probability	Fractional Area of Waste Packages for Advective Flow
10,000 yrs	0.0	0	1.01×10^{-1}	4.37×10^{-2}
25,000 yrs	0.0	0	1.01×10^{-1}	4.37×10^{-2}
50,000 yrs	2.48×10^{-3}	4.00×10^{-5}	1.01×10^{-1}	4.37×10^{-2}

6.7.2.6.4 Top Event MS-IC-4 Probability

Top event MS-IC-4 represents the seepage flux accumulating in the waste package. An advective flow path must be present in order for seepage to accumulate in the waste package. Two advective flow paths into the waste package have been discussed, they are improper heat treatment and general corrosion. The advective flow path due to improper heat treatment does not change over time. The advective flow path due to general corrosion increases with time due to the number of patches. Both of these advective flow paths assume the waste package failures are located on the top on a waste package, which allows water to accumulate within the waste package. This configuration is classified as the waste package bathtub configuration.

The bathtub configuration can exist until a failure occurs in the bottom of the waste package and all of the water is flushed from the waste package. Based on the WAPDEG analyses, a curve was generated detailing the duration the waste package is in a bathtub configuration. The bathtub duration is based on patch growth on the top and bottom of the waste package. The bathtub duration curve is used to calculate the probability that the waste package can accumulate and retain water. The probability of the bathtub duration is based on the time from waste package failure to the time step being evaluated. The probability is calculated assuming the bathtub duration lasts at least as long as the time from first breach to the time step being evaluated. The probability equation used for the calculation is defined in Equation 29.

$$F_X(x) = P(x \geq X) = \int_x^{\infty} f_X(x')dx' \qquad \text{(Eq. 29)}$$

where X represents the required minimum bathtub duration (i.e., the bathtub duration lasts at least as long as the time of first breach to the time step being evaluated or longer). The function f_x represents a Weibull distribution of waste package duration periods with alpha of 16,861.5 and beta of 1.1143 (see Attachment V).

The bathtub duration is based on the corrosion patches occurring on the top of the waste package. The bathtub duration used for calculating the probability is the time step being evaluated minus the time of first patch failure (i.e., time step 50,000 years - 37, 000 years first breach = bathtub duration of 13,000 years). Once a patch occurs on the bottom of the waste package the bathtub configuration is over and the accumulated water is flushed from the waste package. From the WAPDEG analyses and the information discussed in Subsection 6.6.6.2, less than half of all waste packages are in a bathtub configuration at some time. Using the WAPDEG analyses presented in Case (2001), the probability that a waste package is in a bathtub configuration is 0.486 where the alternative configuration has the first patch occurring on the bottom of the waste package. This probability is used only with the waste packages that fail due to general corrosion.

The probabilities for a bathtub duration used in both the baseline analysis and the sensitivity analysis are listed in Table 6-15. Table 6-15 lists the probabilities based on the duration of the bathtub configuration at each time step. It also lists the probability that a waste package will actually have bathtub configuration for those waste packages that fail due to general corrosion (i.e., upper part of the waste package fails before the lower part). The bathtub configuration probability is multiplied with the waste package baseline duration probability to obtain the total probability that a waste package is in a bathtub configuration for the baseline analysis (i.e., column 2 is multiplied with column 3 of Table 6-15 only) since these probabilities are independent. The probability of a bathtub configuration starts at the time of first breach of the waste package and ends at the time step being evaluated. For the baseline analysis, the first patch failure of the waste package occurs at 37,000 years, beyond the 10,000-year period of regulatory concern. For the sensitivity analysis, the first waste package fails due to improper heat treatment at 1,000 years after closure of the repository (CRWMS M&O 1999b, Section 3.9).

Table 6-15. Probability of Bathtub Duration

Time Step	Probability of Bathtub Configuration (general corrosion only)	Duration Probability (Baseline)	Duration Probability (Sensitivity Analysis)
10,000 yrs	4.86×10^{-1}	0.0	6.08×10^{-1}
25,000 yrs	4.86×10^{-1}	0.0	2.27×10^{-1}
50,000 yrs	4.86×10^{-1}	4.73×10^{-1}	3.75×10^{-2}

NOTE: Duration Probability values derived from Figure 6-14.

6.7.2.6.5 Top Event MS-IC-8 Probability

Top event MS-IC-8 represents the degradation of the waste package internal structures and the waste form. This top event states that the waste package internal structures degrade faster than the waste form. Based on the degradation information in Subsection 6.6.10, this top event has a probability of 1.0 for all time steps.

6.7.2.6.6 Top Event MS-IC-16 Probability

Top event MS-IC-16 represents the mechanical collapsing of the waste package basket structure. This configuration requires all of the boron to be flushed from the waste package; therefore, if all of the boron has been flushed from the waste package then the waste package basket has collapsed. This top event has a probability of 1.0 for all time steps since this a required event in this sequence.

6.7.2.6.7 Top Event MS-IC-17 Probability

Top event MS-IC-17 represents the waste package structures containing boron to be fully degraded. For this configuration, all of the boron is flushed from the waste package; therefore, if all of the boron has been flushed from the waste package then the waste package structures containing boron have fully degraded. This top event has a probability of 1.0 for all time steps since this a required event in this sequence.

6.7.2.6.8 Top Event MS-IC-19 Probability

Top event MS-IC-19 represents the corrosion rate of Neutronit. The calculated corrosion rate is based on the time required to corrode all of the Neutronit and flush it from the waste package. The corrosion rate is also dependent on the seepage flux into a waste package. For this configuration, all of the boron must be flushed from the waste package in order for it to become critical. The probability calculation uses the corrosion rate probability density function discussed in Subsection 6.6.10. To calculate the probability for this top event, the required corrosion rate to achieve this sequence needs to be determined based on the time step and the amount of seepage required to support the corrosion rate. The required seepage rate is discussed in Subsection 6.7.2.6.1.

The required seepage and the corrosion rate are correlated based on the boron loss equation discussed in Subsection 6.6.13 and Attachment X. The corrosion rate is obtained by adjusting both the corrosion rate and the seepage flux until all of the Neutronit has degraded and been flushed from the waste package. Because there are many different combinations that will cause all of the Neutronit to degrade and flush, many iterations of the boron loss equation were required to obtain the minimum corrosion rate and seepage flux. The boron loss equation was evaluated until the amount of boron remaining was approximately 0.5 moles. By minimizing the corrosion rate and seepage flux, this correlates to a larger, more conservative event probability as lower values of these variables, particularly the seepage flux, are more likely.

The minimum corrosion rate and seepage flux determined at each time step are now used to calculate their respective probability. The required seepage is used in Subsection 6.7.2.6.1 to obtain the seepage flux needed to reach the drift in order to penetrate the drip shield, waste package, and flush out the boron. The corrosion rate is placed into Equation 30 to determine the probability of having this corrosion rate or greater. To calculate the probability of having this corrosion rate or greater, the probability distribution for Neutronit is used. The probability distribution of Neutronit is a normal distribution with a mean and a standard deviation of 0.468 and 0.175 μm/yr, respectively (see Subsection 6.6.10.2 and Attachment VI). The probability is calculated based on the determined corrosion rate required at each time step. The probability equation used for the calculation is defined in Equation 30.

$$F_X(x) = P(x \geq X) = \int_x^{\infty} f_X(x')dx' \qquad \text{(Eq. 30)}$$

where X represents the minimum corrosion rate required to allow the correlated variables essential for criticality to be within the range where criticality is possible (i.e., the required corrosion rate "x" is equal to or greater than X). The function f_x represents a normal distribution for the corrosion rate.

The probabilities calculated for this top event at each of the time steps are listed in Table 6-16. Table 6-16 lists the lowest possible corrosion rate based on the parameters, which in turn gives the most conservative probability. The required seepage that was also determined with the minimum corrosion rate is listed in Table 6-16. The required seepage is fed into Equation 24 of Subsection 6.7.2.6.1.

Table 6-16. Probabilities Assigned to Top Event MS-IC-19 and Required Seepage

Time Step	Baseline Analysis Corrosion Rate [P(cr ≥ X)]	Baseline Analysis Required Seepage (m^3/yr)	Sensitivity Analysis Corrosion Rate [P(cr ≥ X)]	Sensitivity Analysis Required Seepage (m^3/yr)
10,000 yrs	N/A [FALSE]	N/A	1 μm/yr [8.61×10^{-4}]	0.00792
25,000 yrs	N/A [FALSE]	N/A	0.45 μm/yr [0.527]	0.00259
50,000 yrs	5 μm/yr [FALSE]	0.00338	0.2 μm/yr [0.94]	0.00135

6.7.2.6.9 Top Event WF-TYPE

Top event, WF-TYPE, is designed as a question to either continue with the analysis or stop the analysis. For this configuration, the waste form degrades slower than the waste package internal structures, therefore, this top event is set to TRUE (i.e., guaranteed to occur).

6.7.2.6.10 Top Event CRIT-POT-FUEL Probability

Top event, CRIT-POT-FUEL, represents the criticality potential of the waste form being analyzed. This top event can be used as a question to stop the analysis or in this case define the probability that a 21-PWR with Absorber Plates Waste Package can have a k_{eff} greater than the critical limit. This top event uses the fraction of waste packages that have a k_{eff} greater than the critical limit. An example of the fraction of waste packages having a k_{eff} greater than a critical limit of 0.98 at the different time steps is shown in Figure 6-18 (CRWMS M&O 1998b, Attachment IV). Figure 6-18 is based upon a fully flooded waste package, a 33 percent uniform oxide content, and complete loss of the boron absorber. The figure shows the fraction of waste packages containing PWR waste forms that have a k_{eff} greater than 0.98. This figure represents a random loading (not blended) of the PWR waste form into a 21-PWR with Absorber Plates Waste Package. (Note that the intact waste package k_{eff} will always be less than the critical limit based upon the waste form loading curve. Waste package misload events are discussed in Subsection 6.6.22.) Using the information provided from Figure 6-18, Table 6-17 lists, as a function of the time step, the fraction of a fully flooded waste packages loaded with the PWR waste form that have a k_{eff} greater than 0.98.

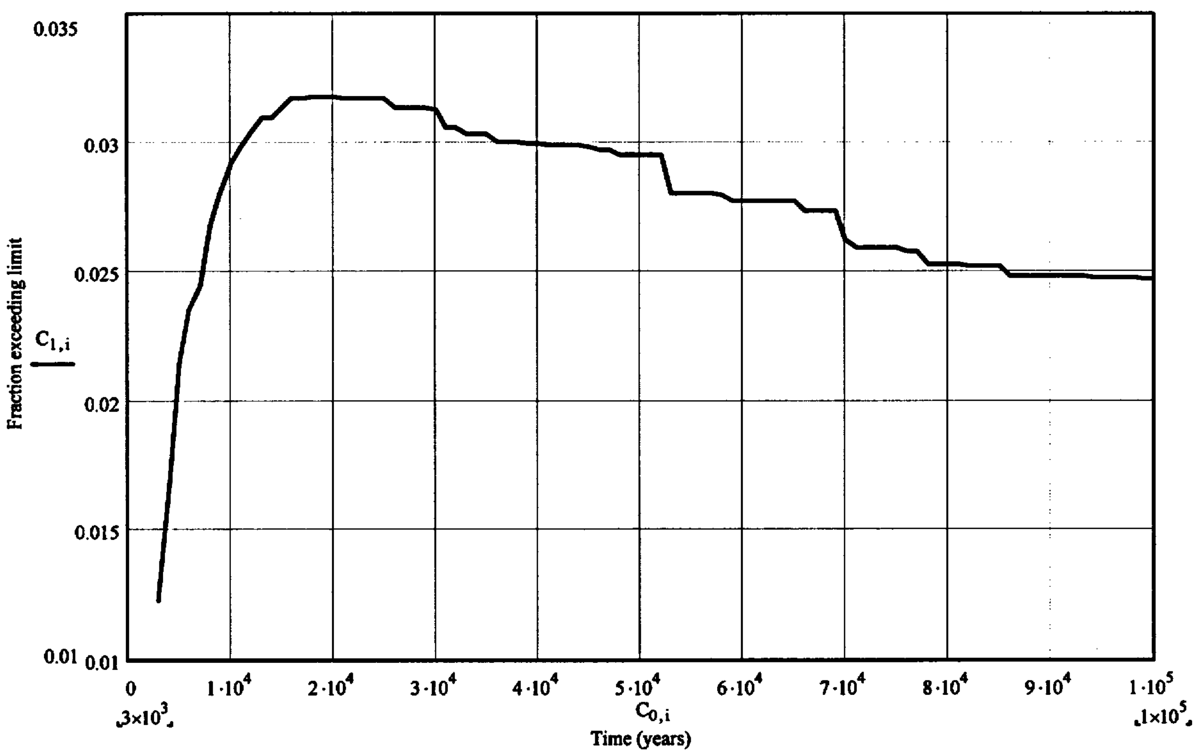


Figure 6-18. Fraction of Waste Packages with k_{eff} Exceeding 0.98 Using Fully Flooded Waste Package and 33 Percent Uniform Oxide

Figure 6-18 was abstracted from Attachment IV of *Probability of a PWR Uncanistered Fuel Waste Package Postclosure Criticality* (CRWMS M&O 1998b) to be used as an example for the fraction of waste packages containing PWR waste forms, which have a k_{eff} greater than 0.98. $C_{0,i}$ in Figure 6-18 represents time after closure of the repository and $C_{1,i}$ represents the fraction of waste packages that have a k_{eff} greater than critical limit of 0.98, assuming the waste package is fully flooded with 33 percent uniform oxide as the waste form and no remaining boron. The initial rise in the curve shown in Figure 6-18 is due to the decay of Pu-240 and the subsequent decline in the curve is from the decay of Pu-239. Thus, $C_{0,i}$ starts at 3,000 years (where the effects of the approximately 6,500-year half-life of Pu-240 become apparent) and increases at 1,000-year intervals up to 100,000 years.

Table 6-17. Probabilities Assigned to Top Event CRIT-POT-FUEL

Time Step	Baseline	Sensitivity
10,000 yrs	2.90×10^{-2}	2.90×10^{-2}
25,000 yrs	3.10×10^{-2}	3.10×10^{-2}
50,000 yrs	2.90×10^{-2}	2.90×10^{-2}

6.7.2.6.11 Top Event MISLOAD

Waste package misload probabilities are not considered in this demonstration analysis and the probability of a misload event is set to zero (i.e., the probability of no waste form loading curve violations is one).

6.7.2.6.12 Results of Baseline and Sensitivity Analysis

The probabilities defined above are input into the SAPHIRE CGM. The degradation sequences that define configuration class IP-3c are analyzed to determine their probability. The results from analyzing the CGM event tree sequences for configuration class IP-3c are shown in Table 6-18. This analysis is based upon having no waste form misloads in the preclosure period. Table 6-18 lists both the overall baseline and sensitivity results at the defined time steps. The individual probabilities and events that are used to quantify the sensitivity results shown in Table 6-18 are listed in Table 6-19.

Table 6-18. Final Baseline and Sensitivity Probability for Configuration Class IP-3c

End State	Baseline Probability	Sensitivity Probability
IP-3C-10K	0.0	7.09×10^{-13}
IP-3C-25K	0.0	2.51×10^{-6}
IP-3C-50K	0.0	5.00×10^{-6}

Table 6-19 lists the cut sets (i.e., combination of events) generated based on the fault tree logic models linked to the CGM event tree. The cut sets listed in Table 6-19 represent the minimal combination of processes required to achieve configuration class IP-3c. The overall probability is also listed for each cut set. In Table 6-19, for example, end state IP-3C-10K lists two separate cut sets that can cause configuration class IP-3c to occur. Each of the cut sets represents the different combinations of failure mechanisms that can lead to configuration class IP-3c along with their respective probability. The probability of each individual failure mechanism is listed in the right hand column of the table. Since all of these processes that are independent must occur for configuration class IP-3c to occur, the individual probabilities are multiplied together

Table 6-19. Sensitivity Analysis of the Individual Sequence Results for Each Time Step

Prob.	Basic Event	Description	Basic Event Prob.[a]
End State: IP-3C-10K Total Probability = 7.09×10^{-13} (Sensitivity)			
7.05×10^{-13}	CSNF-21PWR-ABS	WASTE FORM BEING ANALYZED	1.00
	BE-BATHTUB-10K	PROBABILITY OF BEING IN A BATHTUB AT 10,000 YEARS	6.08×10^{-1}
	BE-DS-EMPLACEMENT	DS IMPROPERLY INSTALLED AND ALLOWS DIRECT WATER INF	5.88×10^{-1}
	BE-MS-IC-16	BASKET STRUCTURAL SUPPORTS MECHANICALLY COLLAPSE	1.00
	BE-MS-IC-17	STRUCTURES CONTAINING NEUTRON ABSORBER FULLY DEGRADE	1.00
	BE-MS-IC-19-10K	SOL. NEUTRON ABSORBER. FLUSHED FROM DEG PART OF BASKET	8.61×10^{-4}
	BE-MS-IC-8	WP INTERNAL STRUCTURES DEGRADE FASTER THAN WF	1.00
	BE-SEEP-FRACT-10K	FRACTION OF WPS THAT SEE SEEPAGE AT 10,000 YEARS	4.47×10^{-2}
	BE-SEEPAGE-10K	WATER (INFIL/ CONDEN) REACHES DRIFT AT 10,000 YEARS	1.75×10^{-5}
	BE-WP-EARLY-F	EARLY FAILURE OF WP	1.01×10^{-1}
	CRIT-POT-IP3C	CRITICALITY POTENTIAL FOR CONFIG CLASS IP-3C	2.90×10^{-2}
	MISLOAD-IP3C	NO VIOLATION OF WASTE FORM LOADING CURVE	1.00
3.75×10^{-15}	CSNF-21PWR-ABS	WASTE FORM BEING ANALYZED	1.00
	BE-BATHTUB-10K	PROBABILITY OF BEING IN A BATHTUB AT 10,000 YEARS	6.08×10^{-1}
	BE-DS-ROCK-FALL	DRIP SHIELD FAILURE DUE TO ROCKFALL OF SUFFICIENT SIZE	3.13×10^{-3}
	BE-MS-IC-16	BASKET STRUCTURAL SUPPORTS MECHANICALLY COLLAPSE	1.00
	BE-MS-IC-17	STRUCTURES CONTAINING NEUTRON ABSORBER FULLY DEGRADE	1.00
	BE-MS-IC-19-10K	SOL. NEUTRON ABSORBER. FLUSHED FROM DEG PART OF BASKET	8.61×10^{-4}
	BE-MS-IC-8	WP INTERNAL STRUCTURES DEGRADE FASTER THAN WF	1.00
	BE-SEEP-FRACT-10K	FRACTION OF WPS THAT SEE SEEPAGE AT 10,000 YEARS	4.47×10^{-2}
	BE-SEEPAGE-10K	WATER (INFIL/ CONDEN) REACHES DRIFT AT 10,000 YEARS	1.75×10^{-5}
	BE-WP-EARLY-F	EARLY FAILURE OF WP	1.01×10^{-1}
	CRIT-POT-IP3C	CRITICALITY POTENTIAL FOR CONFIG CLASS IP-3C	2.90×10^{-2}
	MISLOAD-IP3C	NO VIOLATION OF WASTE FORM LOADING CURVE	1.00
End State: IP-3C-25K Total Probability = 2.51×10^{-6} (Sensitivity)			
2.16×10^{-6}	CSNF-21PWR-ABS	WASTE FORM BEING ANALYZED	1.00
	BE-BATHTUB-25K	PROBABILITY OF BEING IN A BATHTUB AT 25,000 YEARS	2.27×10^{-1}
	BE-DS-EMPLACEMENT	DS IMPROPERLY INSTALLED AND ALLOWS DIRECT WATER INF	5.88×10^{-1}
	BE-MS-IC-16	BASKET STRUCTURAL SUPPORTS MECHANICALLY COLLAPSE	1.00
	BE-MS-IC-17	STRUCTURES CONTAINING NEUTRON ABSORBER FULLY DEGRADE	1.00
	BE-MS-IC-19-25K	SOL. NEUTRON ABSORBER. FLUSHED FROM DEG PART OF BASKET	5.27×10^{-1}
	BE-MS-IC-8	WP INTERNAL STRUCTURES DEGRADE FASTER THAN WF	1.00
	BE-SEEP-FRACT-25K	FRACTION OF WPS THAT SEE SEEPAGE AT 25,000 YEARS	4.47×10^{-2}
	BE-SEEPAGE-25K	WATER (INFIL/ CONDEN) REACHES DRIFT AT 25,000 YEARS	2.19×10^{-1}
	BE-WP-EARLY-F	EARLY FAILURE OF WP	1.01×10^{-1}
	CRIT-POT-IP3C	CRITICALITY POTENTIAL FOR CONFIG CLASS IP-3C	3.10×10^{-2}
	MISLOAD-IP3C	NO VIOLATION OF WASTE FORM LOADING CURVE	1.00

Table 6-19. Sensitivity Analysis of the Individual Sequence Results for Each Time Step (Continued)

Prob.	Basic Event	Description	Basic Event Prob.[a]
3.41×10^{-7}	CSNF-21PWR-ABS	WASTE FORM BEING ANALYZED	1.00
	BE-BATHTUB-25K	PROBABILITY OF BEING IN A BATHTUB AT 25,000 YEARS	2.27×10^{-1}
	BE-DS-GENCOR-25K	DRIP SHIELD FAILURE DUE TO GEN COR AT 25,000 YEARS	9.30×10^{-2}
	BE-MS-IC-16	BASKET STRUCTURAL SUPPORTS MECHANICALLY COLLAPSE	1.00
	BE-MS-IC-17	STRUCTURES CONTAINING NEUTRON ABSORBER FULLY DEGRADE	1.00
	BE-MS-IC-19-25K	SOL. NEUTRON ABSORBER. FLUSHED FROM DEG PART OF BASKET	5.27×10^{-1}
	BE-MS-IC-8	WP INTERNAL STRUCTURES DEGRADE FASTER THAN WF	1.00
	BE-SEEP-FRACT-25K	FRACTION OF WPS THAT SEE SEEPAGE AT 25,000 YEARS	4.47×10^{-2}
	BE-SEEPAGE-25K	WATER (INFIL/ CONDEN) REACHES DRIFT AT 25,000 YEARS	2.19×10^{-1}
	BE-WP-EARLY-F	EARLY FAILURE OF WP	1.01×10^{-1}
	CRIT-POT-IP3C	CRITICALITY POTENTIAL FOR CONFIG CLASS IP-3C	3.10×10^{-2}
	MISLOAD-IP3C	NO VIOLATION OF WASTE FORM LOADING CURVE	1.00
1.15×10^{-8}	CSNF-21PWR-A	WASTE FORM BEING ANALYZED	1.00
	BS BE-BATHTUB-25K	PROBABILITY OF BEING IN A BATHTUB AT 25,000 YEARS	2.27×10^{-1}
	BE-DS-ROCK-FALL	DRIP SHIELD FAILURE DUE TO ROCKFALL OF SUFFICIENT SIZE	3.13×10^{-3}
	BE-MS-IC-16	BASKET STRUCTURAL SUPPORTS MECHANICALLY COLLAPSE	1.00
	BE-MS-IC-17	STRUCTURES CONTAINING NEUTRON ABSORBER FULLY DEGRADE	1.00
	BE-MS-IC-19-25K	SOL. NEUTRON ABSORBER. FLUSHED FROM DEG PART OF BASKET	5.27×10^{-1}
	BE-MS-IC-8	WP INTERNAL STRUCTURES DEGRADE FASTER THAN WF	1.00
	BE-SEEP-FRACT-25K	FRACTION OF WPS THAT SEE SEEPAGE AT 25,000 YEARS	4.47×10^{-2}
	BE-SEEPAGE-25K	WATER (INFIL/ CONDEN) REACHES DRIFT AT 25,000 YEARS	2.19×10^{-1}
	BE-WP-EARLY-F	EARLY FAILURE OF WP	1.01×10^{-1}
	CRIT-POT-IP3C	CRITICALITY POTENTIAL FOR CONFIG CLASS IP-3C	3.10×10^{-2}
	MISLOAD-IP3C	NO VIOLATION OF WASTE FORM LOADING CURVE	1.00
End State: IP-3C-50K Total Probability =5.00×10^{-6} (Sensitivity)			
2.74×10^{-6}	CSNF-21PWR-ABS	WASTE FORM BEING ANALYZED	1.00
	BE-BATHTUB-50K-EF	PROB OF BEING IN A BATHTUB AT 50,000 YEARS (WP EARLY FAILURE)	3.75×10^{-2}
	BE-DS-GENCOR-50K	DS DEGRADES DUE TO GENERAL CORROSION AT 50,000 YEAR	7.15×10^{-1}
	BE-MS-IC-16	BASKET STRUCTURAL SUPPORTS MECHANICALLY COLLAPSE	1.00
	BE-MS-IC-17	STRUCTURES CONTAINING NEUTRON ABSORBER FULLY DEGRADE	1.00
	BE-MS-IC-19-50K-EF	SOL. NEUTRON ABSORBER. FLUSHED FROM DEG PART OF BASKET	9.36×10^{-1}
	BE-MS-IC-8	WP INTERNAL STRUCTURES DEGRADE FASTER THAN WF	1.00
	BE-SEEP-FRACT-50K	FRACTION OF WPS THAT SEE SEEPAGE AT 50,000 YEARS	4.47×10^{-2}
	BE-SEEPAGE-50K-EF	WATER (INFIL/ CONDEN) REACHES DRIFT AT 50,000 YEARS	8.33×10^{-1}
	BE-WP-EARLY-F	EARLY FAILURE OF WP	1.01×10^{-1}
	CRIT-POT-IP3C	CRITICALITY POTENTIAL FOR CONFIG CLASS IP-3C	2.90×10^{-2}
	MISLOAD-IP3C	NO VIOLATION OF WASTE FORM LOADING CURVE	1.00

Table 6-19. Sensitivity Analysis of the Individual Sequence Results for Each Time Step (Continued)

Prob.	Basic Event	Description	Basic Event Prob.[a]
2.25×10^{-6}	CSNF-21PWR-ABS	WASTE FORM BEING ANALYZED	1.00
	BE-BATHTUB-50K-EF	PROB OF BEING IN A BATHTUB AT 50,000 YEARS (WP EARLY FAILURE)	3.75×10^{-2}
	BE-DS-EMPLACEMENT	DS IMPROPERLY INSTALLED AND ALLOWS DIRECT WATER INF	5.88×10^{-1}
	BE-MS-IC-16	BASKET STRUCTURAL SUPPORTS MECHANICALLY COLLAPSE	1.00
	BE-MS-IC-17	STRUCTURES CONTAINING NEUTRON ABSORBER FULLY DEGRADE	1.00
	BE-MS-IC-19-50K-EF	SOL. NEUTRON ABSORBER. FLUSHED FROM DEG PART OF BASKET	9.36×10^{-1}
	BE-MS-IC-8	WP INTERNAL STRUCTURES DEGRADE FASTER THAN WF	1.00
	BE-SEEP-FRACT-50K	FRACTION OF WPS THAT SEE SEEPAGE AT 50,000 YEARS	4.47×10^{-2}
	BE-SEEPAGE-50K-EF	WATER (INFIL/ CONDEN) REACHES DRIFT AT 50,000 YEARS	8.33×10^{-1}
	BE-WP-EARLY-F	EARLY FAILURE OF WP	1.01×10^{-1}
	CRIT-POT-IP3C	CRITICALITY POTENTIAL FOR CONFIG CLASS IP-3C	2.90×10^{-2}
	MISLOAD-IP3C	NO VIOLATION OF WASTE FORM LOADING CURVE	1.00
1.20×10^{-8}	CSNF-21PWR-ABS	WASTE FORM BEING ANALYZED	1.00
	BE-BATHTUB-50K-EF	PROB OF BEING IN A BATHTUB AT 50,000 YEARS (WP EARLY FAILURE)	3.75×10^{-2}
	BE-DS-ROCK-FALL	DRIP SHIELD FAILURE DUE TO ROCKFALL OF SUFFICIENT SIZE	3.13×10^{-3}
	BE-MS-IC-16	BASKET STRUCTURAL SUPPORTS MECHANICALLY COLLAPSE	1.00
	BE-MS-IC-17	STRUCTURES CONTAINING NEUTRON ABSORBER FULLY DEGRADE	1.00
	B E-MS-IC-19-50K-EF	SOL. NEUTRON ABSORBER. FLUSHED FROM DEG PART OF BASKET	9.36×10^{-1}
	BE-MS-IC-8	WP INTERNAL STRUCTURES DEGRADE FASTER THAN WF	1.00
	BE-SEEP-FRACT-50K	FRACTION OF WPS THAT SEE SEEPAGE AT 50,000 YEARS	4.47×10^{-2}
	BE-SEEPAGE-50K-EF	WATER (INFIL/ CONDEN) REACHES DRIFT AT 50,000 YEARS	8.33×10^{-1}
	BE-WP-EARLY-F	EARLY FAILURE OF WP	1.01×10^{-1}
	CRIT-POT-IP3C	CRITICALITY POTENTIAL FOR CONFIG CLASS IP-3C	2.90×10^{-2}
	MISLOAD-IP3C	NO VIOLATION OF WASTE FORM LOADING CURVE	1.00

NOTES: ABS = absorber plate waste package; DS = drip shield; WF = waste form; WP = waste package.

[a] Product of basic event probabilities.

[b] Overall probability values for each cut set.

and the result listed in the left-hand column of the table. The overall probability listed at the top of the individual cut sets is the summation of the individual cut sets since the end-states of configuration classes are mutually exclusive.

6.7.2.7 Configuration Class IP-3d

Configuration class IP-3d is described as the class in which the waste package internals degrade faster than the PWR waste form and the waste package is in a bathtub configuration. This configuration class also has significant neutron absorber degradation before structural collapse with the absorber material separating from the waste form but remaining within the waste package. The processes required to reach configuration class IP-3d as defined by the CGM event tree (Figures I-10, I-17, and I-18) are listed in Table 6-20. Table 6-20 lists the process events, their description, and provides the probability assigned to each process. If no probability analysis is required for the top events, then N/A is used to represent that no probability was calculated. The processes are listed in sequential order that lead to configuration class IP-3d.

Table 6-20. Configuration Class IP-3d Event Tree Sequences

Event Tree Top Event	Top Event Identifier	Assigned Probability
MS-IC-1	Water reaches drift	N/A
MS-IC-2	Water drips on waste package	N/A
MS-IC-3	Waste package penetration at top surface	N/A
MS-IC-4	Liquid accumulates in waste package	N/A
MS-IC-8	Waste package internal structures degrade faster than waste form	N/A
MS-IC-22	Significant neutron absorber degradation before structural collapse occurs	N/A
WF-TYPE	Waste form degrades according to configuration class	N/A
CRIT-POT-FUEL	Criticality potential of waste form	FALSE

For a PWR waste form loaded in a waste package, certain requirements and parameters are required in order for it to become critical. Two important parameters required for in-package criticality are moderation and loss of neutron absorbing poison. Another important parameter or feature is the geometry of the PWR waste form inside the waste package. For configuration class IP-3d, the waste package internal structure has degraded significantly prior to basket collapse. The waste package basket structure remains relatively intact while allowing a significant portion of the neutron absorber to degrade and separate from the waste form but remain within the waste package. This configuration class assumes the waste package is full of water or has a sufficient amount of water to provide moderation. This configuration class also has the PWR waste form remaining intact.

Based on the configuration class information and parameters, the PWR waste form loaded in the waste package does not have the potential to become critical. The configuration class IP-3d does not exhibit lasting stability with PWR waste forms, transitioning to the configuration class IP-3c as the boron absorber is eventually flushed. The geometry of the waste form and having boron absorber (partially) remaining inside the waste package eliminates the potential for criticality. Thus, the configuration has no potential for criticality.

Configuration class IP-3d with a PWR waste form loaded into a waste package requires no probability analysis since the configuration cannot become critical. Top event CRIT-POT-FUEL will be set to FALSE (i.e., a criticality event cannot occur for this particular configuration class) in the SAPHIRE model. By setting this top event to FALSE, this sets all of configuration class IP-3d sequences to a zero probability; therefore, these sequences do not contribute to the overall probability of a criticality event.

6.7.2.8 Configurations Classes IP-4a, IP-4b, IP-5a, IP-6a

Configuration classes IP-4a, IP-4b, IP-5a, and IP-6a are described classes in which the waste packages have a flow-through geometry. A flow-through geometry is defined as a breach in both the top and bottom of the waste package. These configurations classes do not allow water to accumulate inside the waste package, which is a necessary requirement for PWR waste forms to become critical. As there is no water retained inside the waste package these configurations have no potential for criticality. Based on the configuration parameters and information, configuration classes IP-4a, IP-4b, IP-5a, and IP-6a for PWR waste forms are excluded from analysis since these configuration classes cannot result in a critical event. Top event CRIT-POT-FUEL is set to FALSE (i.e., a criticality event cannot occur for these particular configuration classes) in the SAPHIRE model for each of these configuration classes. By setting this top event to FALSE, this sets all of these configuration class sequences to a zero probability; therefore, these sequences do not contribute to the total probability of criticality.

7. VALIDATION

Validation of the CGM model is performed in accordance with the method specified in the technical work plan (BSC 2002a, Subsection 2.1.17) for the model. Because the CGM is a probabilistic model, indirect validation methods are used since experimental data are not available for comparison with model results. Use of qualified computer codes (i.e., OCRWM baseline of qualified software) is an integral part of the configuration generator process and these codes do not require additional validation. AP-SI.1Q requires documentation of the appropriateness and range of applicability for software qualified for use by the YMP. Further qualification is not required for specific analyses unless the qualification criteria are revised. In addition, the CGM uses the output from a number of validated model abstractions that do not need further validation.

Validation activities include the CGM and the remaining model abstractions not validated elsewhere. Model input data required for these activities are the degradation scenarios as identified in Table 4-1. Validation activities are as follows:

- The mathematical basis for the CGM is the SAPHIRE software that has been baselined. Attachment IV documents the probability distribution functions for the drift seepage flow as a function of the climatic era developed from the validated TSPA-SR model (CRWMS M&O 2000b).

- The adequacy and completeness of the event tree/fault tree representation of the degradation sequences derived from master criticality scenarios was verified by the technical checker and the AP-2.14Q interdisciplinary review process.

- Determination of the goodness-of-fit for parameter abstraction submodels developed as part of the CGM. Attachment VI contains the data abstractions for use in the CGM and the statistical quality test results for the corrosion rates of Carbon Steel Type 516, Stainless Steel Type 304, and Stainless Steel Type 316 developed and validated in this document. Each set of corrosion rates was fitted to a Lognormal, Normal, and a Weibull distribution. The Anderson-Darling test (Attachment VI) at a five percent significance level was used to determine the quality of the fit of the parameter equations to the abstracted data. This test is suitable for a small number of data points. The technique requires the test value from a distribution to be less than a critical limit based upon the number of data points for the quality of fit to be acceptable at a prescribed significance level. The quality test results were used to select the particular distribution for use in the CGM.

Results from the goodness-of-fit tests for corrosion rates of Carbon Steel Type 516 were 0.276 for the Lognormal distribution, 1.02 for the Normal distribution, and 0.856 for the Weibull distribution. The Anderson-Darling critical limit at the five percent significance level is 0.752 for the number of data points available, thus only the Lognormal distribution is acceptable for representing Carbon Steel Type 516 corrosion rates. The test values for Stainless Steel Type 304 corrosion rates were 0.296 for the Lognormal distribution, 1.502 for the Normal distribution, and 0.325 for the Weibull distribution. Thus, either the Lognormal or Weibull distributions are acceptable for representing Stainless Steel Type 304 corrosion rates. The test values for Stainless Steel Type 316 corrosion rates were 0.946 for the Lognormal distribution, 0.433 for the Normal distribution, and 0.537 for the Weibull distribution. Thus, either the Normal or Weibull distributions are acceptable for representing Stainless Steel Type 316 corrosion rates.

The level of confidence determined for the CGM, according to AP-SIII.10Q, *Models*, is low since analyses using the CGM will not be used in design analyses or as direct input to TSPA. However, analyses using the CGM will be used to define configuration classes for criticality consequence analysis in the unlikely event that criticality is not screened out from TSPA-LA evaluations. Results obtained from analyses using the CGM have a low level of importance (Level 1) with respect to repository dose estimates. The CGM is a process with a mathematical basis and the validation criterion from the technical work plan (BSC 2002a) is technical review of the mathematical basis.

8. CONCLUSIONS

The CGM for in-package criticality, as directed by the technical work plan (BSC 2002a), was to provide a method to perform the probability screening analysis of degraded waste form configurations internal to waste packages that have potential for criticality. The components in the model were to address the scenarios identified in Section 3.3 of *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003) related to FEPs as having the potential to increase the reactivity of the in-package system.

Submodels required for the demonstration analysis, in certain cases, were used from validated sources and, in other cases, validated in this model description. The latter category consists of the model abstractions and the statistical quality test results for the corrosion rates of Carbon Steel Type 516, Stainless Steel Type 304, and Stainless Steel Type 316. The Anderson-Darling test (Attachment VI) at a five percent significance level was used to determine the quality of the fit of the parameter equations to the abstracted data. According to this test, only the Lognormal distribution was acceptable for representing corrosion rates of Carbon Steel Type 516, either the Lognormal or Weibull distributions were acceptable for representing Stainless Steel Type 304 corrosion rates, and either the Normal or Weibull distributions were acceptable for representing Stainless Steel Type 316 corrosion rates.

The degradation scenarios from *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003, Section 3.3) related to FEPs were integrated into an event tree/fault tree model that forms the central analytical tool for the CGM. The event tree/fault tree structure is flexible, permitting both the event trees and fault trees to be tailored to specific requirements. Additional information required to perform analyses with the CGM includes probability distributions of fundamental variables, correlations with uncertainties for dependent parameters, and descriptions of both the waste package and waste form. The model discussion includes a subsection describing the steps required to perform an analysis, configuration parameters required for a CGM analysis, and results from a demonstration analysis using a 21-PWR with Absorber Plates Waste Package and waste form.

The CGM, documented in this report, contributes to or meets the acceptance criteria stated in Section 4.2 through:

- Development of degradation scenarios coupled with evaluation methods for identifying configurations that have potential of criticality
- Development of processes to determine potential external radionuclide source terms
- Processes based upon probabilistic risk-informed methods
- Methods permit analyses to span, at the minimum, the period of regulatory concern.

The NRC safety evaluation report (Reamer 2000) for *Disposal Criticality Analysis Methodology Topical Report* (YMP 1998) contained six open items (Reamer 2000, pp. 77 to 79) that concerned the configuration generator model. These Open Items, numbers 5, 6, 9, 10, 18, and 19, concern the k_{eff} regression analysis associated with the previous approach to the configuration generator model discussed in *Disposal Criticality Analysis Methodology Topical Report* (YMP 1998). However, use of a k_{eff} regression analysis is not part of the current configuration generator methodology and, thus, the referenced open items are no longer considered applicable and will not be further addressed.

This report contains a discussion of and the results from an analysis, using the CGM, of a 21-PWR with Absorber Plates Waste Package and waste form as defined in the Site Recommendation baseline configuration (DOE 2001a). No criticality screening was performed in this analysis since the probability of achieving any of the end state configurations was below the probability limit of 10 CFR 63, Section 114(d). This CSNF analysis is included in this report as a demonstration of and a guide through the CGM process and is not necessarily applicable for License Application activities. Analyses of the various waste forms expected for disposal in the monitored geologic repository are expected to be documented in reports referenced in the License Application.

Based upon the model validation and supported by the demonstration analysis, it is recommended that the CGM be an integral part of the disposal criticality methodology for the Yucca Mountain Project subject to the following limitations:

- The requirement that probability density functions be specified for the set of basic parameters that are themselves derived from model abstractions.
- Mineral losses from the waste packages are evaluated for soluble species transport only.
- Degradation scenarios for waste forms other than commercial spent nuclear fuel (CSNF) have not been fully evaluated.

9. INPUTS AND REFERENCES

9.1 DOCUMENTS CITED

Ang, A.H-S. and Tang, W.H. 1975. "Basic Principles." Volume I of *Probability Concepts in Engineering Planning and Design.* New York, New York: John Wiley & Sons. TIC: 8346.

BSC (Bechtel SAIC Company, LLC) 2001a. *Analysis of Preclosure Design Basis Rock Fall onto Waste Package.* ANL-EBS-MD-000061 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20011127.0110.

BSC 2001b. *EBS Radionuclide Transport Abstraction.* ANL-WIS-PA-000001 REV 00 ICN 03. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20010806.0076.

BSC 2001c. *FY01 Supplemental Science and Performance Analyses, Volume 1: Scientific Bases and Analyses.* TDR-MGR-MD-000007 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20010712.0062.

BSC 2001d. *Generic Degraded Configuration Probability Analysis for DOE Codisposal Waste Package.* ANL-EDC-NU-000001 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20010613.0248.

BSC 2001e. *In-Package Chemistry for Waste Forms.* ANL-EBS-MD-000056 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20010322.0490.

BSC 2001f. *Waste Package Misload Probability.* CAL-WHS-MD-000001 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20011212.0186.

BSC 2001g. *Flow of Water and Pooling in a Waste Package.* ANL-EBS-MD-000055 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20010604.0218.

BSC 2001h. *Igneous Consequence Modeling for the TSPA-SR.* ANL-WIS-MD-000017 REV 00 ICN 02. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20011107.0005.

BSC 2001i. *Radiolytic Specie Generation from Internal Waste Package Criticality.* CAL-EBS-NU-000017 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20011017.0090.

BSC 2001j. *Drift Degradation Analysis.* ANL-EBS-MD-000027 REV 01 ICN 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20011029.0311.

BSC 2002a. *Technical Work Plan for: Risk and Criticality Department.* TWP-EBS-MD-000014 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20021209.0011.

BSC 2002b. *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.

BSC 2002c. *Repository Design Project, Repository/PA IED Typical Waste Package Components Assembly.* 800-IED-EBS0-00100-000-00A. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20021015.0310.

BSC 2002d. *Gamma and Neutron Radiolysis in the 21-PWR Waste Package from Ten to One Million Years.* 000-00C-DSU0-00700-000-00A. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20021004.0002.

BSC 2003a. *Criticality Model Report.* MDL-EBS-NU-000003 REV 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20030701.0006.

BSC 2003b. *Analysis of Mechanisms for Early Waste Package/Drip Shield Failure.* CAL-EBS-MD-000030 REV A. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20030227.0002.

Case, J.B. 2001. "WAPDEG and Analysis of Bathtub Delays Using the WAPDEG Output Data." Memorandum from J.B. Case to Record Processing Center, May 30, 2001, PROJ.05/01.068, with enclosures. ACC: MOL.20010531.0066.

CRWMS M&O (Civilian Radioactive Waste Management System Management and 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.

CRWMS M&O 1998a. *EQ6 Calculations for Chemical Degradation of PWR LEU and PWR MOX Spent Fuel Waste Packages.* BBA000000-01717-0210-00009 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980701.0483.

CRWMS M&O 1998b. *Probability of a PWR Uncanistered Fuel Waste Package Postclosure Criticality.* BBA000000-01717-0210-00010 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980806.0607.

CRWMS M&O 1999a. *Generic Degradation Scenario and Configuration Analysis for DOE Codisposal Waste Package.* BBA000000-01717-0200-00071 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19991118.0180.

CRWMS M&O 1999b. *Probability of PWR UCF WP Postclosure Criticality for Enhanced Design Alternatives.* BBA000000-01717-0210-00072 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19990927.0365.

CRWMS M&O 2000a. *Total System Performance Assessment (TSPA) Model for Site Recommendation.* MDL-WIS-PA-000002 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20001226.0003.

CRWMS M&O 2000b. *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.

CRWMS M&O 2000c. *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.

CRWMS M&O 2000d. *Analysis of Mechanisms for Early Waste Package Failure.* ANL-EBS-MD-000023 REV 02. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20001011.0196.

CRWMS M&O 2000e. *Rock Fall on Drip Shield.* CAL-EDS-ME-000001 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000509.0276.

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

CRWMS M&O 2000g. *Design Analysis for UCF Waste Packages.* ANL-UDC-MD-000001 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000526.0336.

CRWMS M&O 2000h. *Waste Form Degradation Process Model Report.* TDR-WIS-MD-000001 REV 00 ICN 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000713.0362.

CRWMS M&O 2000i. *Features, Events, and Processes: Disruptive Events.* ANL-WIS-MD-000005 REV 00 ICN 1. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20001218.0007.

CRWMS M&O 2000j. *Characterize Framework for Seismicity and Structural Deformation at Yucca Mountain, Nevada.* ANL-CRW-GS-000003 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000510.0175.

CRWMS M&O 2000k. *Design Analysis for the Ex-Container Components.* ANL-XCS-ME-000001 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000525.0374.

CRWMS M&O 2000l. *Design Analysis for the Defense High-Level Waste Disposal Container.* ANL-DDC-ME-000001 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000627.0254.

CRWMS M&O 2000m. *Stress Corrosion Cracking of the Drip Shield, the Waste Package Outer Barrier, and the Stainless Steel Structural Material.* ANL-EBS-MD-000005 REV 00 ICN 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20001102.0340.

CRWMS M&O 2000n. *Effects of Fault Displacement on Emplacement Drifts.* ANL-EBS-GE-000004 REV 00 ICN 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000504.0297.

CRWMS M&O 2000o. *Waste Packages and Source Terms for the Commercial 1999 Design Basis Waste Streams.* CAL-MGR-MD-000001 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000214.0479.

CRWMS M&O 2000p. *Expected Number of Key Blocks Throughout the Emplacement Drifts as a Function of Block Size.* CAL-EBS-MD-000012 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20001102.0064.

CRWMS M&O 2001a. *Abstraction of Drift Seepage.* ANL-NBS-MD-000005 REV 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20010309.0019.

CRWMS M&O 2001b. *Abstraction of NFE Drift Thermodynamic Environment and Percolation Flux.* ANL-EBS-HS-000003 REV 00 ICN 02. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20010221.0160.

CRWMS M&O 2001c. *Clad Degradation – Summary and Abstraction.* ANL-WIS-MD-000007 REV 00 ICN 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20010214.0229.

D'Agostino, R.B. and Stephens, M.A. 1986. *Goodness-Of-Fit Techniques.* Statistics, Textbooks and Monographs Volume 68. New York, New York: Marcel Dekker. TIC: 253256.

DOE (U.S. Department of Energy) 2001a. *Yucca Mountain Preliminary Site Suitability Evaluation.* DOE/RW-0540. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.20011101.0082.

DOE 2001b. *Yucca Mountain Science and Engineering Report.* DOE/RW-0539. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.20010524.0272.

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.

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.

Kügler, A. 1997. Sheet and Plate for Nuclear Engineering, Bohler Neutronit A976. Houston, Texas: Bohler Bleche GmbH. TIC: 246410.

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

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.

Reamer, C.W. 2000. "Safety Evaluation Report for Disposal Criticality Analysis Methodology Topical Report, Revision 0." Letter from C.W. Reamer (NRC) to S.J. Brocoum (DOE/YMSCO), June 26, 2000, with enclosure. ACC: MOL.20000919.0157.

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.

YMP (Yucca Mountain Site Characterization Project) 1998. *Disposal Criticality Analysis Methodology Topical Report.* YMP/TR-004Q, Rev. 0. Las Vegas, Nevada: Yucca Mountain Site Characterization Office. ACC: MOL.19990210.0236.

YMP 2000. *Disposal Criticality Analysis Methodology Topical Report.* YMP/TR-004Q, Rev. 01. Las Vegas, Nevada: Yucca Mountain Site Characterization Office. ACC: MOL.20001214.0001.

YMP 2001. *Q-List.* YMP/90-55Q, Rev. 7. Las Vegas, Nevada: Yucca Mountain Site Characterization Office. ACC: MOL.20010409.0366.

YMP 2003. *Disposal Criticality Analysis Methodology Topical Report.* YMP/TR-004Q, Rev. 02D. Las Vegas, Nevada: Yucca Mountain Site Characterization Office. ACC: MOL.20030617.0322. TBV-5172.

9.2 CODES, STANDARDS, REGULATIONS, AND PROCEDURES CITED

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

60 FR 42622. Use of Probabilistic Risk Assessment Methods in Nuclear Regulatory Activities; Final Policy Statement. Readily available.

AP-2.14Q, Rev. 2, ICN 2. *Review of Technical Products and Data.* Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: DOC.20030206.0001.

AP-2.22Q, Rev. 0, ICN 1. *Classification Criteria and Maintenance of the Monitored Geologic Repository Q-List.* Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: DOC.20030422.0009.

AP-2.27Q, Rev. 0, ICN 0. *Planning for Science Activities.* Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.20020701.0184.

AP-6.1Q, Rev. 7, ICN 0. *Document Control.* Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.20030120.0178.

AP-17.1Q, Rev. 2, ICN 4. *Record Source Responsibilities for Inclusionary Records.* Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: DOC.20030501.0081.

AP-SI-1Q, Rev 5, ICN 1. *Software Management.* Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Package. ACC: DOC.200300707.0001.

AP-SIII.10Q, Rev. 1, ICN 2. *Models.* Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: DOC.20030627.0003.

AP-SV.1Q, Rev. 0, ICN 3. *Control of the Electronic Management of Information.* Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.20020917.0133.

ASTM A 240/A 240M-02a. 2002. *Standard Specification for Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels and for General Applications.* West Conshohocken, Pennsylvania: American Society for Testing and Materials. TIC: 253994.

LP-SA-001Q-BSC, Rev. 0. *Determination of Importance and Site Performance Protection Evaluations.* Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.20020510.0386.

9.3 SOURCE DATA, LISTED BY DATA TRACKING NUMBER

MO0010MWDWAP01.009. Data Generated from WAPDEG Analysis of Waste Package and Drip Shield Degradation ANL-EBS-PA-000001 REV 00 ICN 01. Submittal date: 10/24/2000.

MO0211SPASDR01.004. Steel Degradation Rates in Aqueous Environments. Submittal date: 11/14/2002.

MO0301SEPFEPS1.000. LA FEP List. Submittal date: 01/21/2003.

MO0303SPAMCRAQ.000. Materials Corrosion Rates in Aqueous Environments. Submittal date: 03/05/2003.

SN0006T0502900.002. Updated Igneous Consequence Data for Total System Performance Assessment-Site Recommendation (TSPA-SR). Submittal date: 06/15/2000.

9.4 SOFTWARE CODES

Software Code: EQ3/6. V7.2b. LLNL: UCRL-MA-110662.

Software Code: EQ6. 7.2bLV. PC. 10075-7.2bLV-02. Windows NT, 2000.

Software Code: GoldSim. 6.04.007. PC, Windows NT. 10344-6.04.007-00.

Software Code: MCNP. 4B2LV. HP. 30033 V4B2LV.

Software Code: SAPHIRE. V6.69. PC. 10325-6.69-00.

Software Code: SAPHIRE. V7.18. PC - Windows 2000/NT 4.0. 10325-7.18-00.

10. ATTACHMENTS

Attachments to this model report are as follows:

Attachment I	-	Configuration Generator Model Event Tree
Attachment II	-	Fault Tree Models
Attachment III	-	CGM SAPHIRE Model Rules
Attachment IV	-	Seepage Flux Abstraction
Attachment V	-	Waste Package Bathtub Duration
Attachment VI	-	Steel Corrosion Rate Abstraction
Attachment VII	-	Zircaloy Cladding Creep Failure
Attachment VIII	-	Triangular Distribution Derivation
Attachment IX	-	Probability of Drip Shield Failure Due to Rock Fall
Attachment X	-	Boron Loss Abstraction
Attachment XI	-	List of the Electronic Files in Attachment XII
Attachment XII	-	Compact Disk with CGM Data Files

ATTACHMENT I
CONFIGURATION GENERATOR MODEL EVENT TREE

ATTACHMENT I

CGM EVENT TREE

The model event tree (shown in Figures I-1 through I-32) starts with the different waste forms anticipated for the proposed monitored geologic repository. Listing the different waste forms provides a bookkeeping mechanism. However, for analysis, specific waste forms will be used in order to adjust the degradation parameters for both the waste form and waste package. The event tree then lists in sequential order the degradation processes required to reach each of the six IP configurations. The top events on the event tree are the specific processes required for degradation. The branching under the top events (degradation processes) provides a traceable path to each configuration class. The different configuration classes are noted as end states on the event tree. (Note that 97 percent of the repository waste packages (Figure I-1) are CSNF and DOE SNF waste packages.)

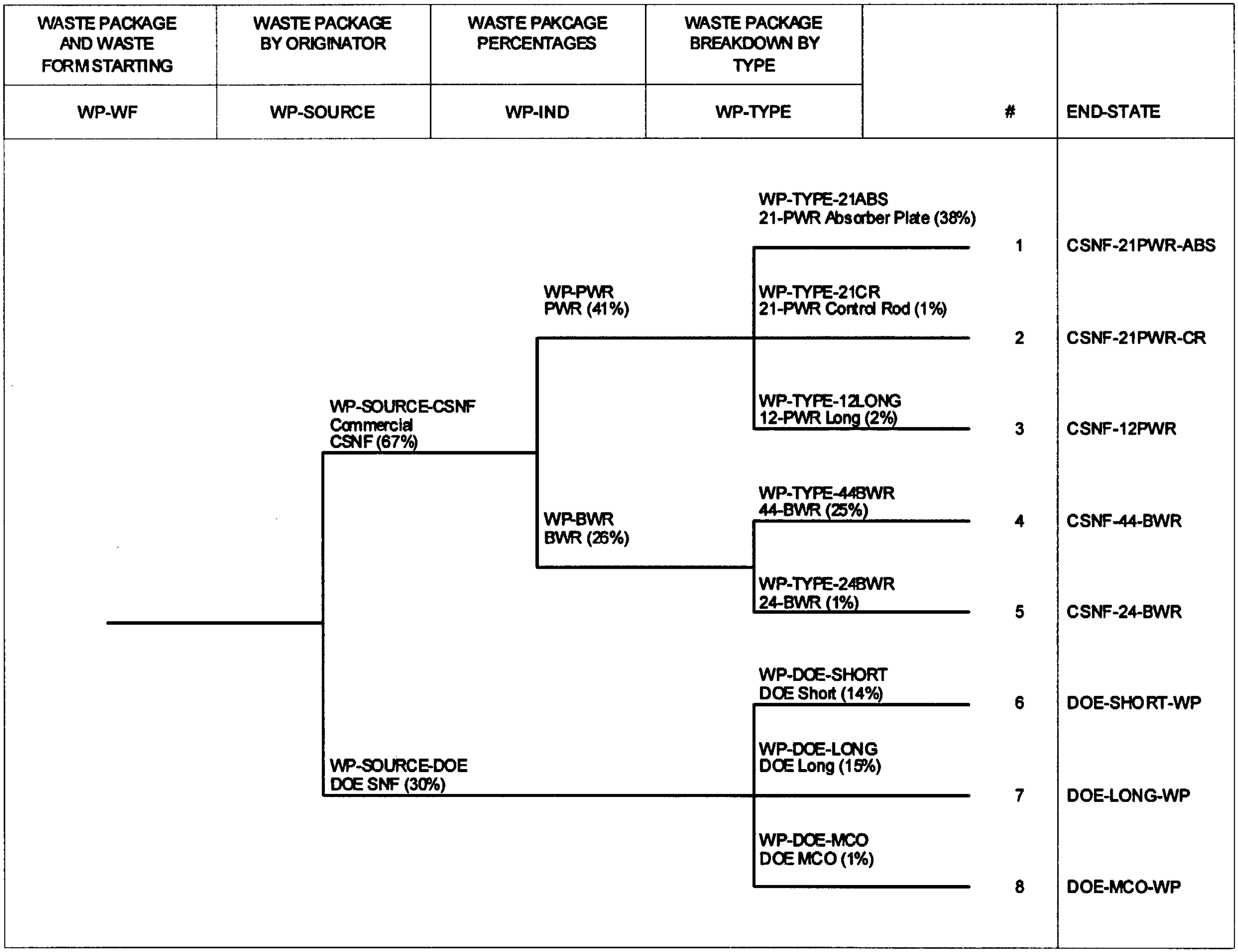


Figure I-1. Waste Forms Expected at the Monitored Geological Repository

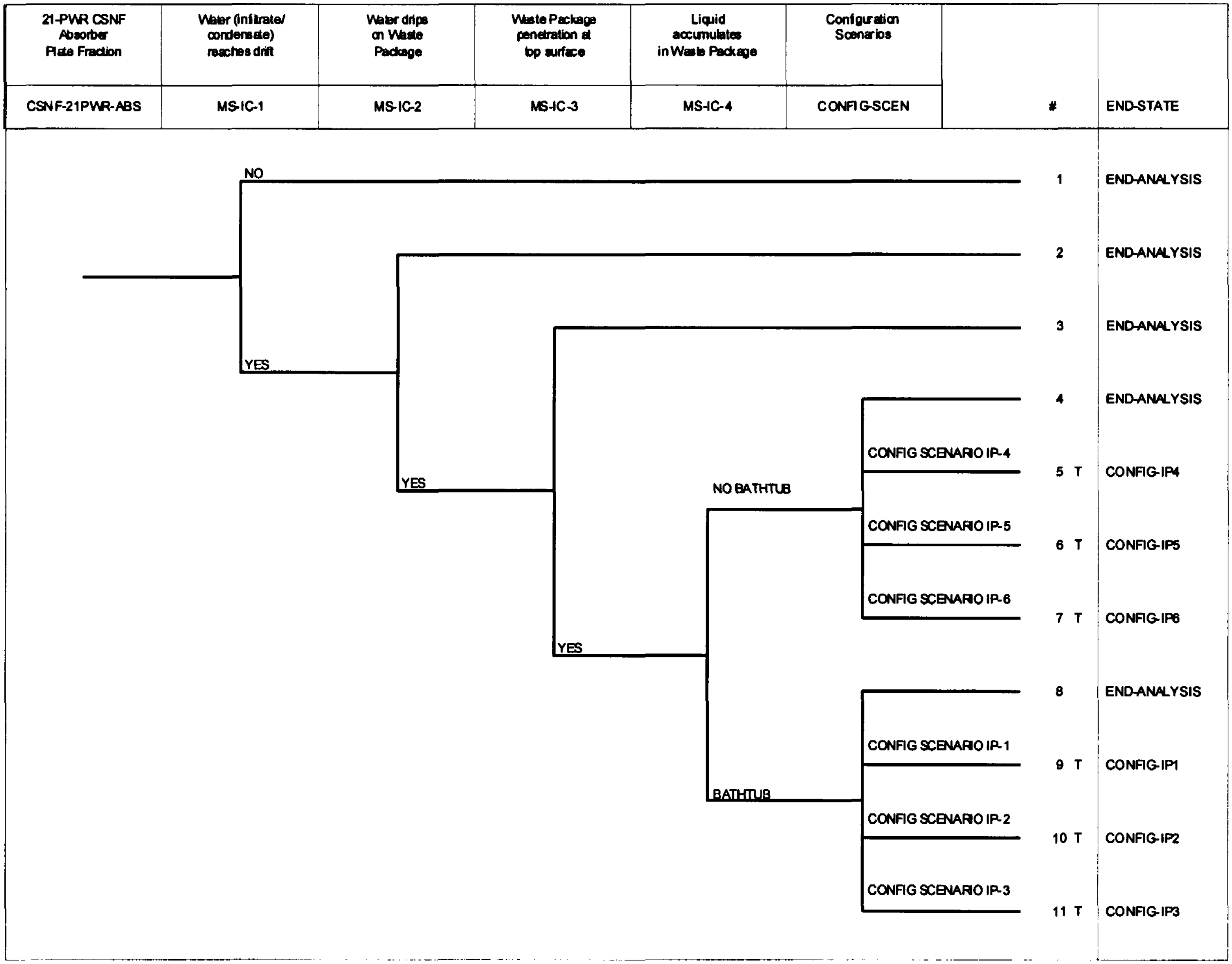


Figure I-2. Commercial Spent Nuclear Fuel in a 21-PWR With Absorber Plates Waste Package

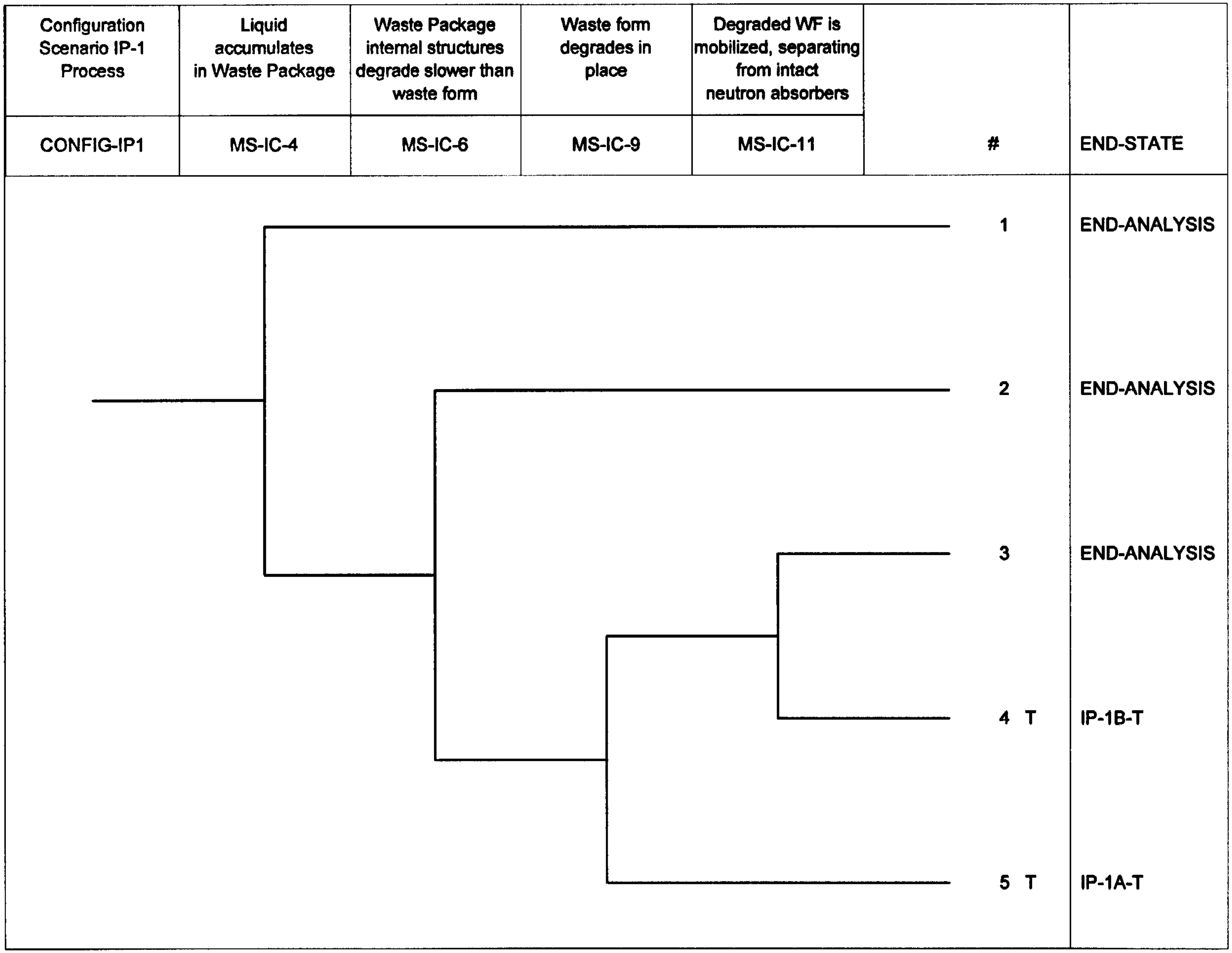


Figure I-3. Configuration Scenarios In-Package 1

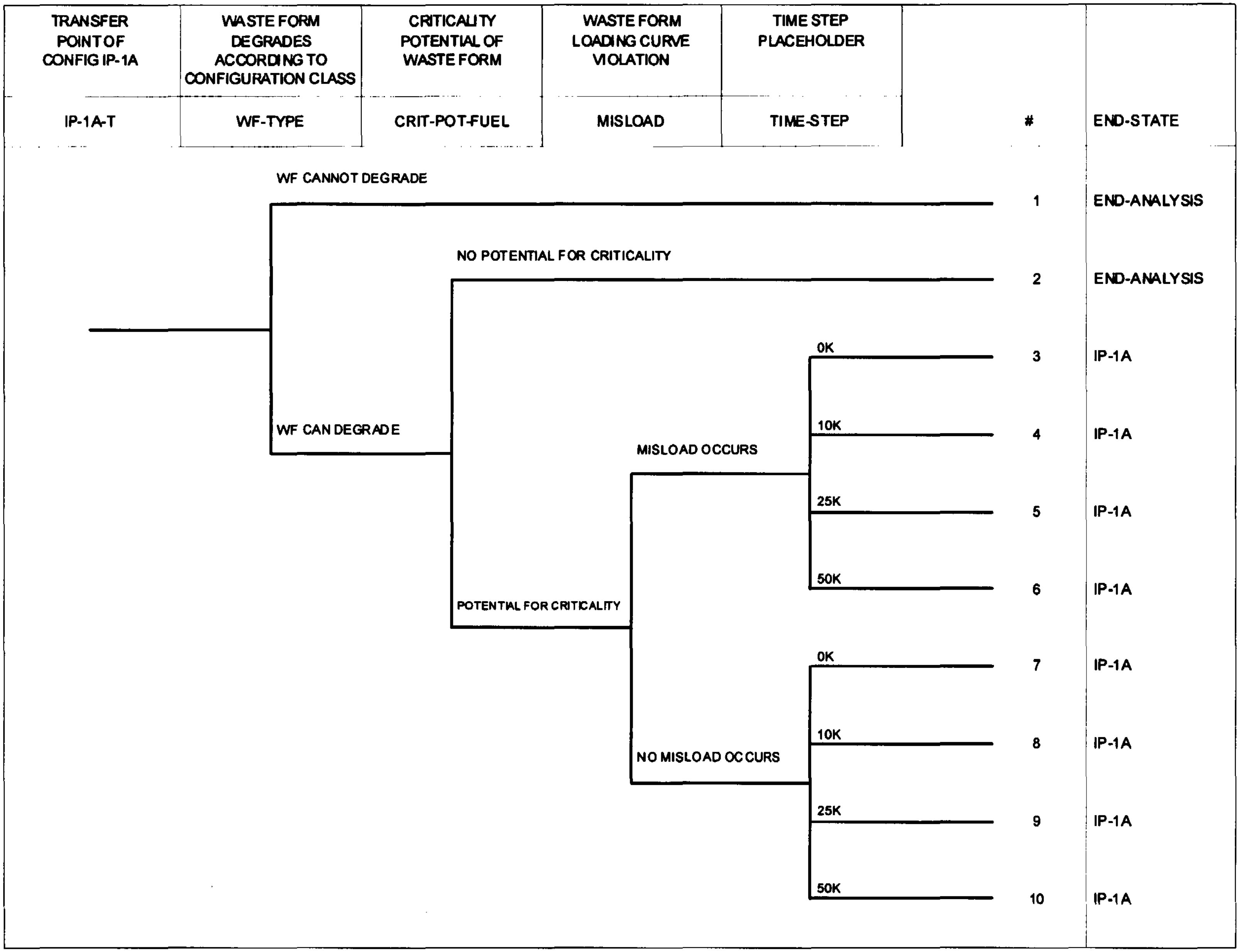


Figure I-4. Configuration Class In-Package 1A End States

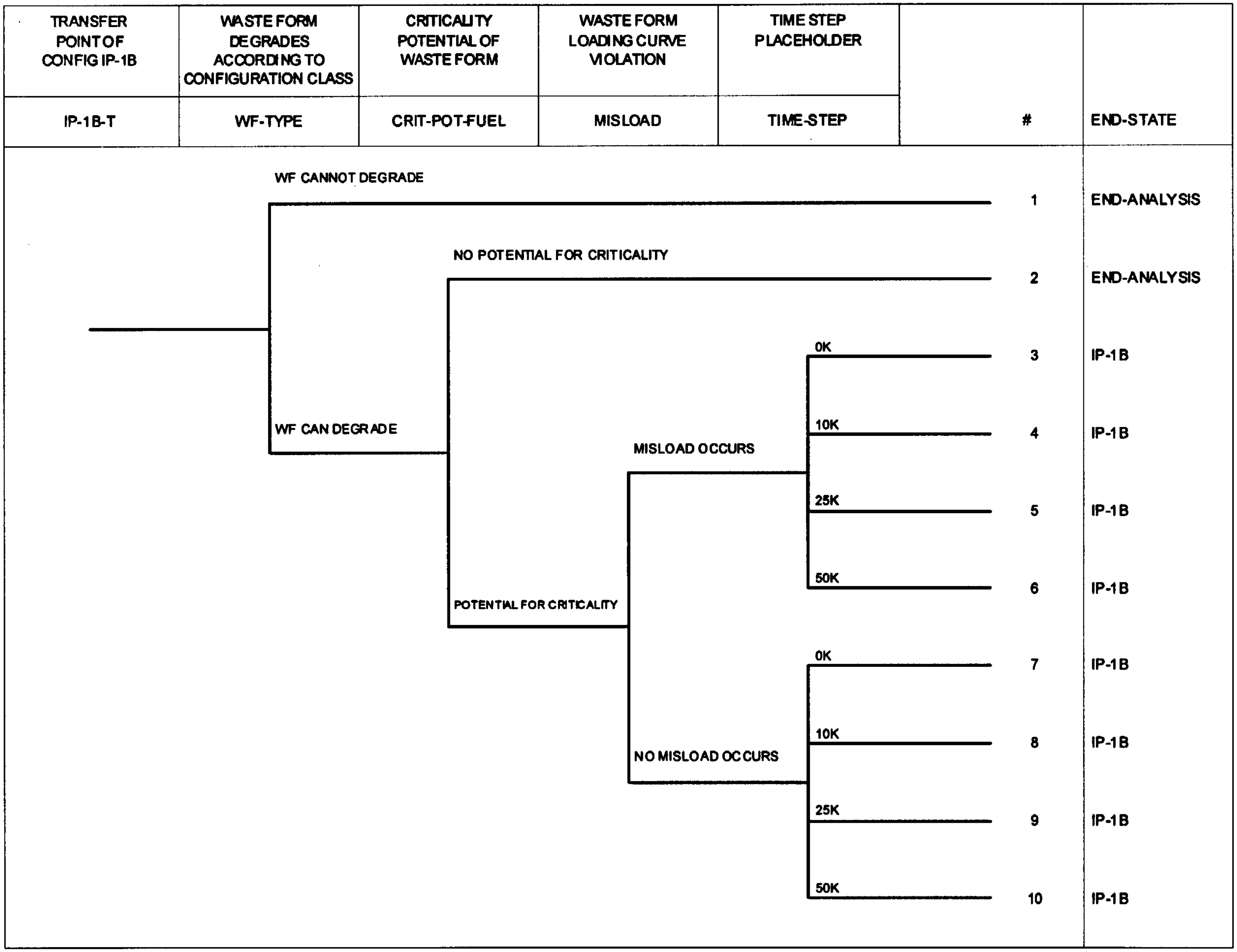


Figure I-5. Configuration Class In-Package 1B End States

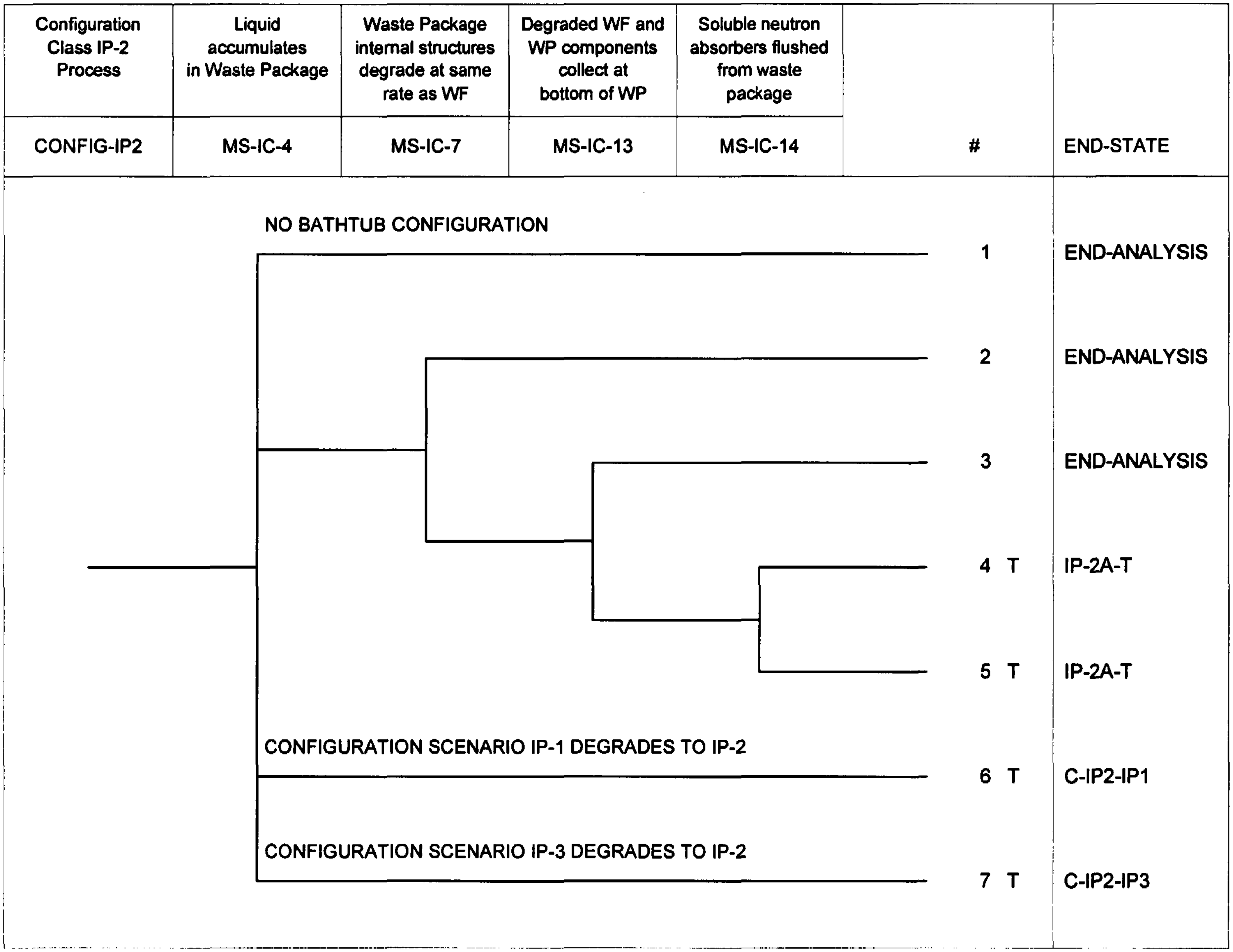


Figure I-6. Configuration Scenario In-Package 2

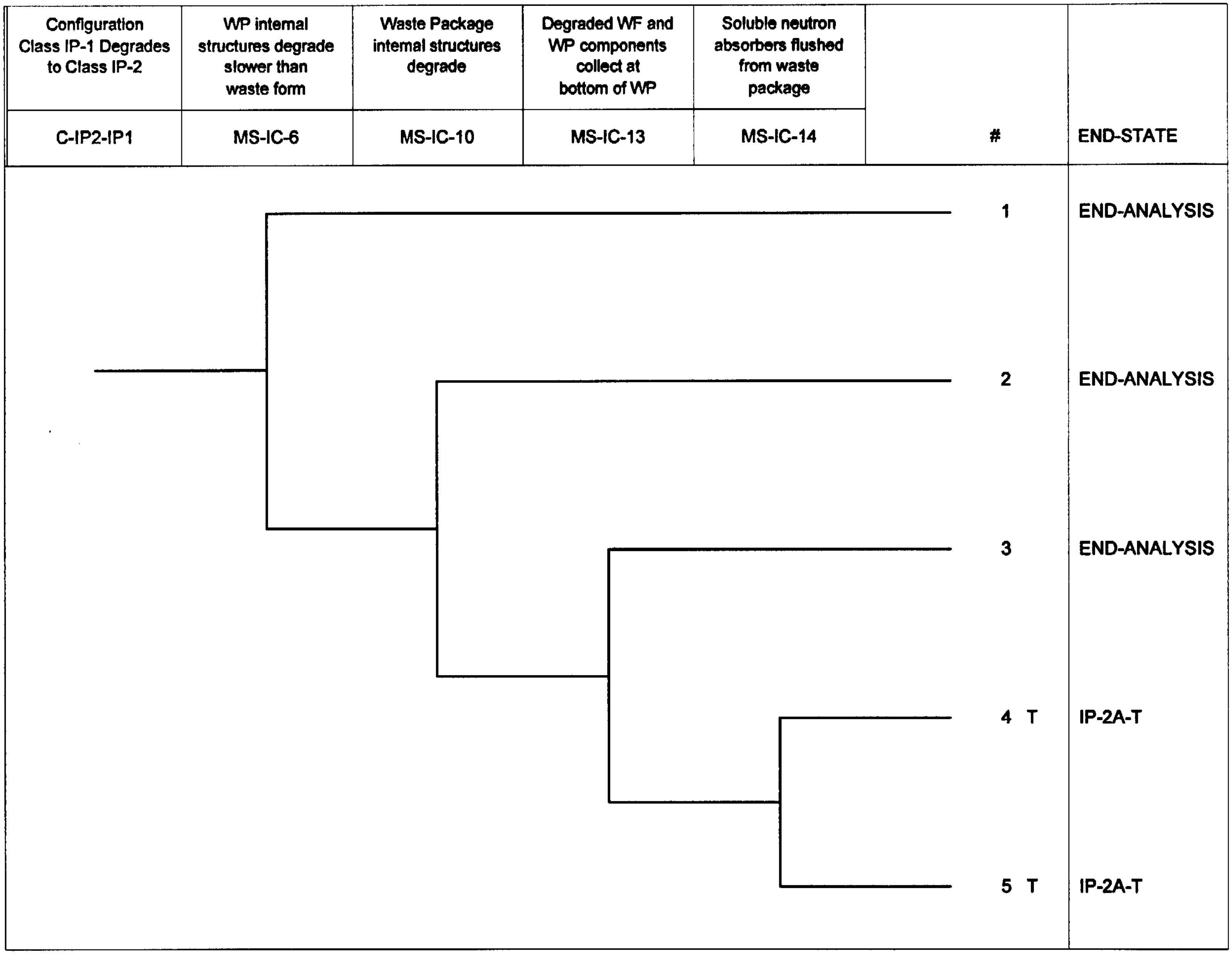


Figure I-7. Configuration Scenario In-Package 2 (Path from Configuration Scenario IP-1)

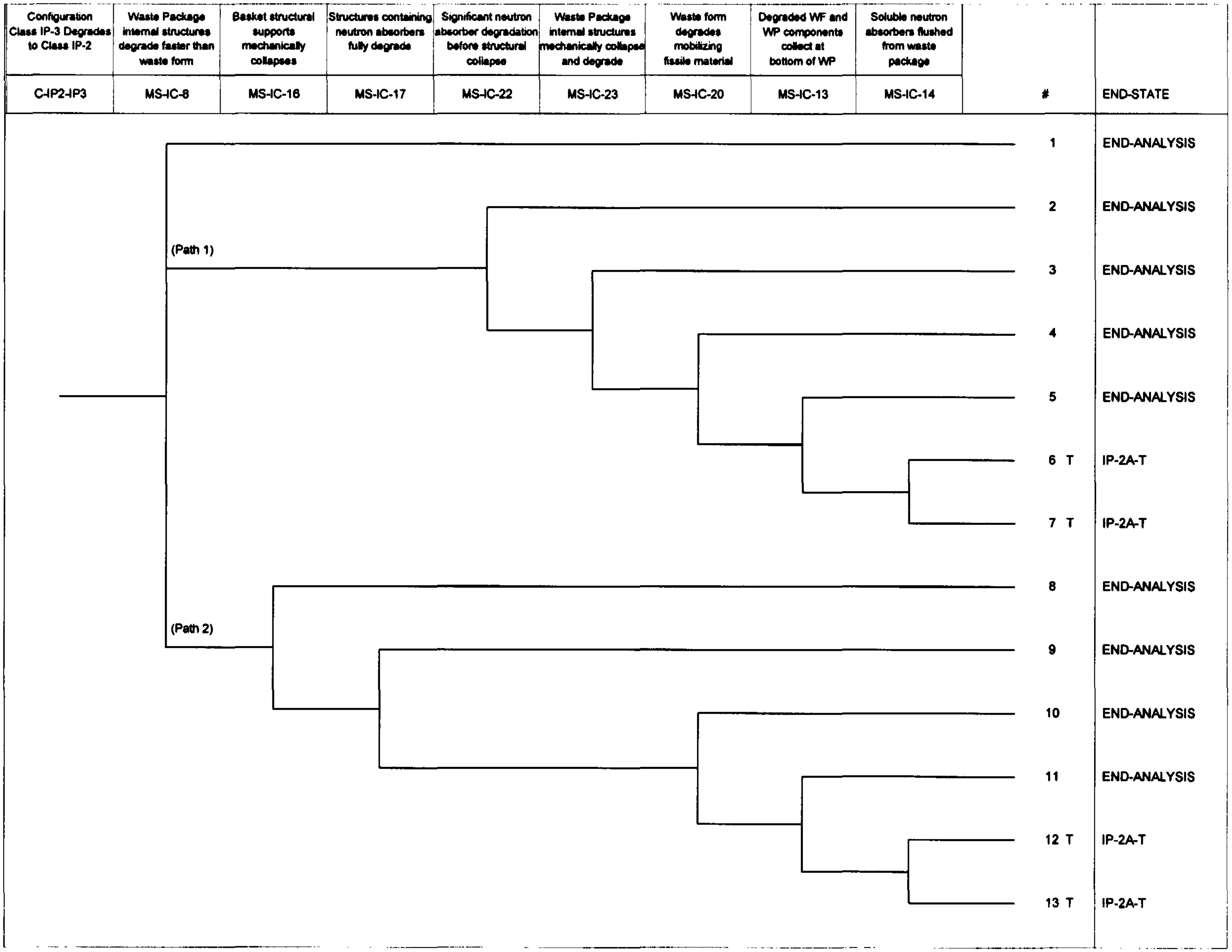


Figure I-8. Configuration Scenario In-Package 2 (Path from Configuration Scenario IP-3)

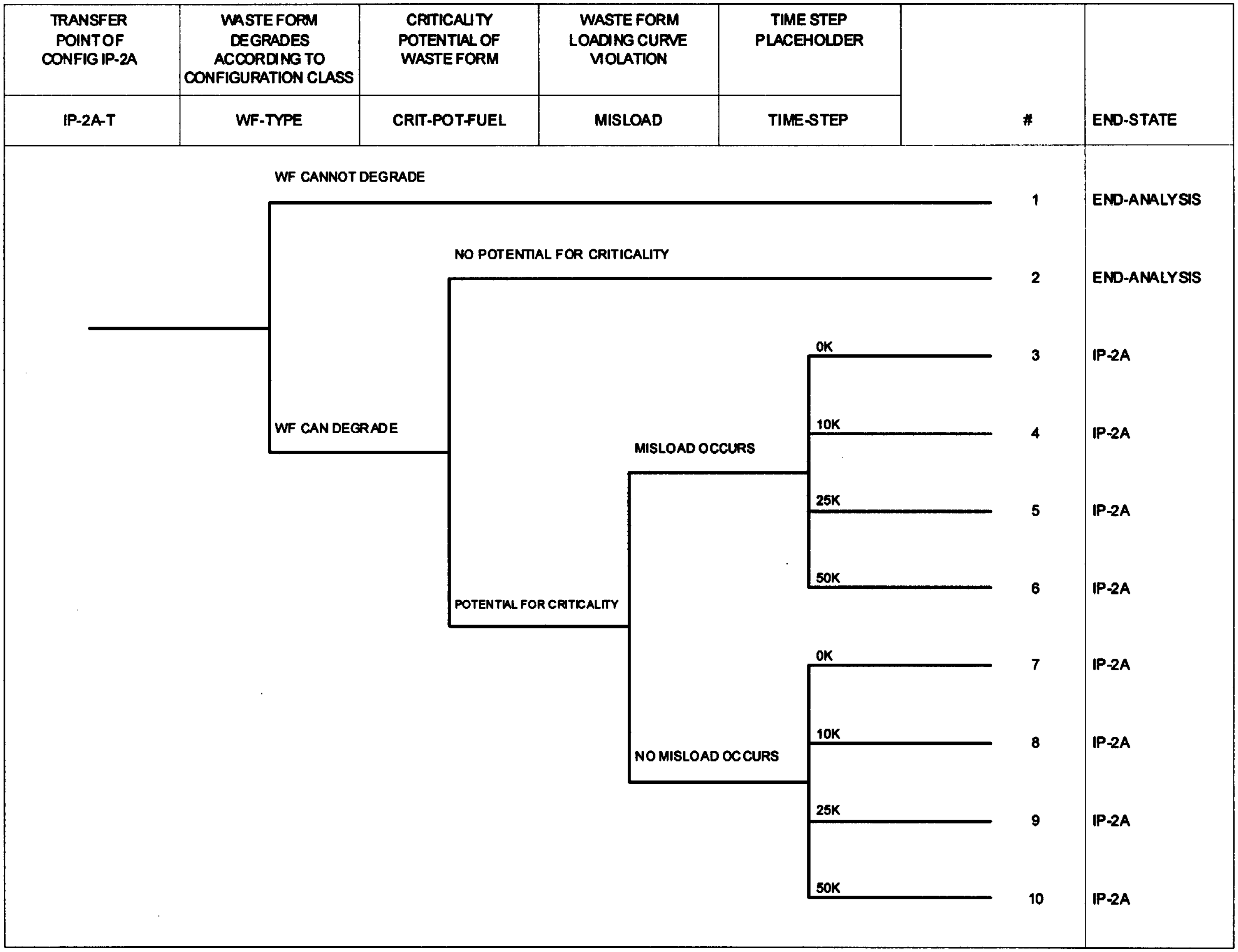


Figure I-9. Configuration Class In-Package 2A End States

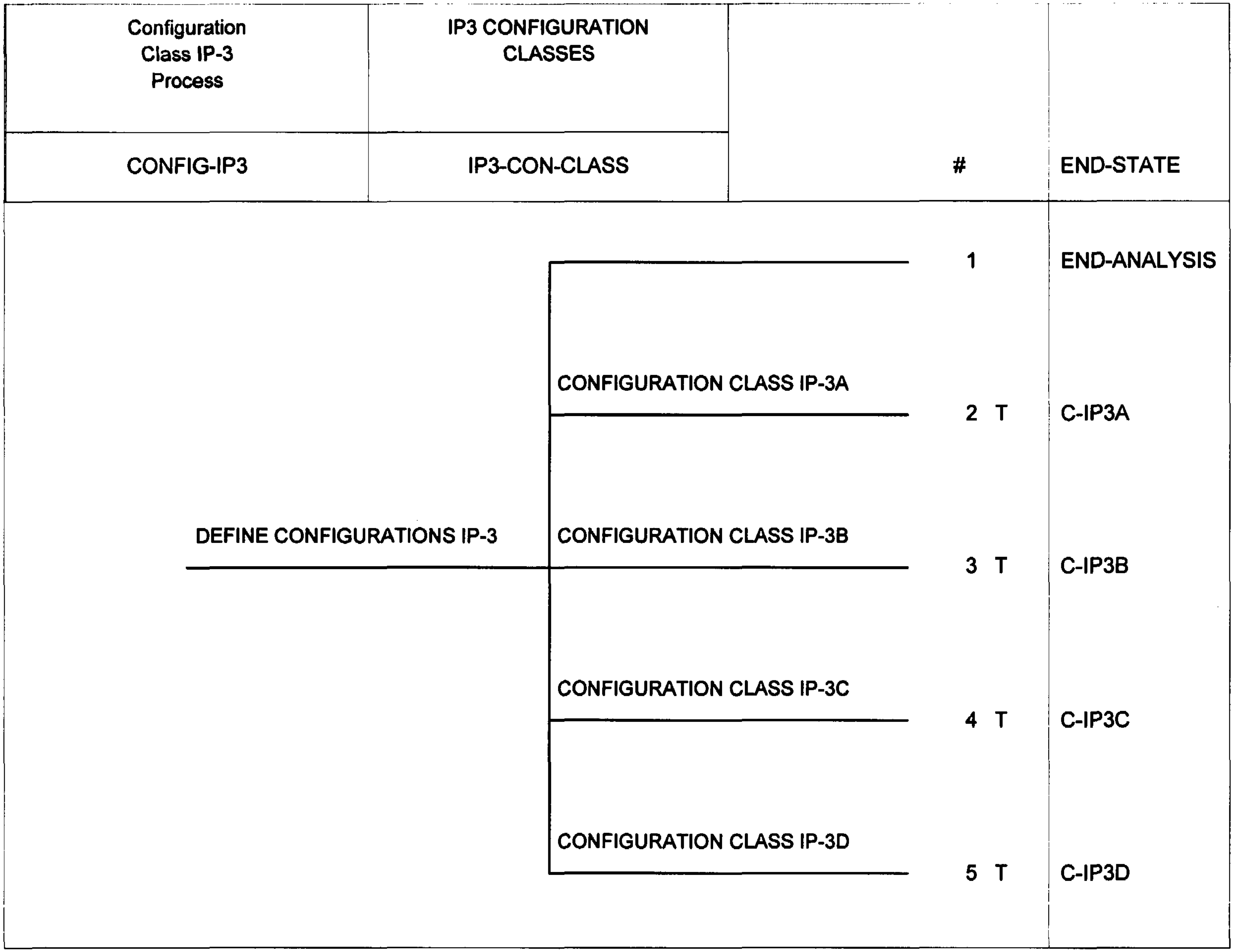


Figure I-10. Configuration Scenarios In-Package 3

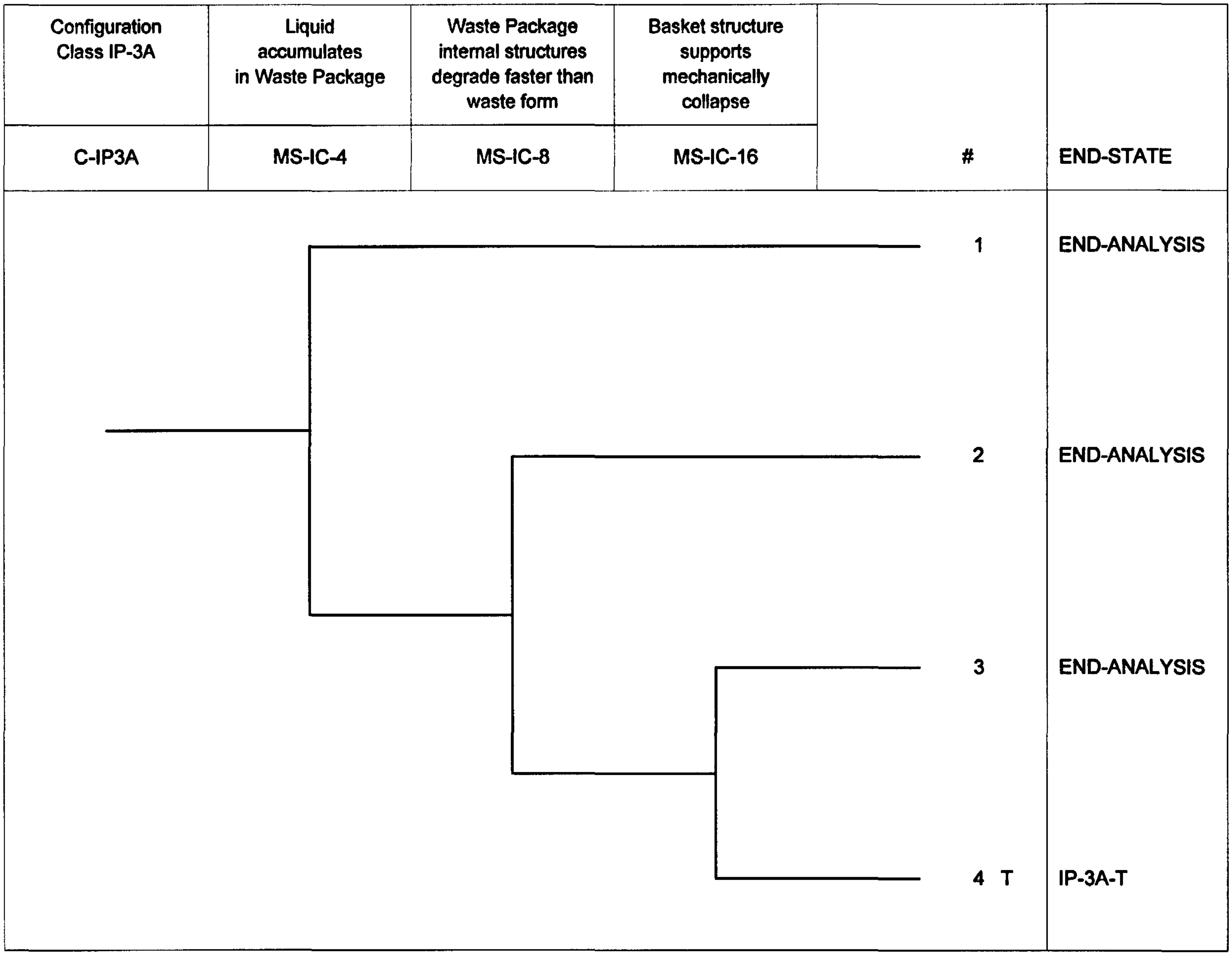


Figure I-11. Configuration Class In-Package 3A

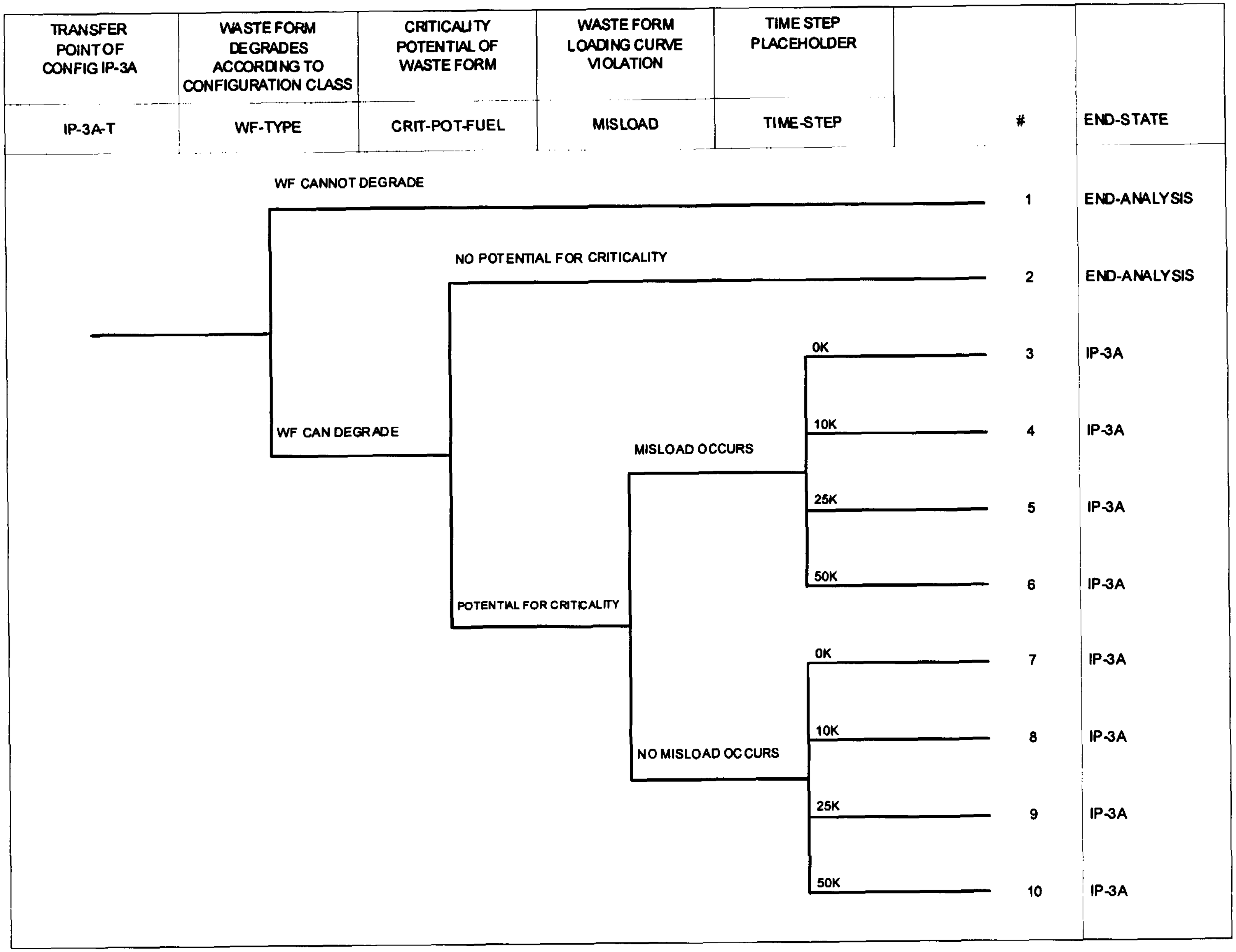


Figure I-12. Configuration Class In-Package 3A End States

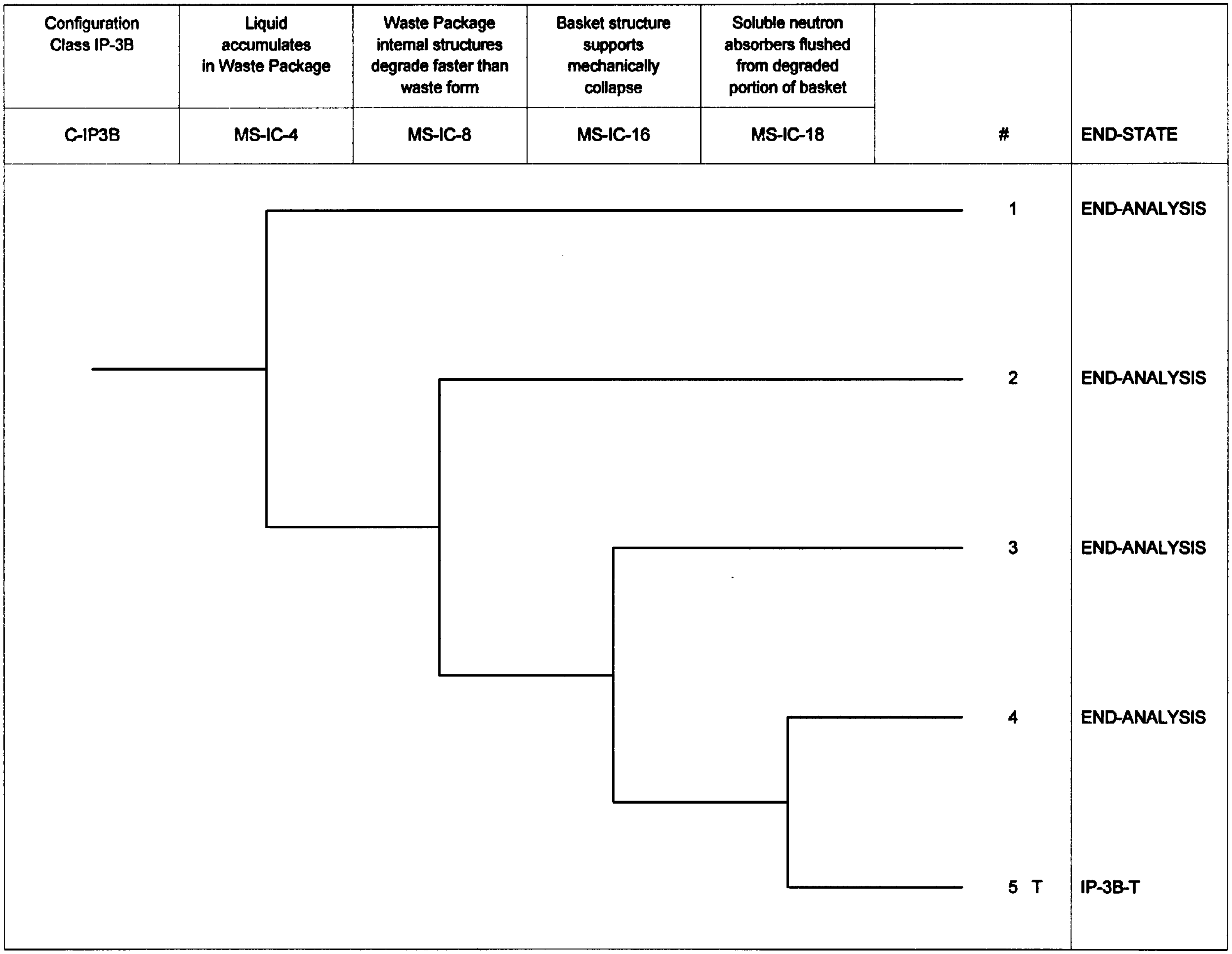


Figure I-13. Configuration Class In-Package 3B

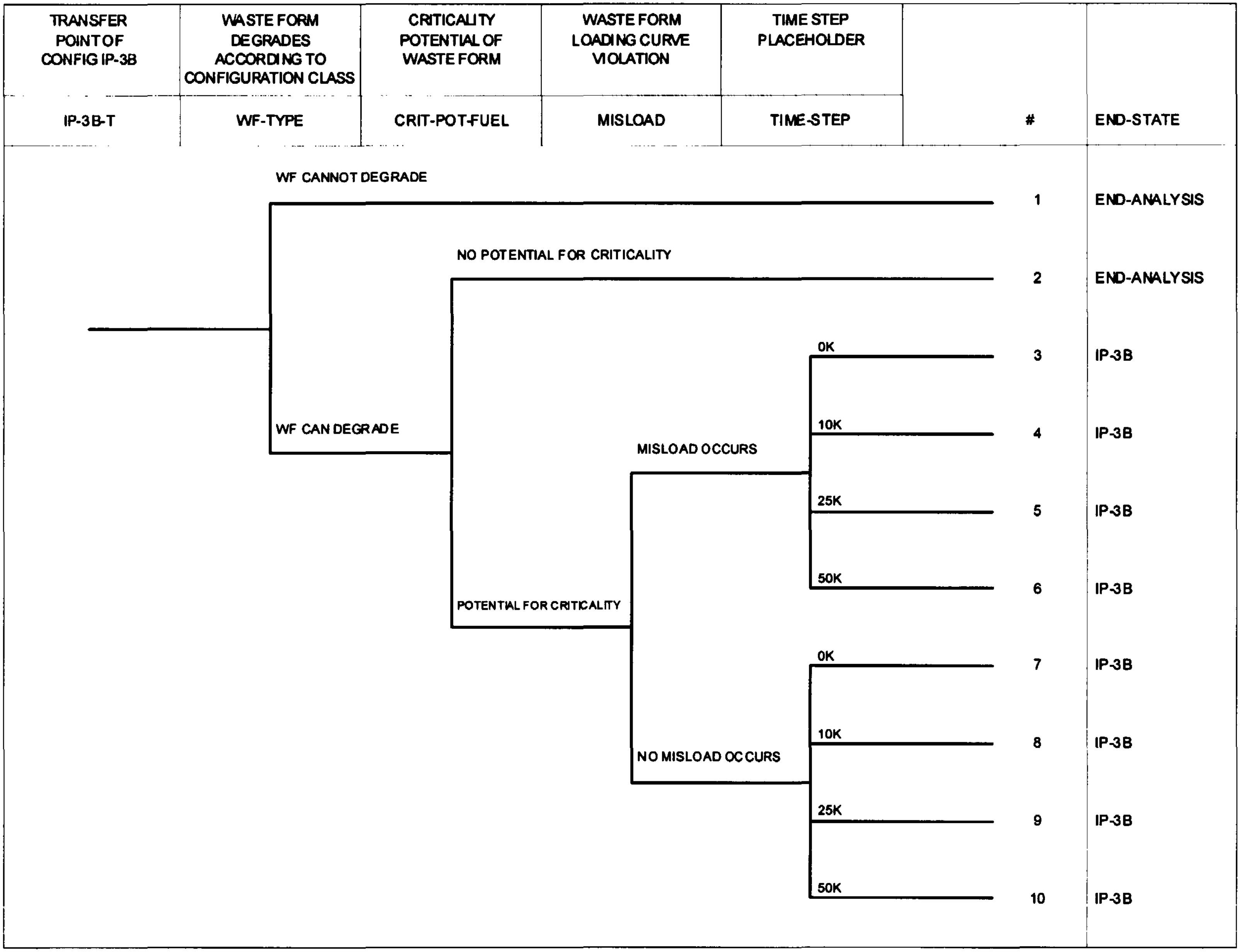


Figure I-14. Configuration Class In-Package 3B End States

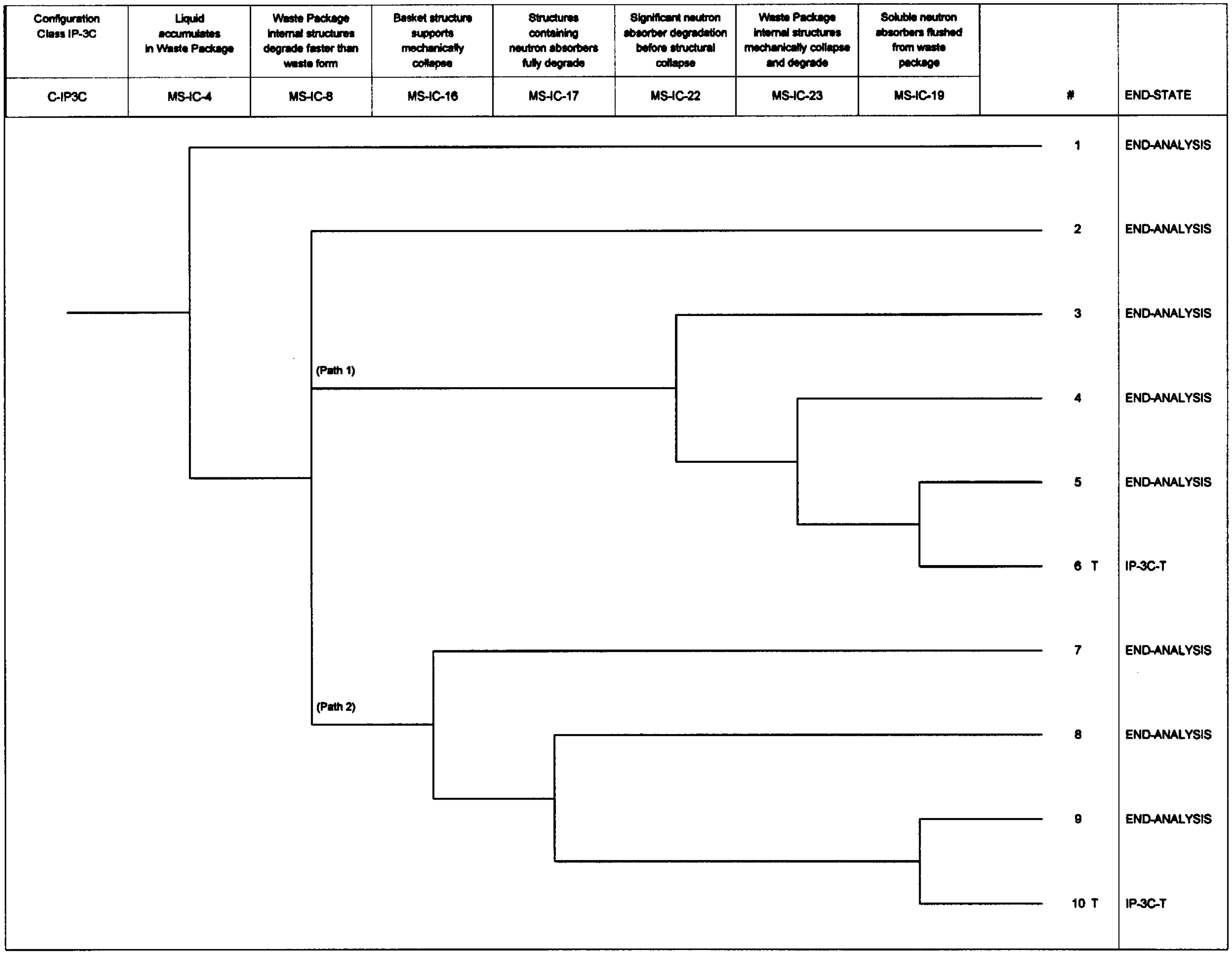


Figure I-15. Configuration Class In-Package 3C

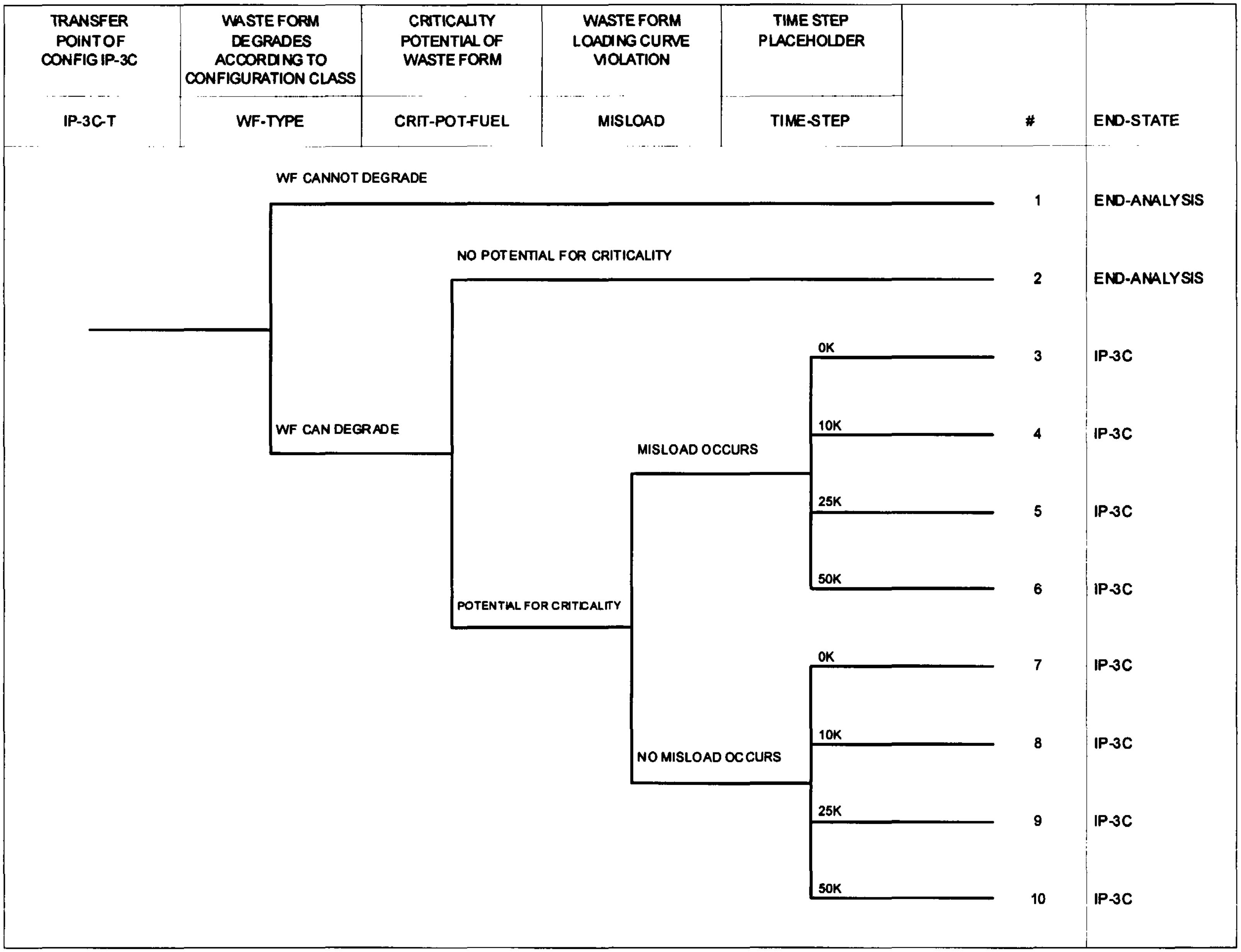


Figure I-16. Configuration Class In-Package 3C End States

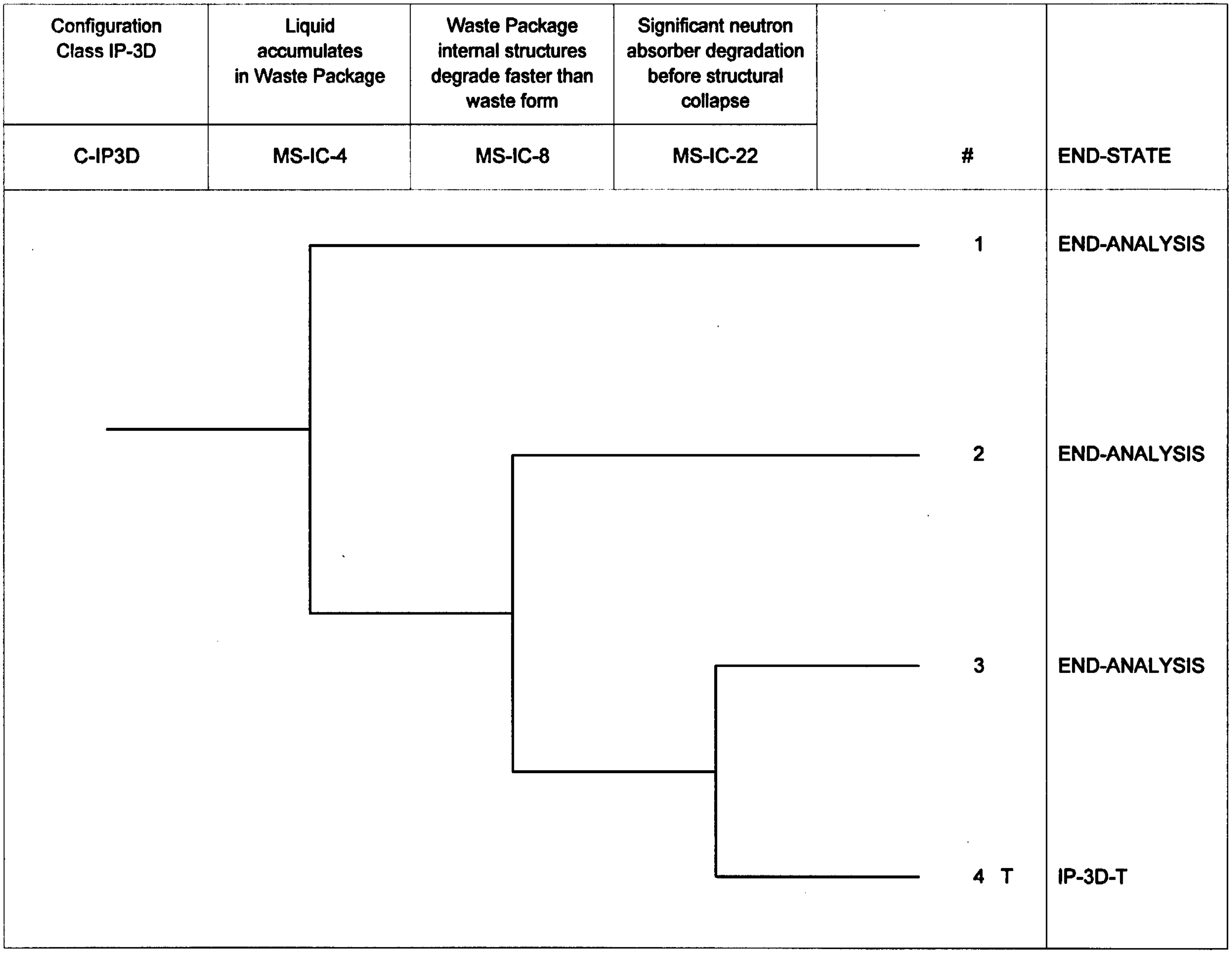


Figure I-17. Configuration Class In-Package 3D

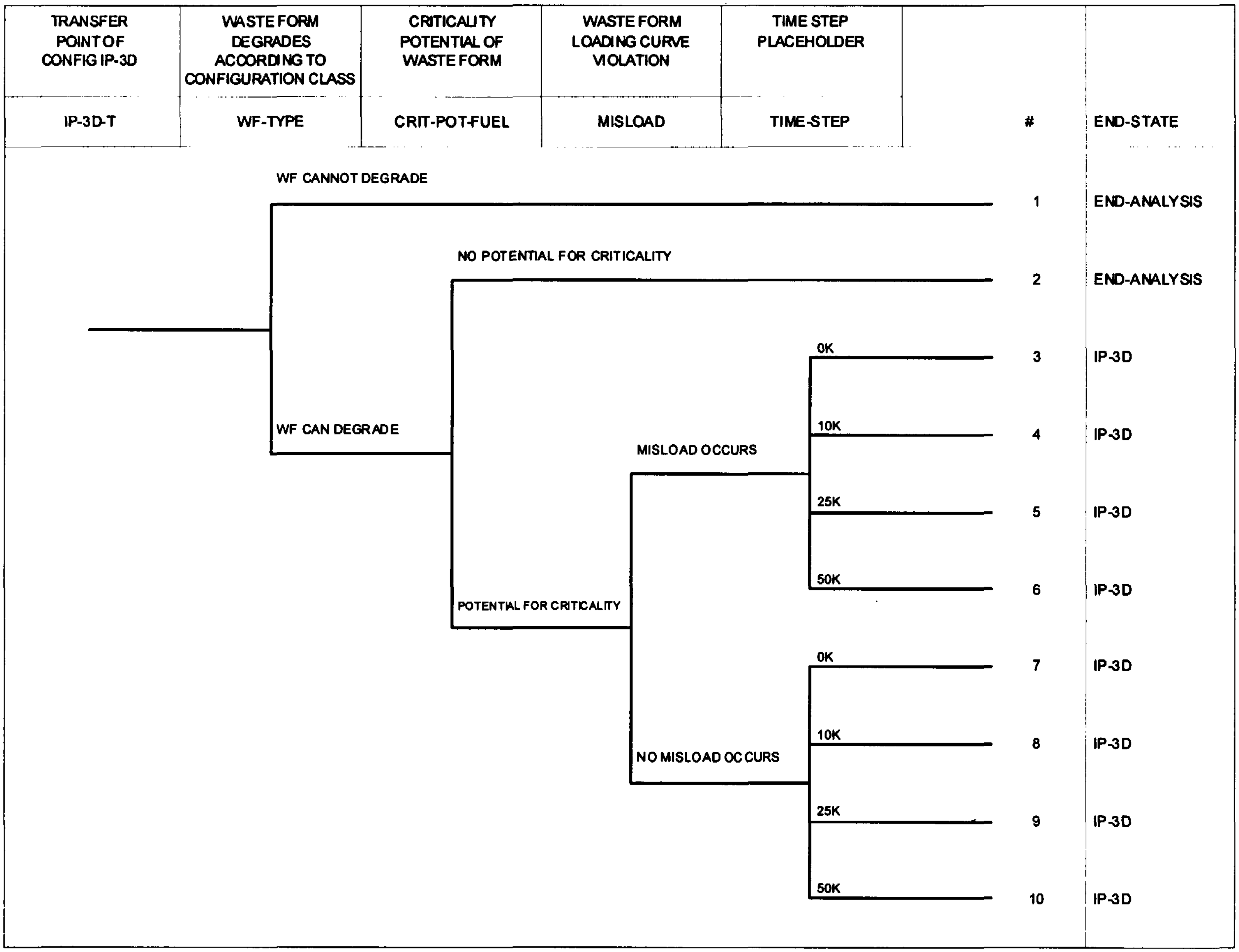


Figure I-18. Configuration Class In-Package 3D End States

Configuration Class IP-4 Process	IP-4 CONFIGURATION CLASSES		
CONFIG-IP4	IP4-CON-CLASS	#	END-STATE
		1	END-ANALYSIS
DEFINE CONFIGURATIONS IP-4	CONFIGURATION CLASS IP-4A	2 T	C-IP4A
	CONFIGURATION CLASS IP-4B	3 T	C-IP4B

Figure I-19. Configuration Scenarios In-Package 4

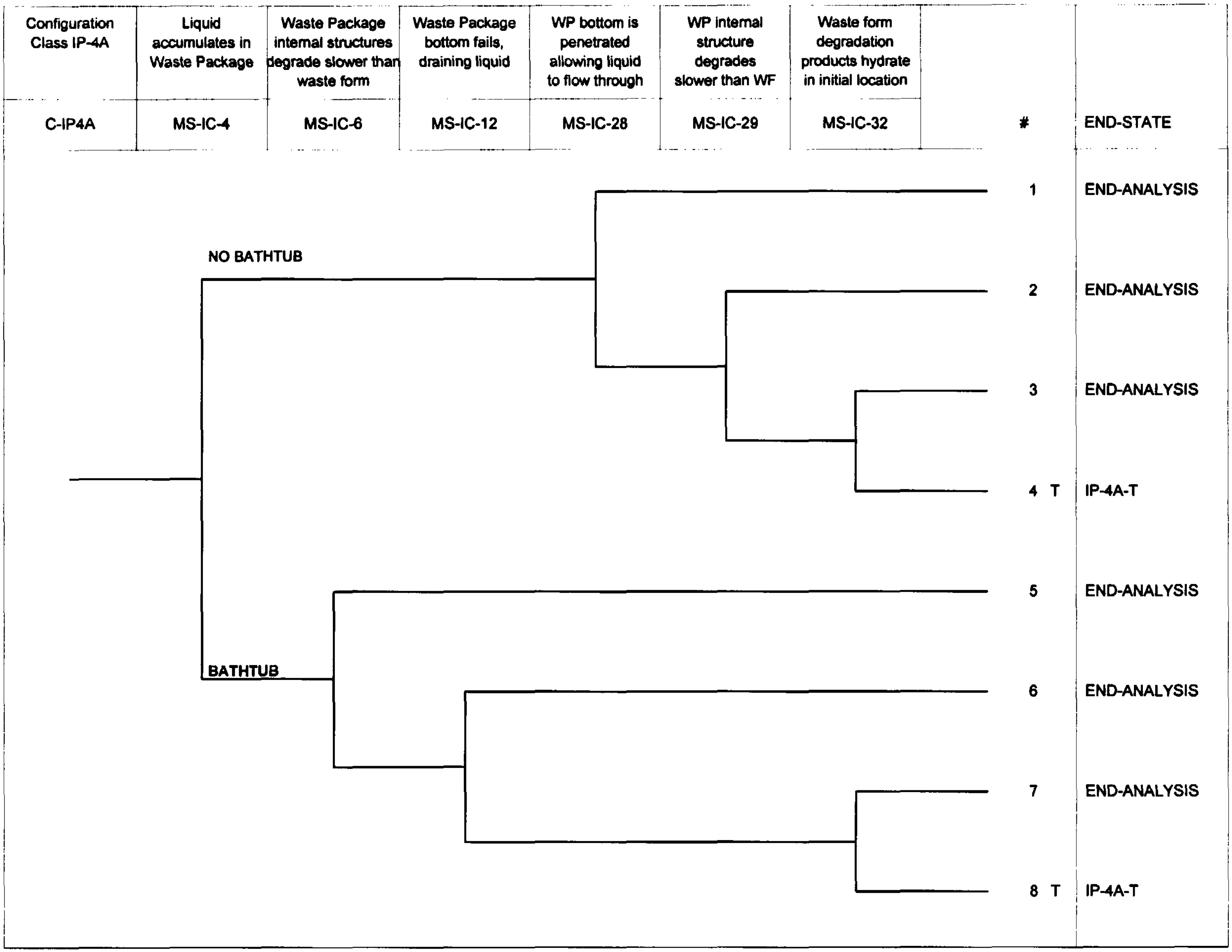


Figure I-20. Configuration Class In-Package 4A

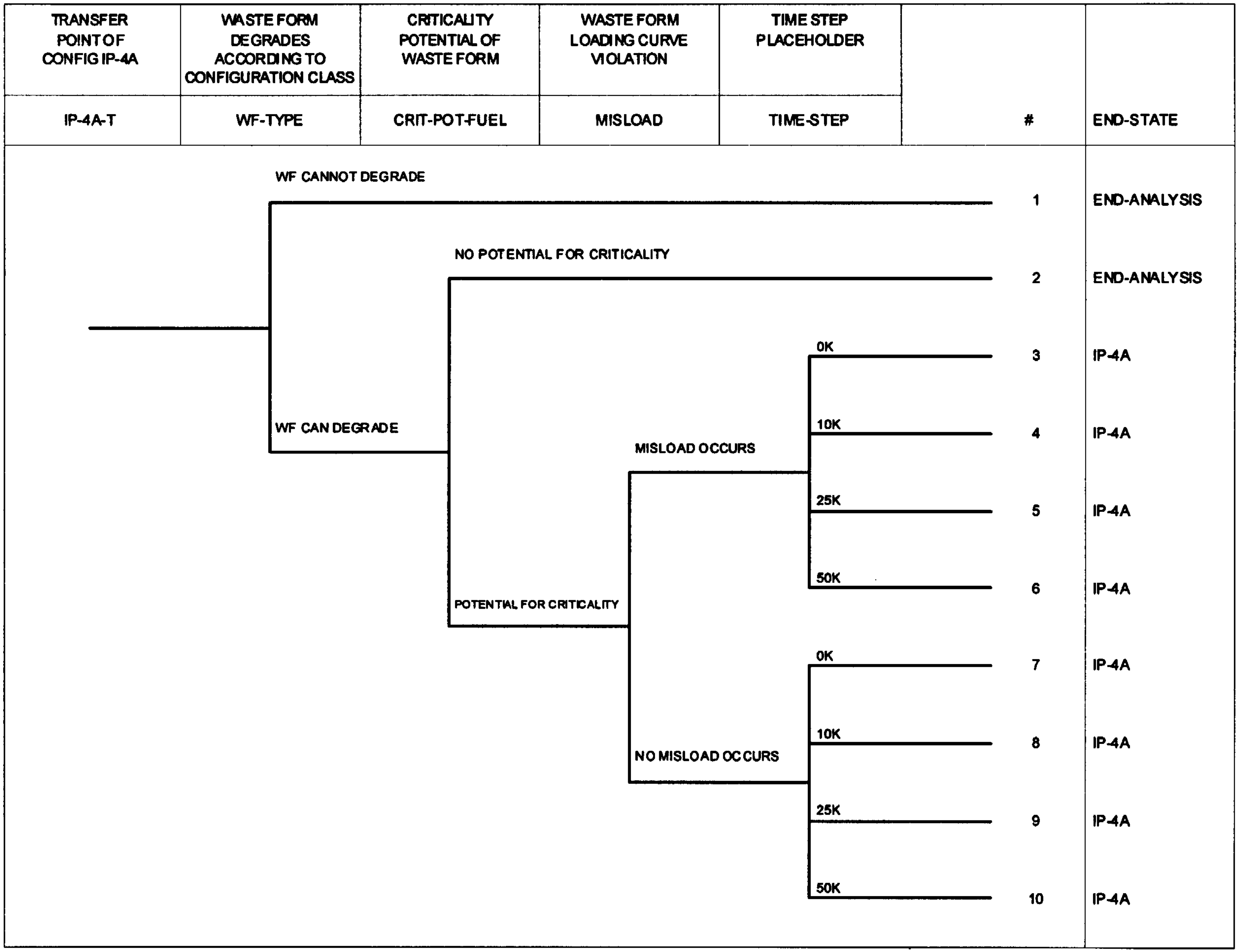


Figure I-21. Configuration Class In-Package 4A End States

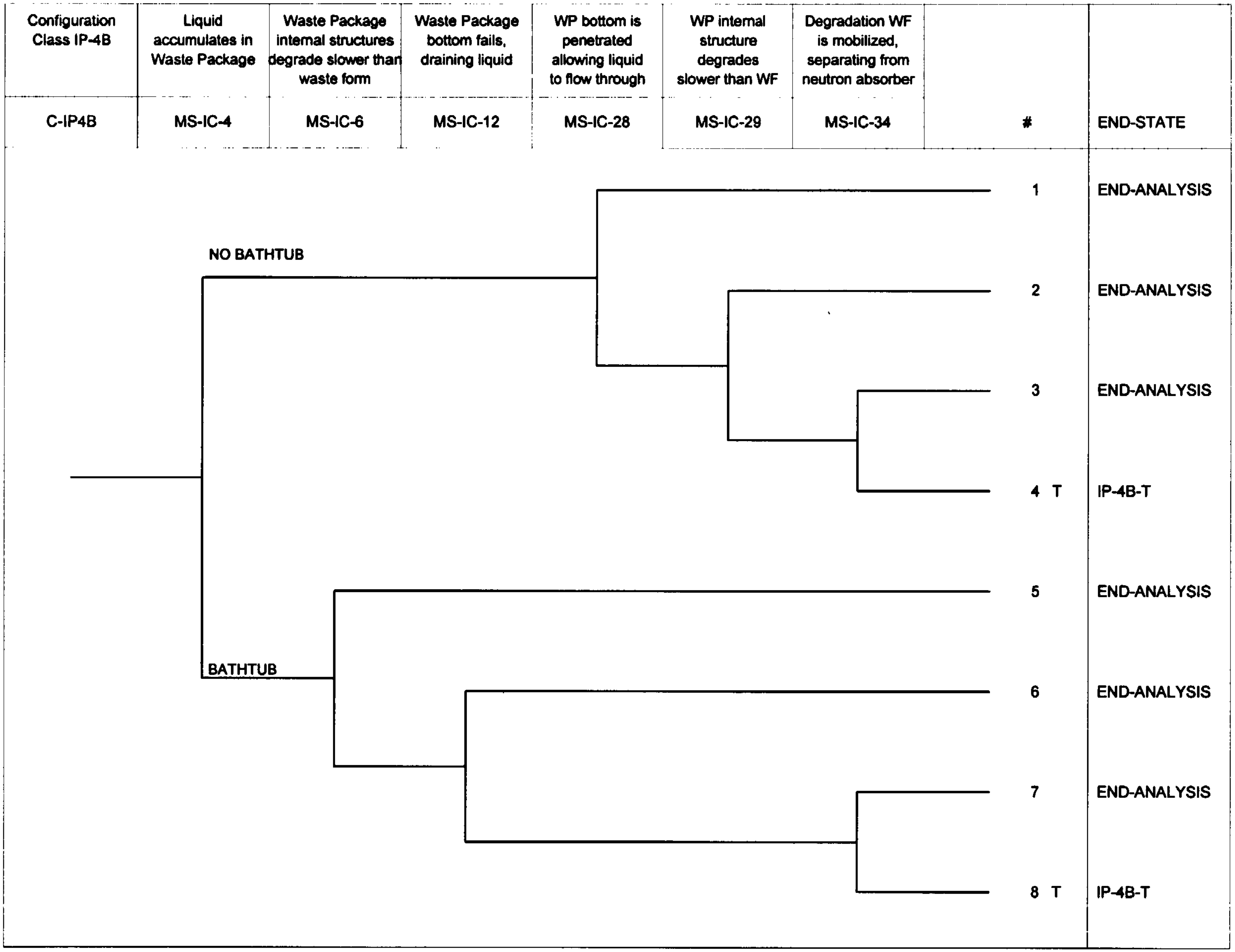


Figure I-22. Configuration Class In-Package 4B

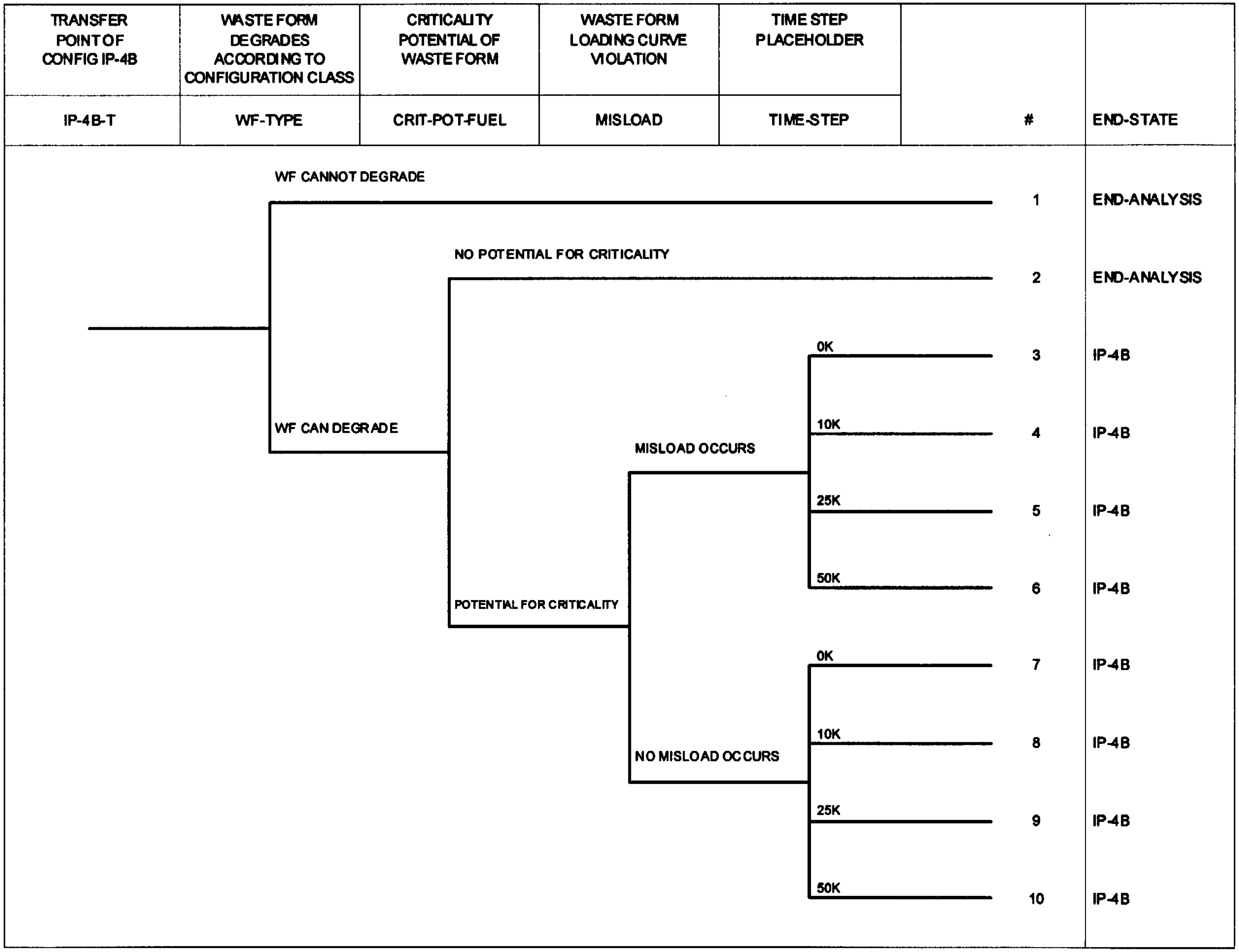


Figure I-23. Configuration Class In-Package 4B End States

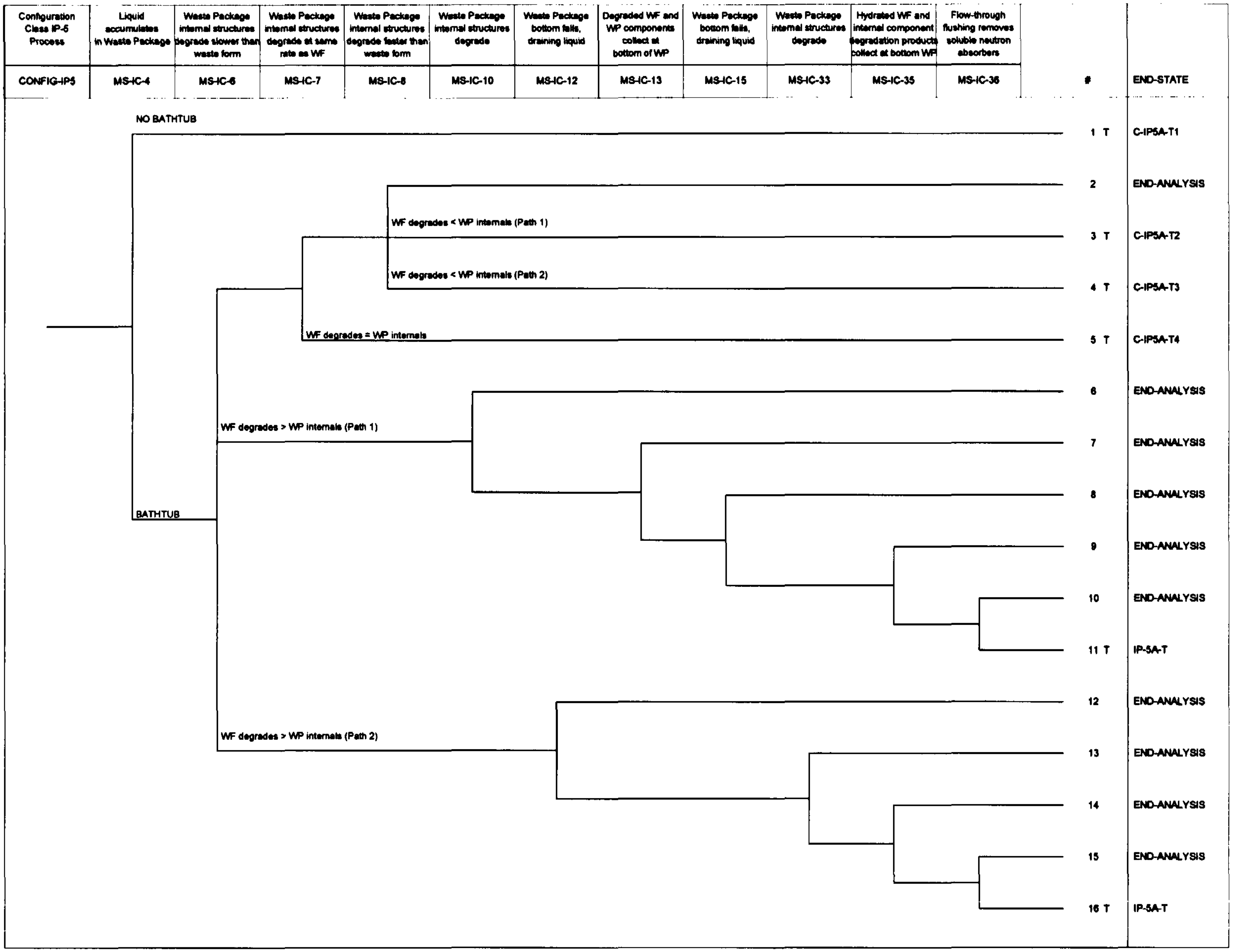


Figure I-24. Configuration Scenario In-Package 5

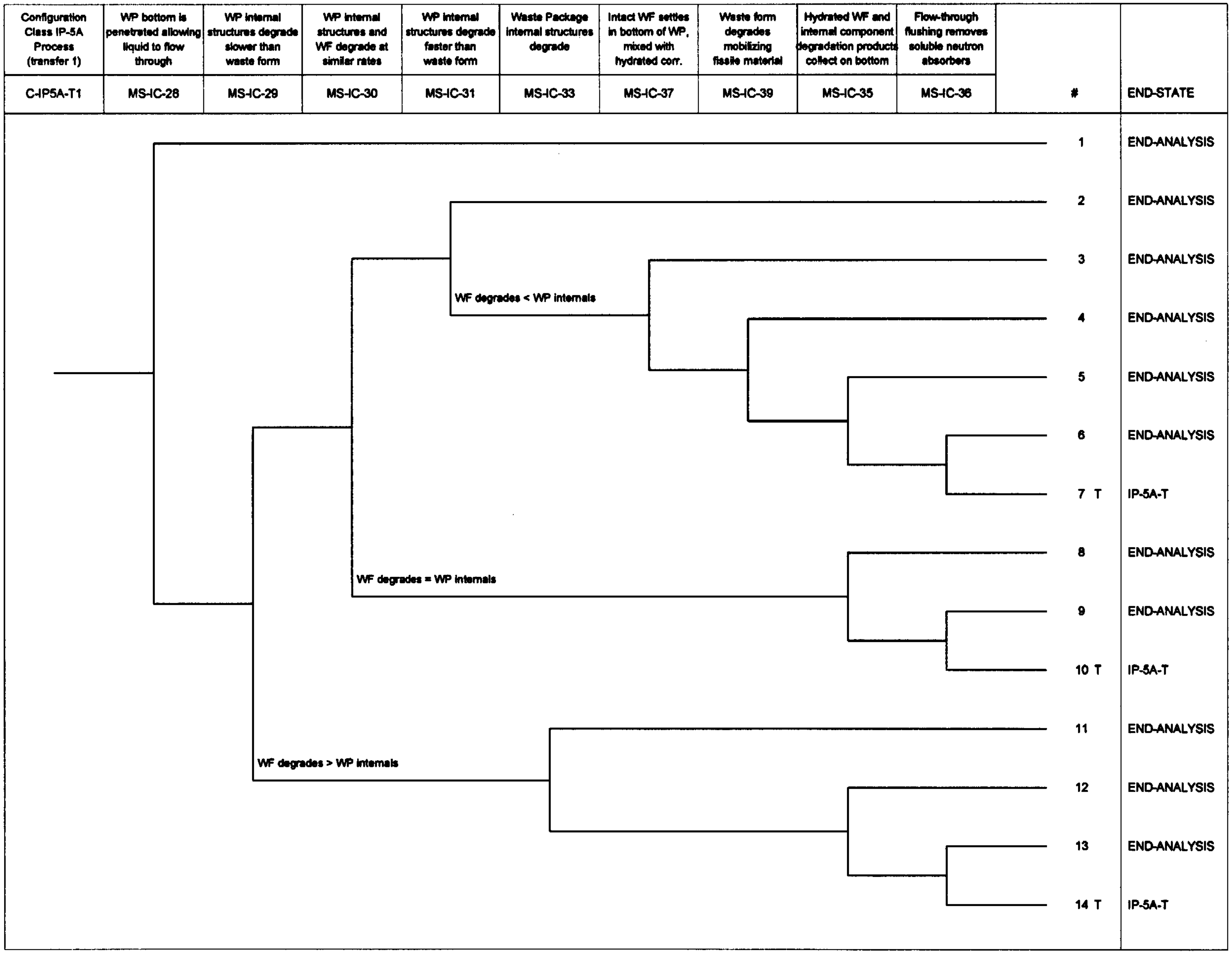


Figure I-25. Configuration Class In-Package 5A (Path Given Flow-Through From the Start)

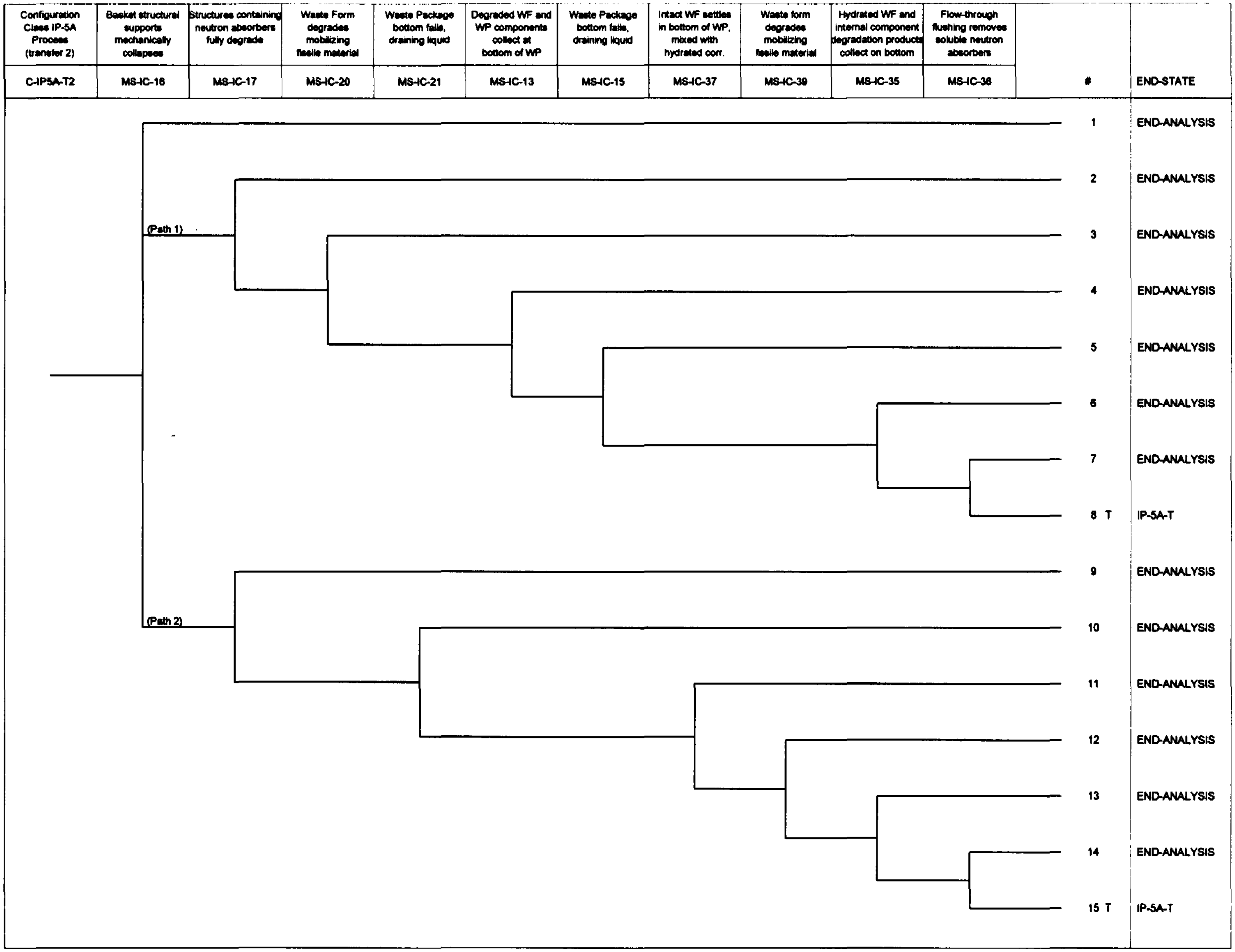


Figure I-26. Configuration Class In-Package 5A (Path 1 Given Waste Form Degrades Slower Than Waste Package Internals)

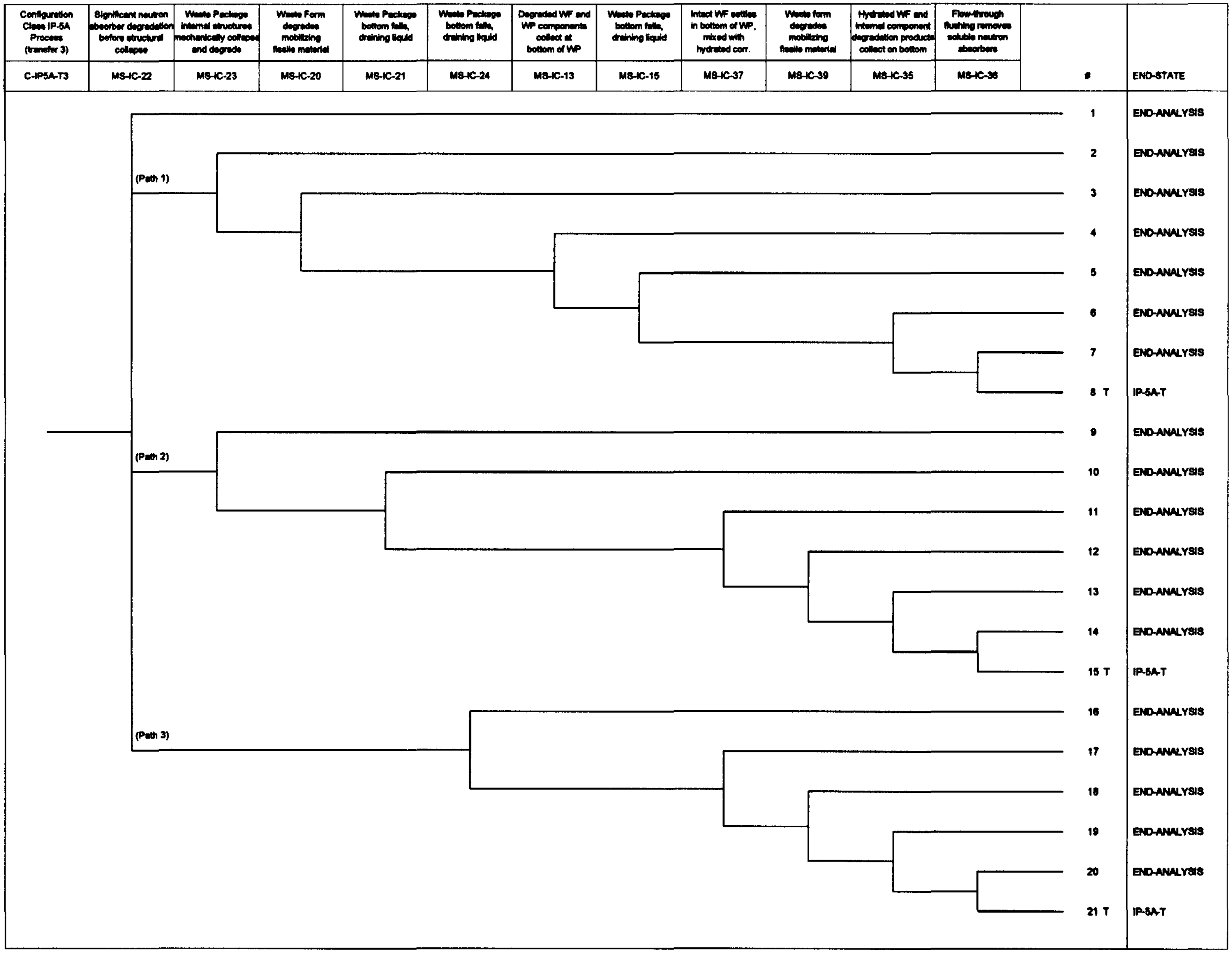


Figure I-27. Configuration Class In-Package 5A (Path 2 Given Waste Form Degrades Slower Than Waste Package Internals)

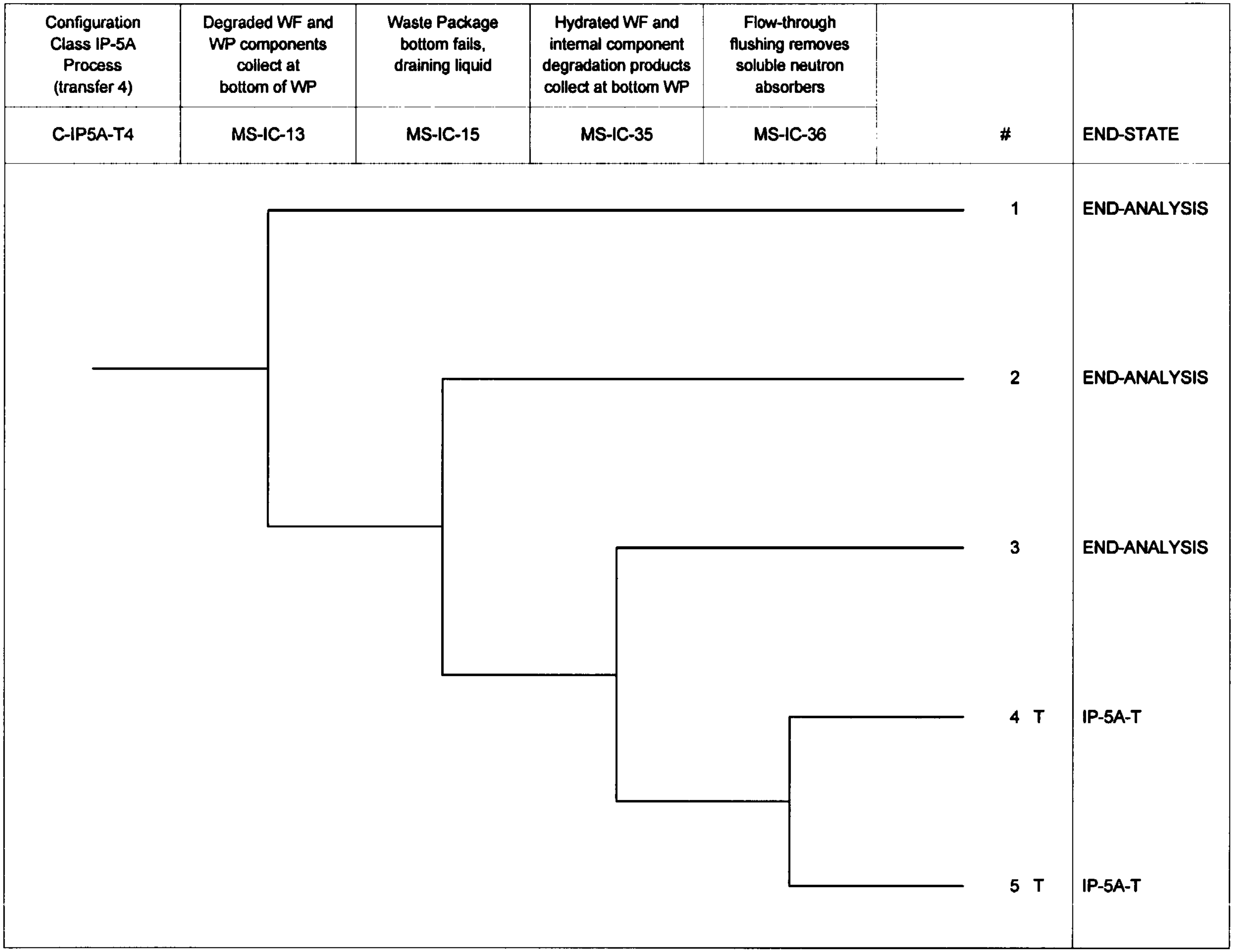


Figure I-28. Configuration Class In-Package 5A (Path Given Waste Form Degrades at Same Rate as Waste Package Internals)

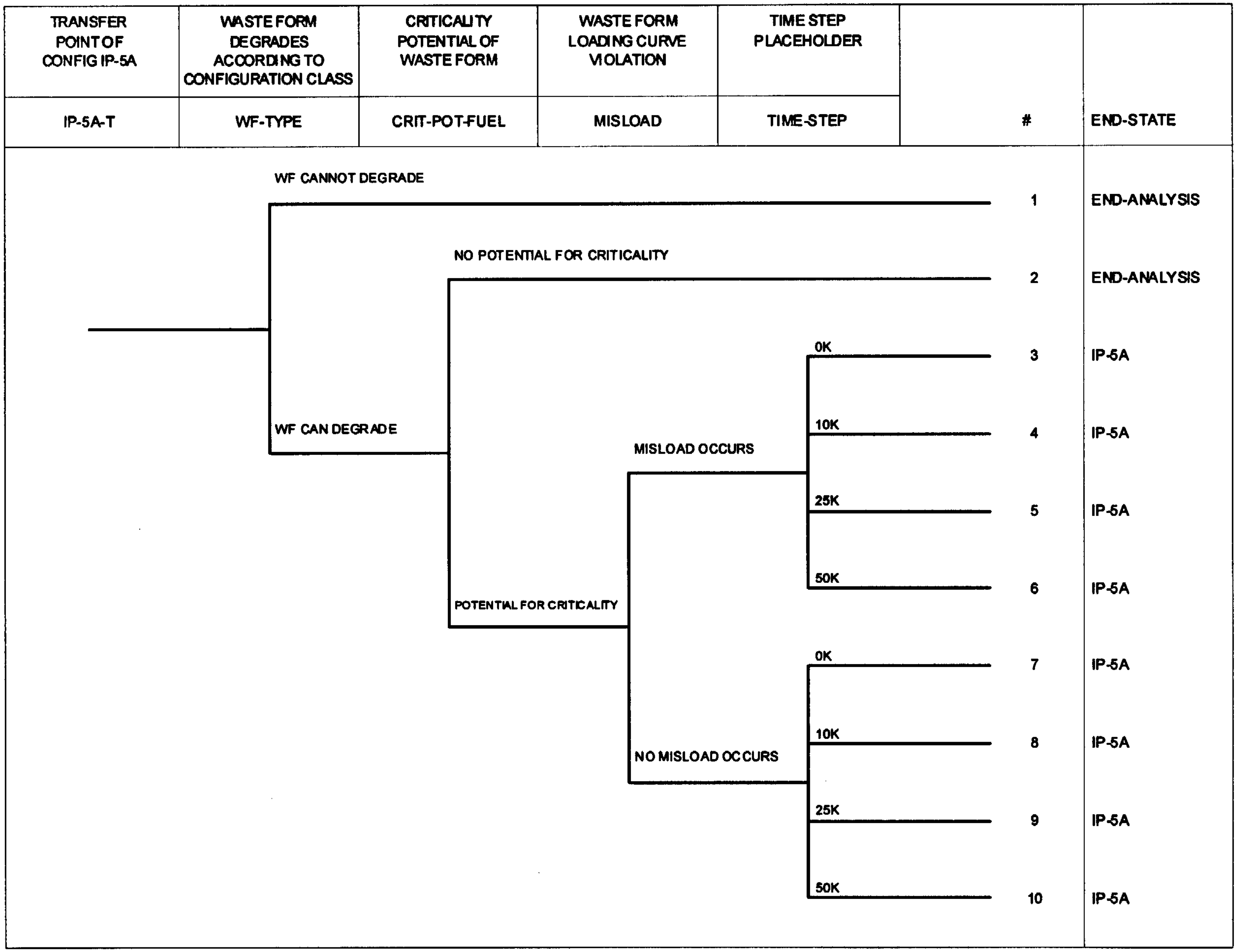


Figure I-29. Configuration Class In-Package 5A End States

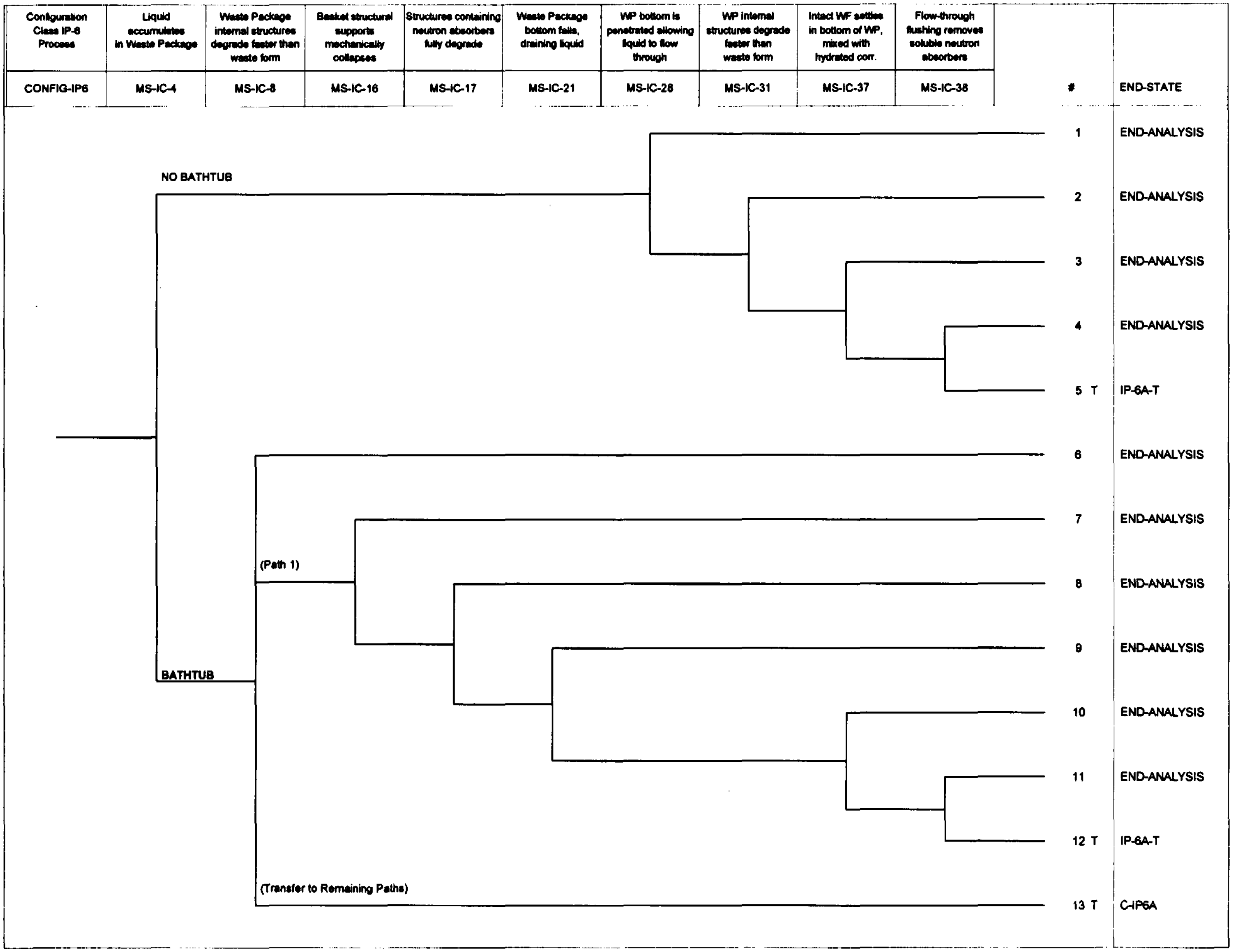


Figure I-30. Configuration Scenario In-Package 6

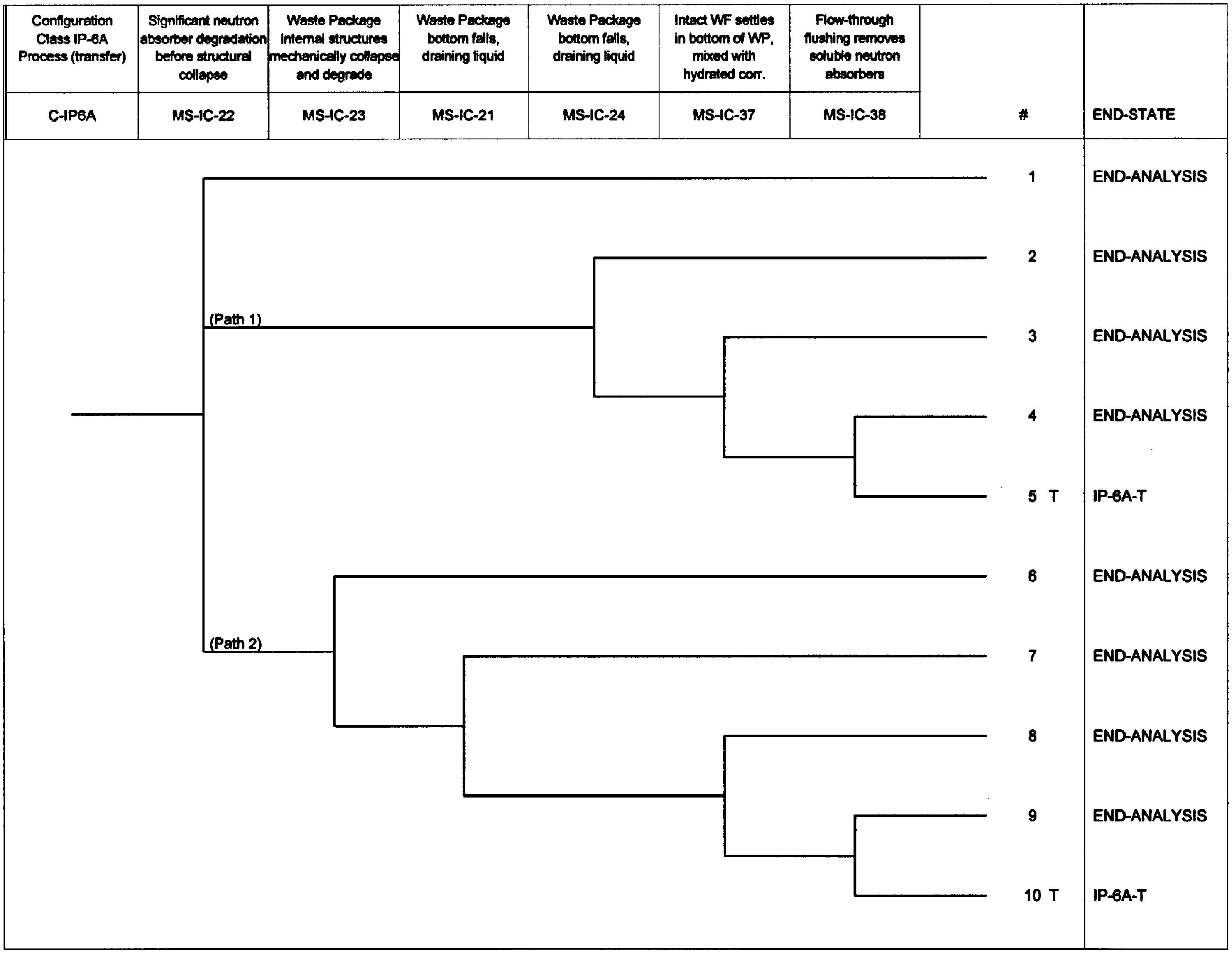


Figure I-31. Configuration Class In-Package 6A (Path Given Waste Form Degrades Slower Than Waste Package Internals)

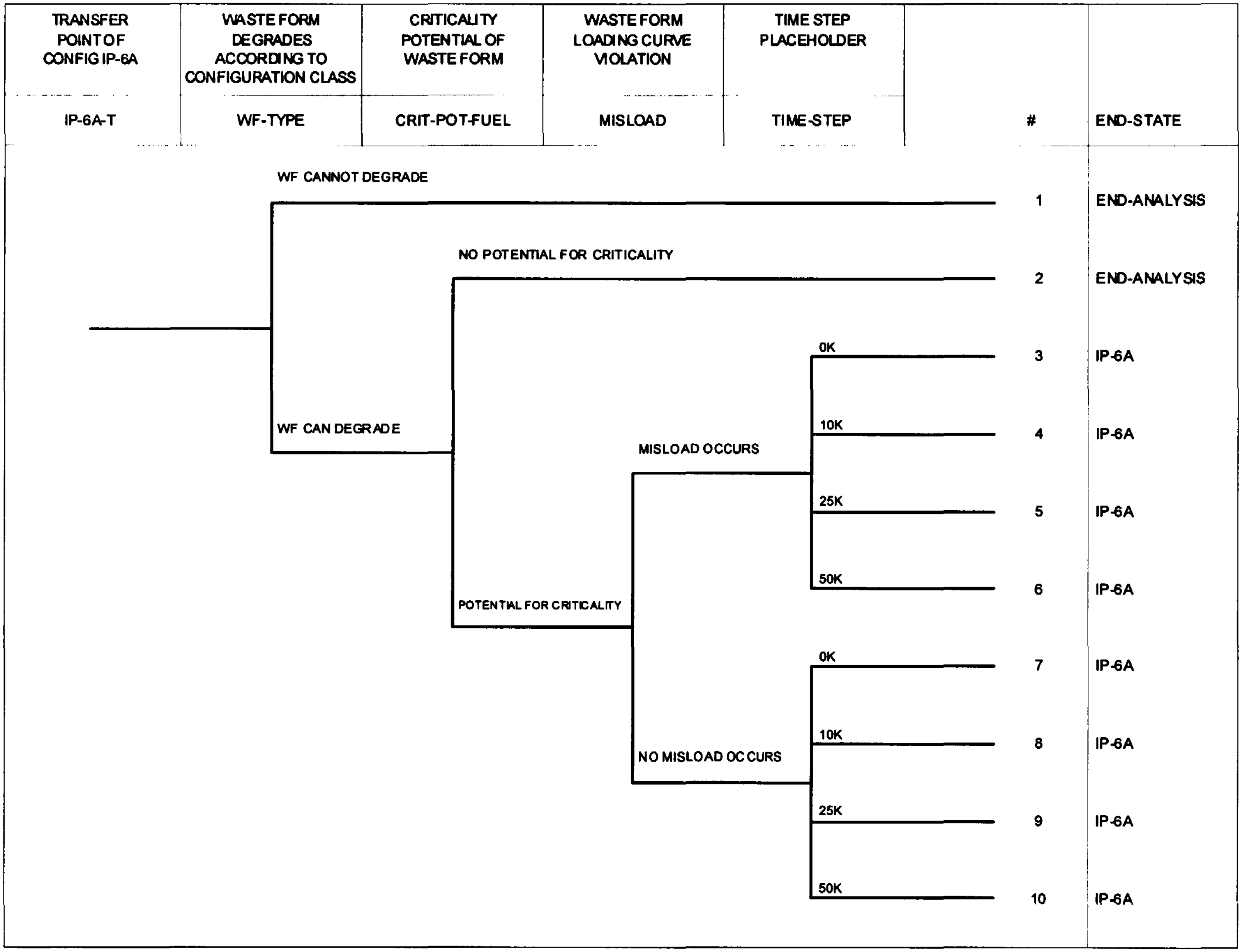


Figure I-32. Configuration Class In-Package 6A End States

ATTACHMENT II
FAULT TREE MODELS

ATTACHMENT II

FAULT TREE MODELS

The degradation processes listed as top events on the event trees listed in Attachment I are developed into fault tree models. The fault tree models contain either single inputs or multiple inputs. The fault trees listed in this attachment (Figures II-1 through II-10) provide an example set of how the fault trees are created and used in the CGM. The fault trees listed here are those used to evaluate configuration class IP-3C. The other configuration class fault trees will use the same type of modeling.

The fault trees are broken down into different gates, which are used to calculate the probability of the process occurring at the time step stated on the event tree. The logic models will only allow the probability for the process at the specific time to be used in the evaluation. In order to allow only one probability to come through the fault tree logic at each time step, house events are used. A house event is used to allow certain basic events (or logic process) to be generated by turning the house event either on or off. A house event can be viewed like a light switch, which allows the basic event (or logic process) to be generated or not. The house events are set to toggle on or off depending on the specific time step being evaluated. However, if the basic event probability is not time dependent it will be evaluated for all time steps.

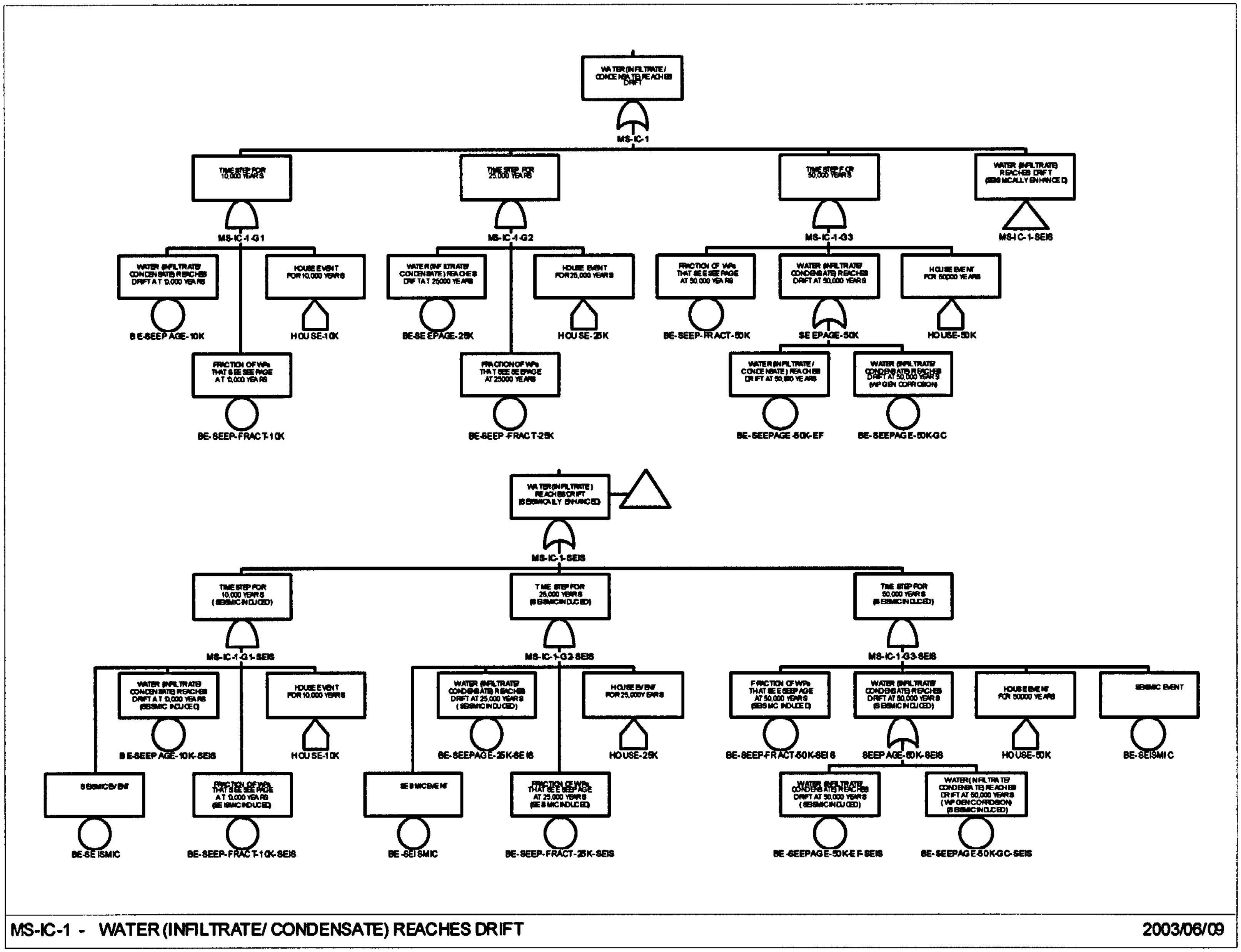


Figure II-1. Fault Tree MS-IC-1, Water Reaches the Drift via Infiltration or Condensation

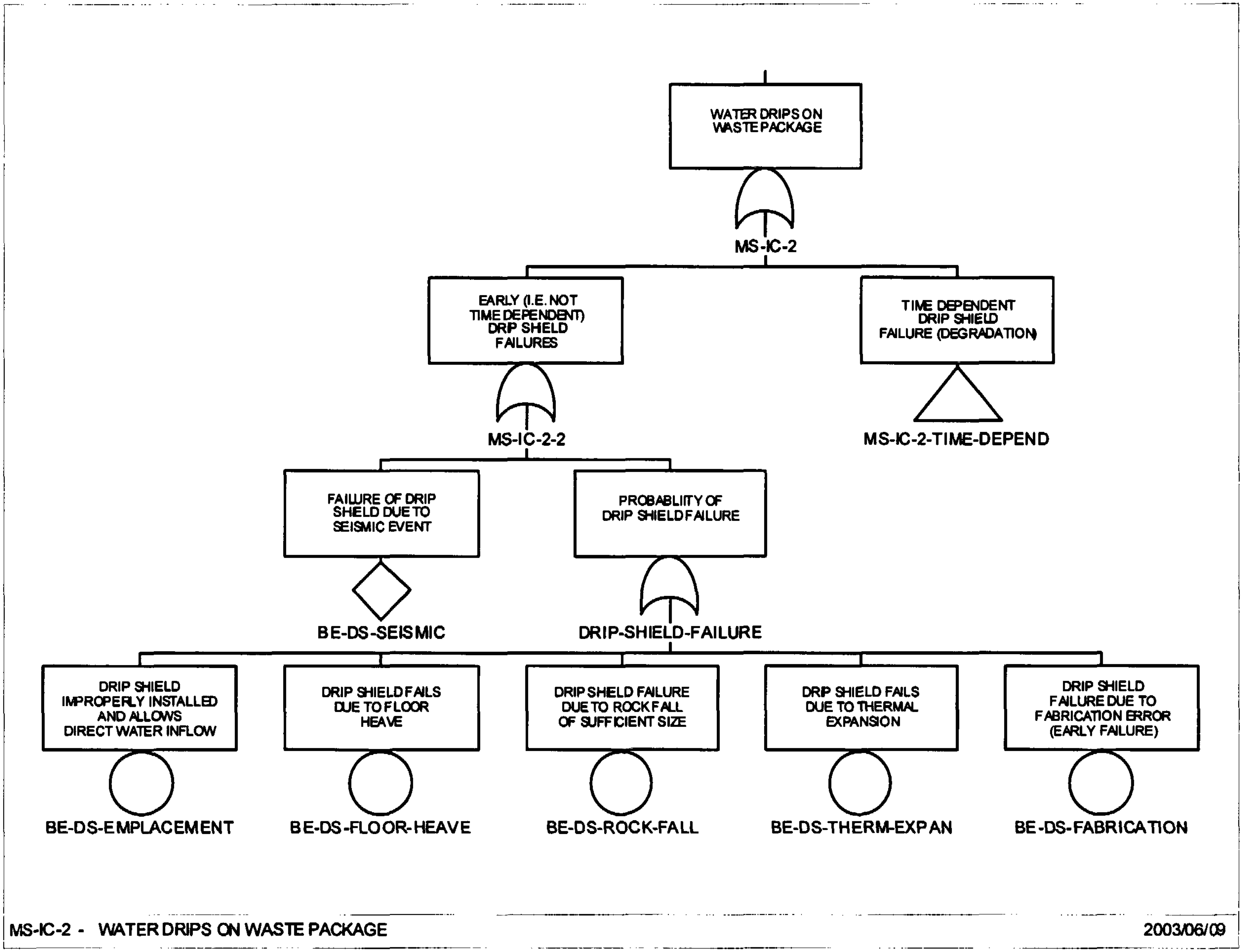


Figure II-2. Fault Tree MS-IC-2, Water Drips on Waste Package via Drip Shield Failures

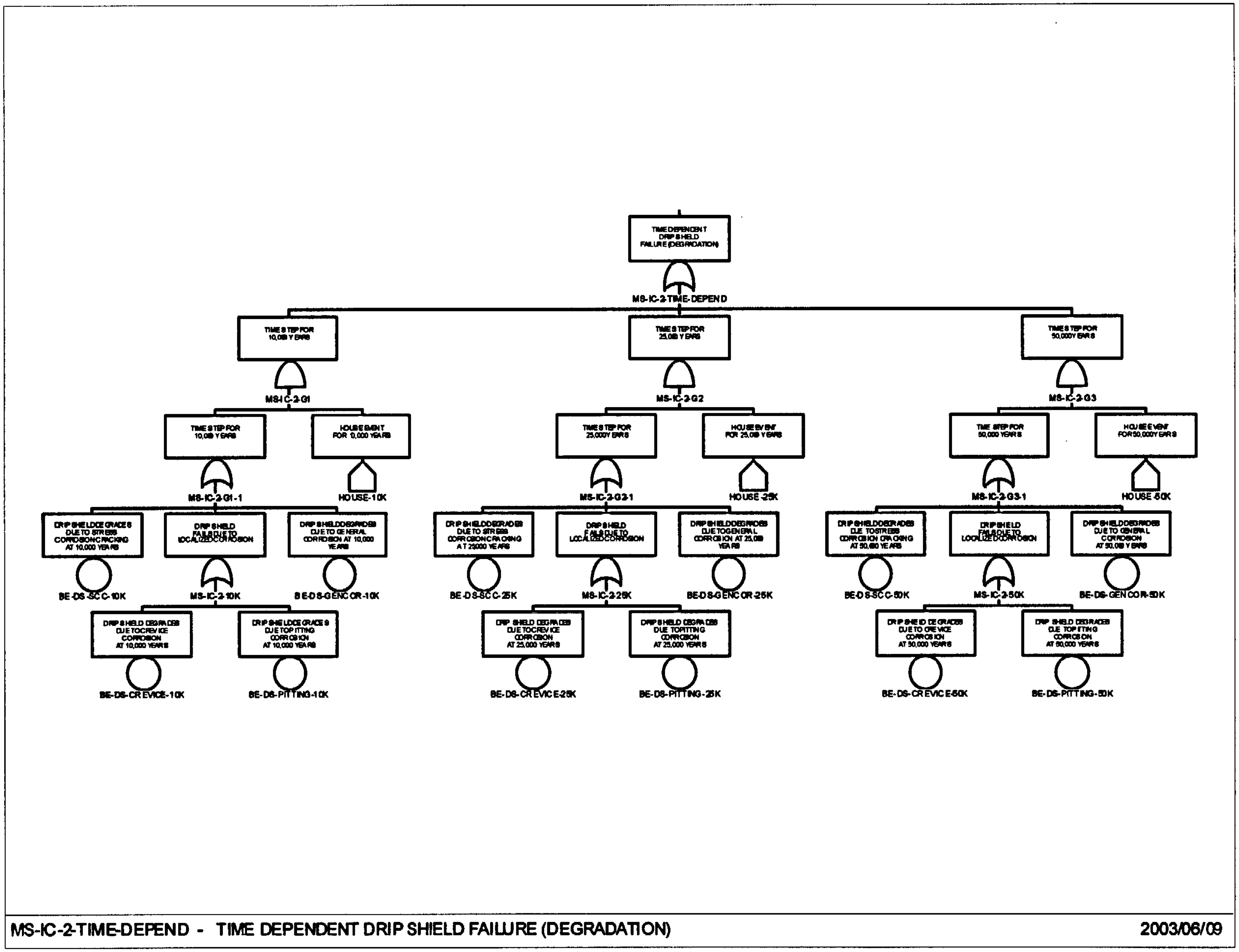


Figure II-3 Fault Tree MS-IC-2 Time-Dependent, Water Drips on Waste Package via Drip Shield Failures

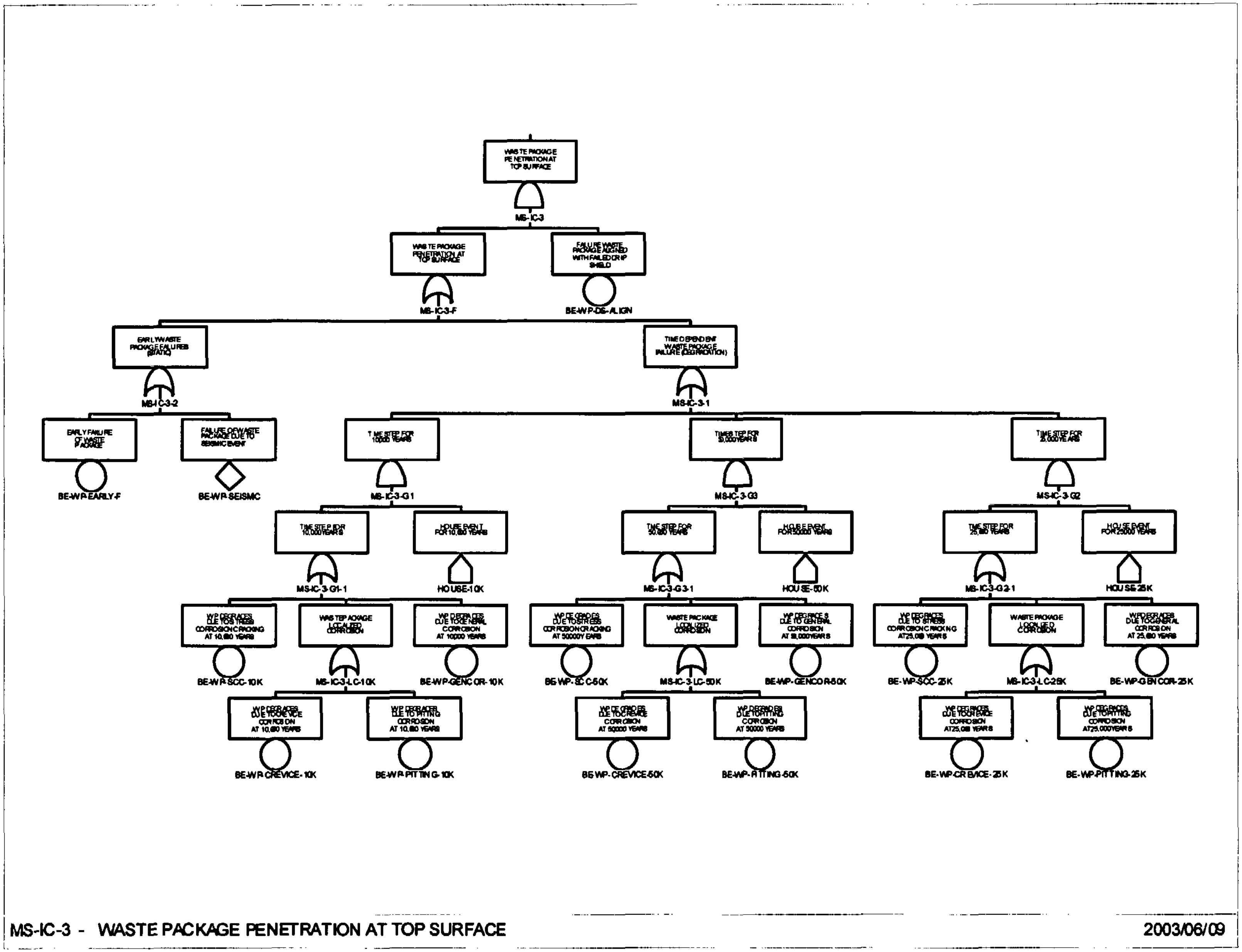


Figure II-4. Fault Tree MS-IC-3, Waste Package Top Failures

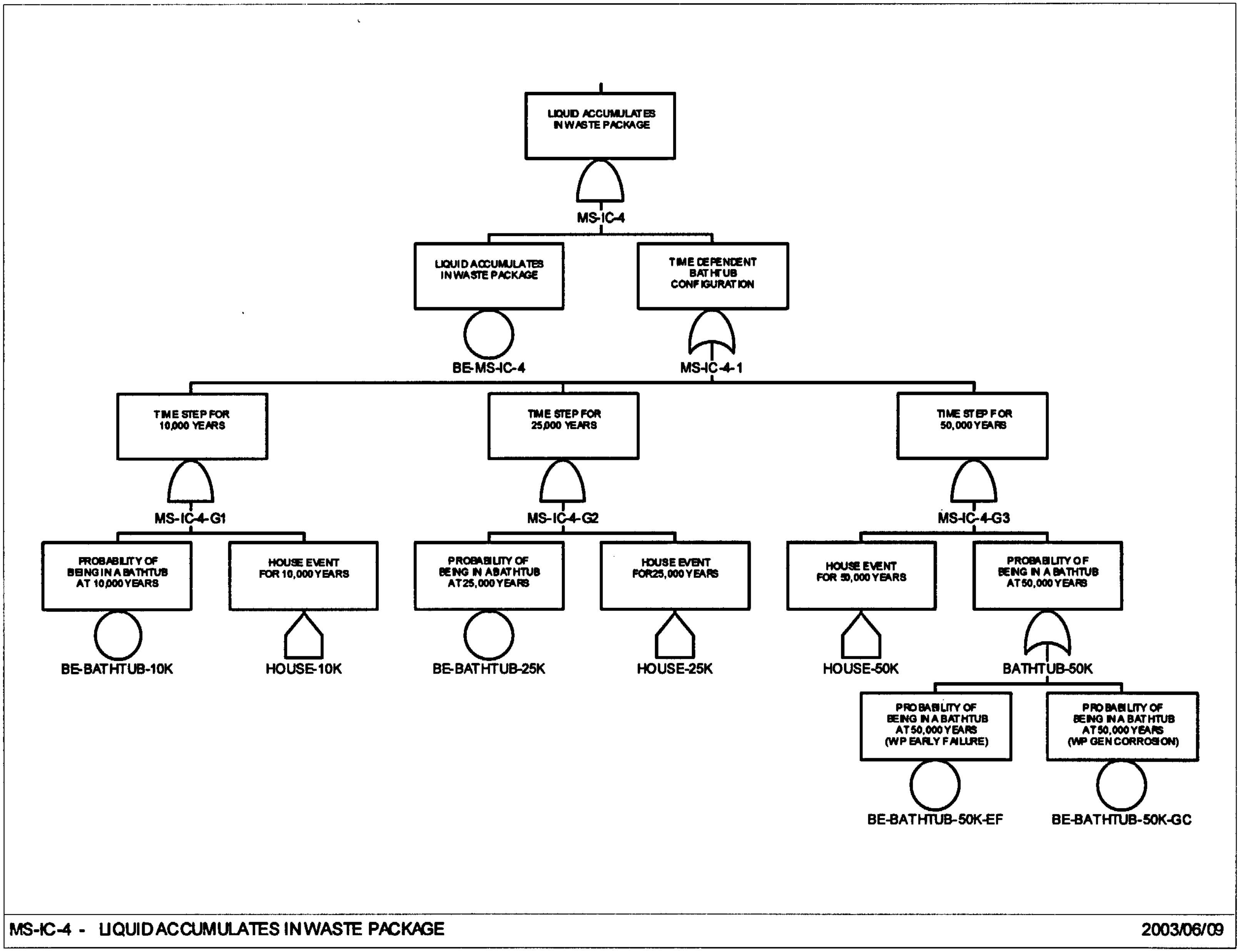


Figure II-5. Fault Tree MS-IC-4, Water Accumulates Inside the Waste Package

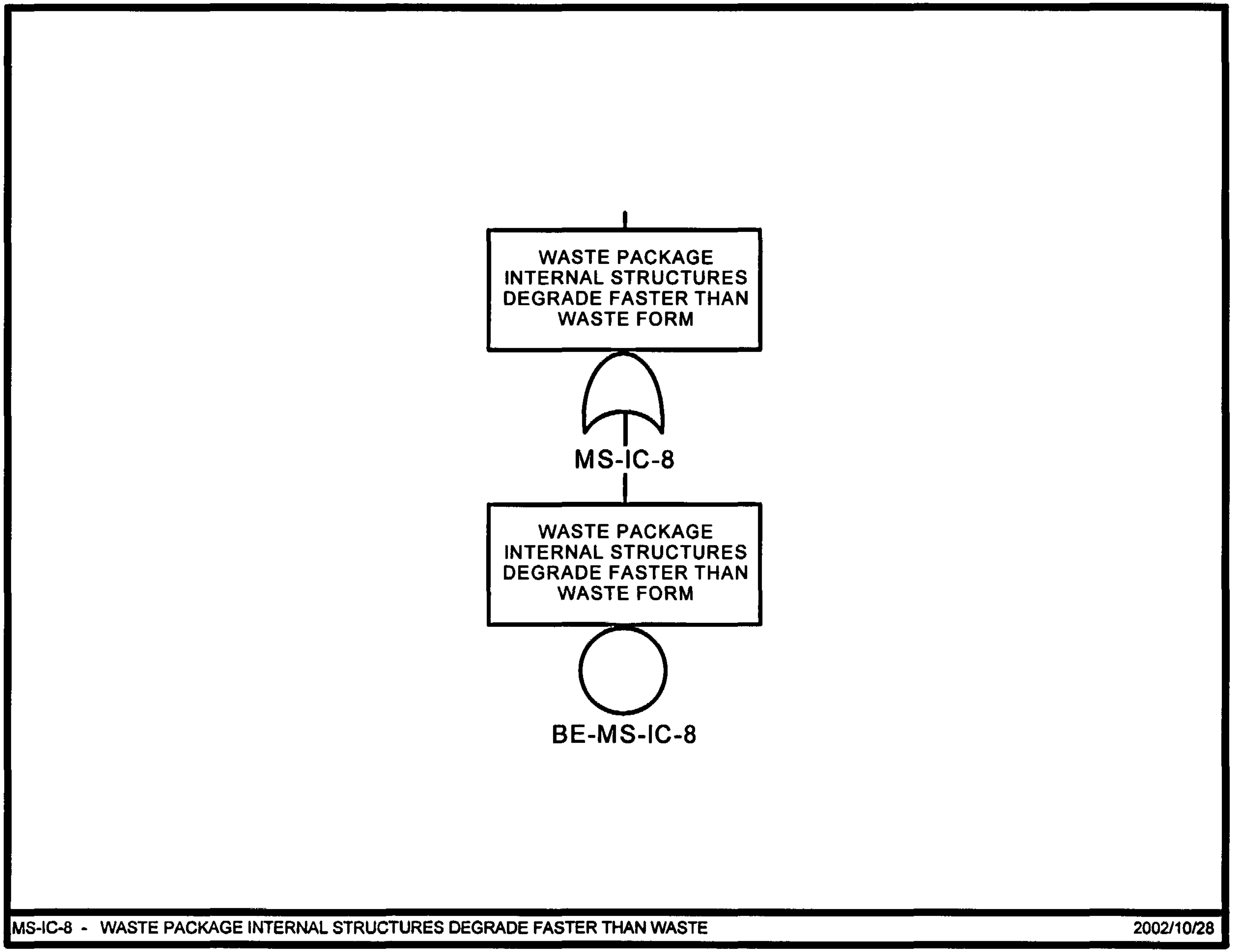


Figure II-6. Fault Tree MS-IC-8, Waste Package Internal Structures Degrade Faster Than Waste Form

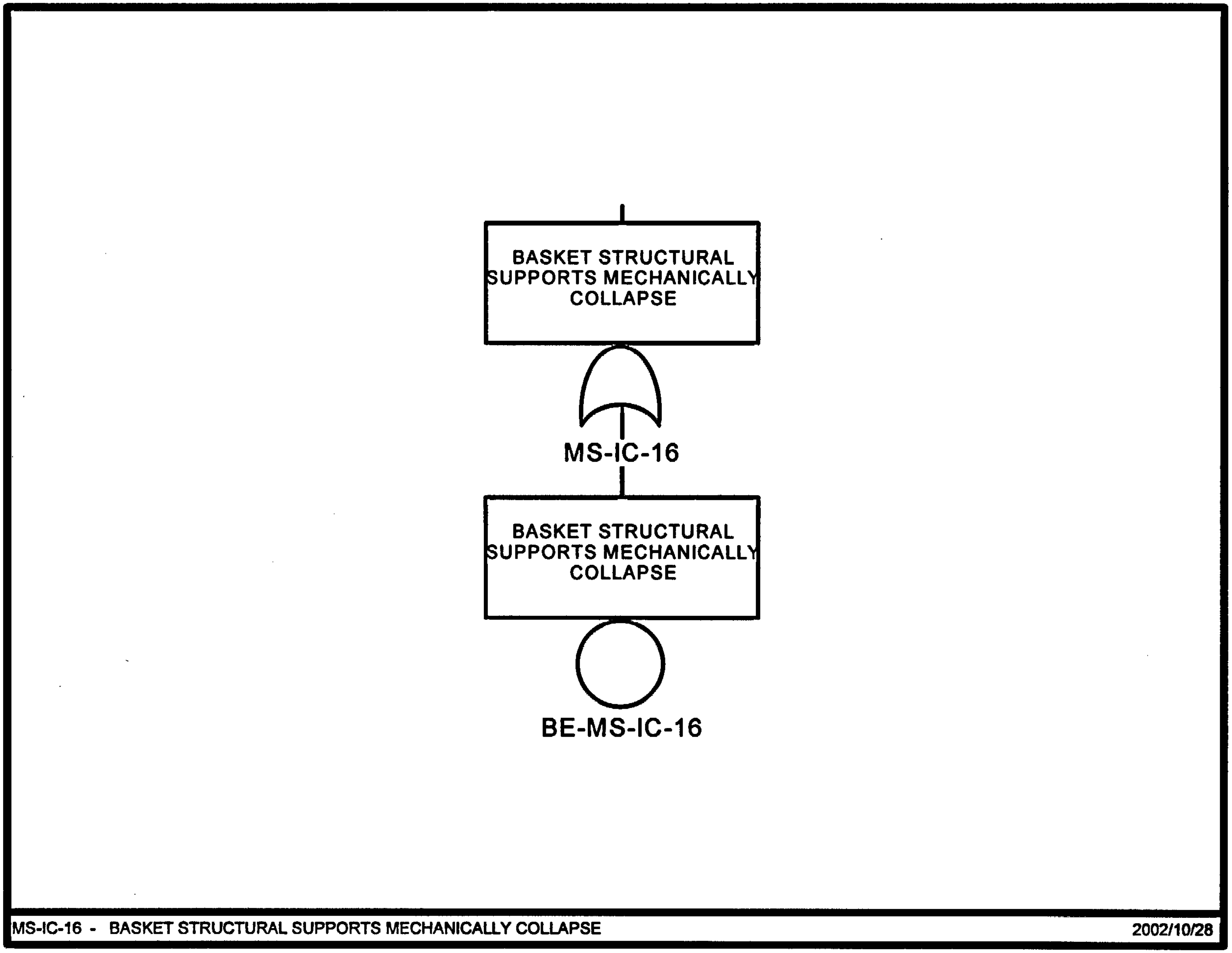


Figure II-7. Fault Tree MS-IC-16, Waste Package Basket Structural Supports Mechanically Collapse

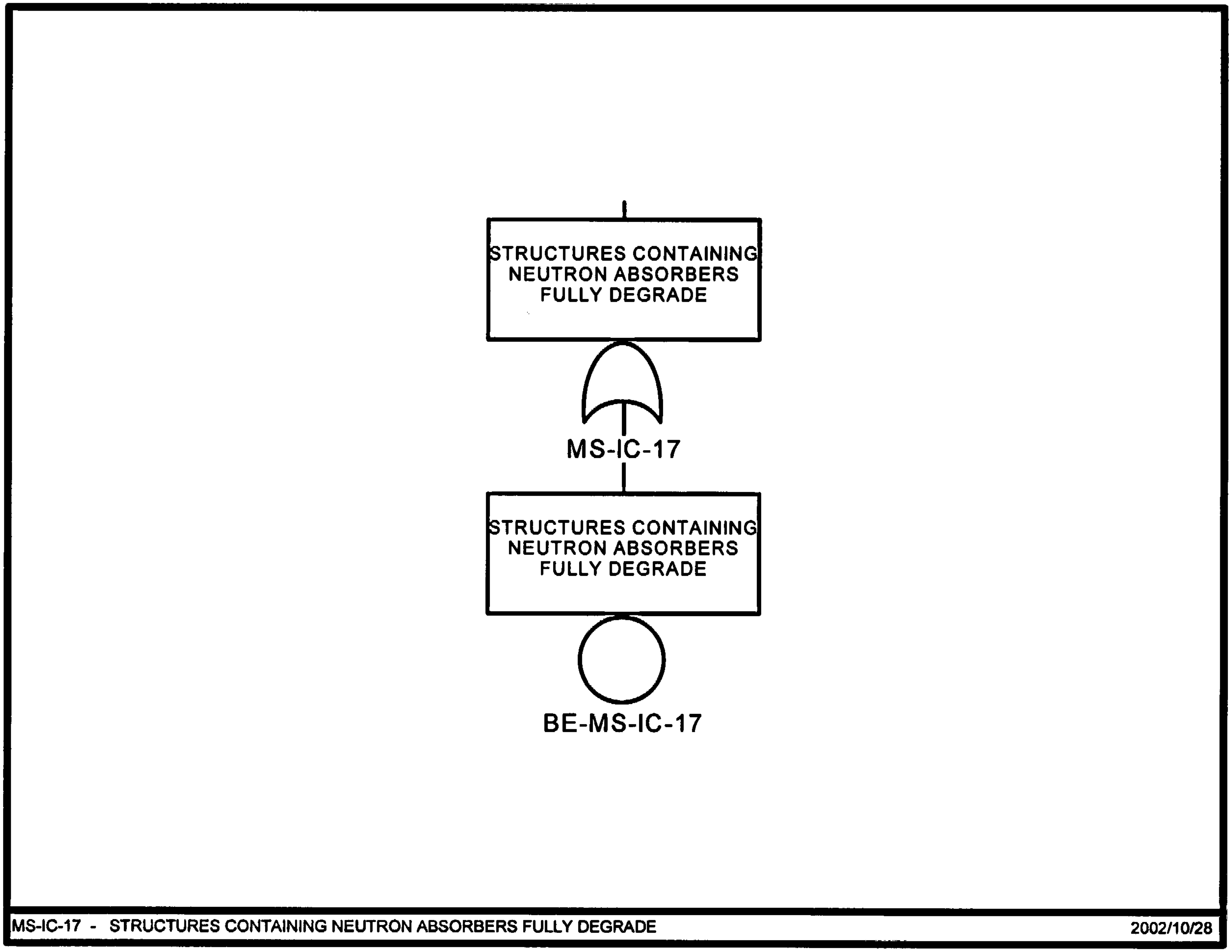


Figure II-8. Fault Tree MS-IC-17, Waste Package Structures Containing Neutron Absorbers Fully Degrade

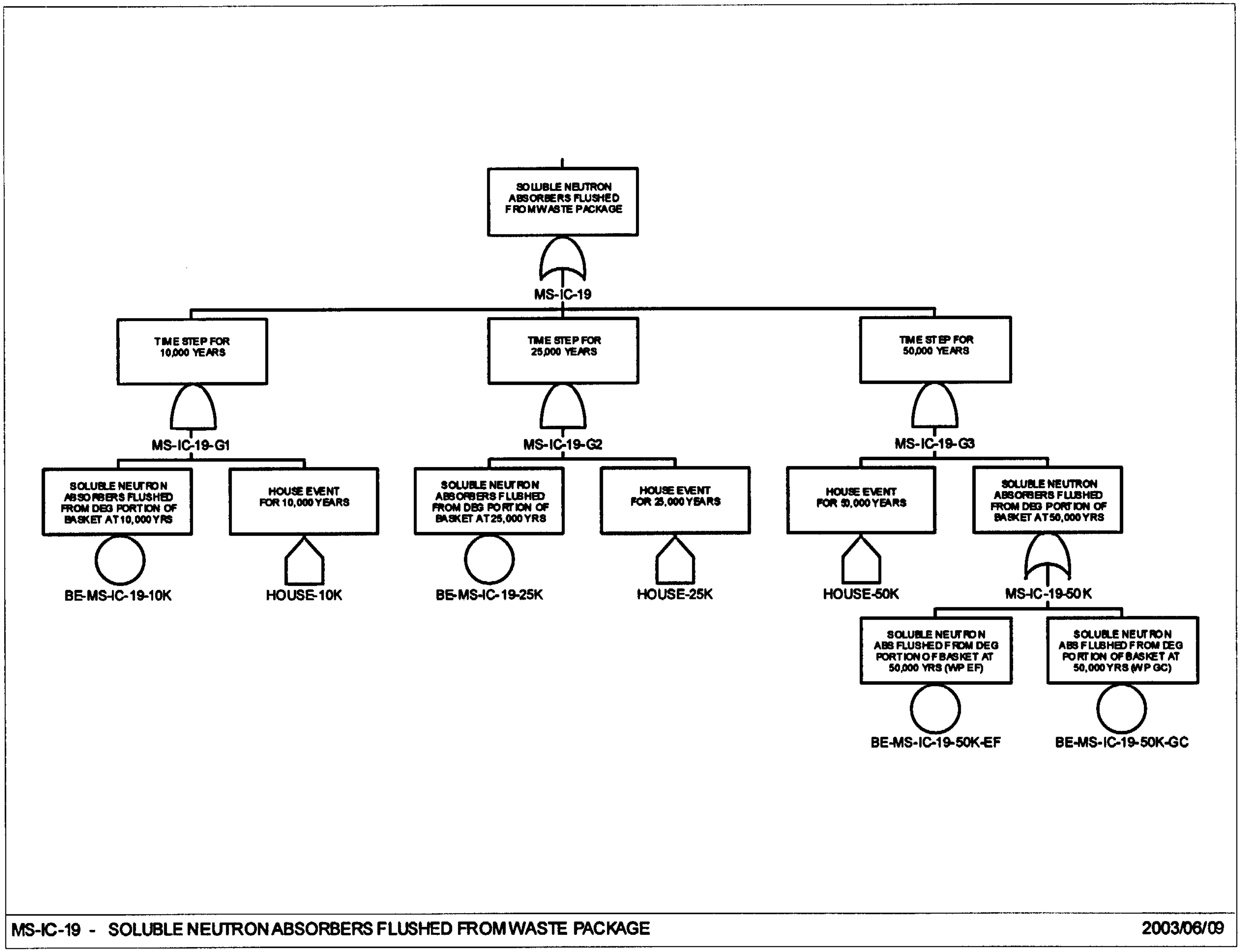


Figure II-9. Fault Tree MS-IC-19, Soluble Neutron Absorbers Flushed From Waste Package

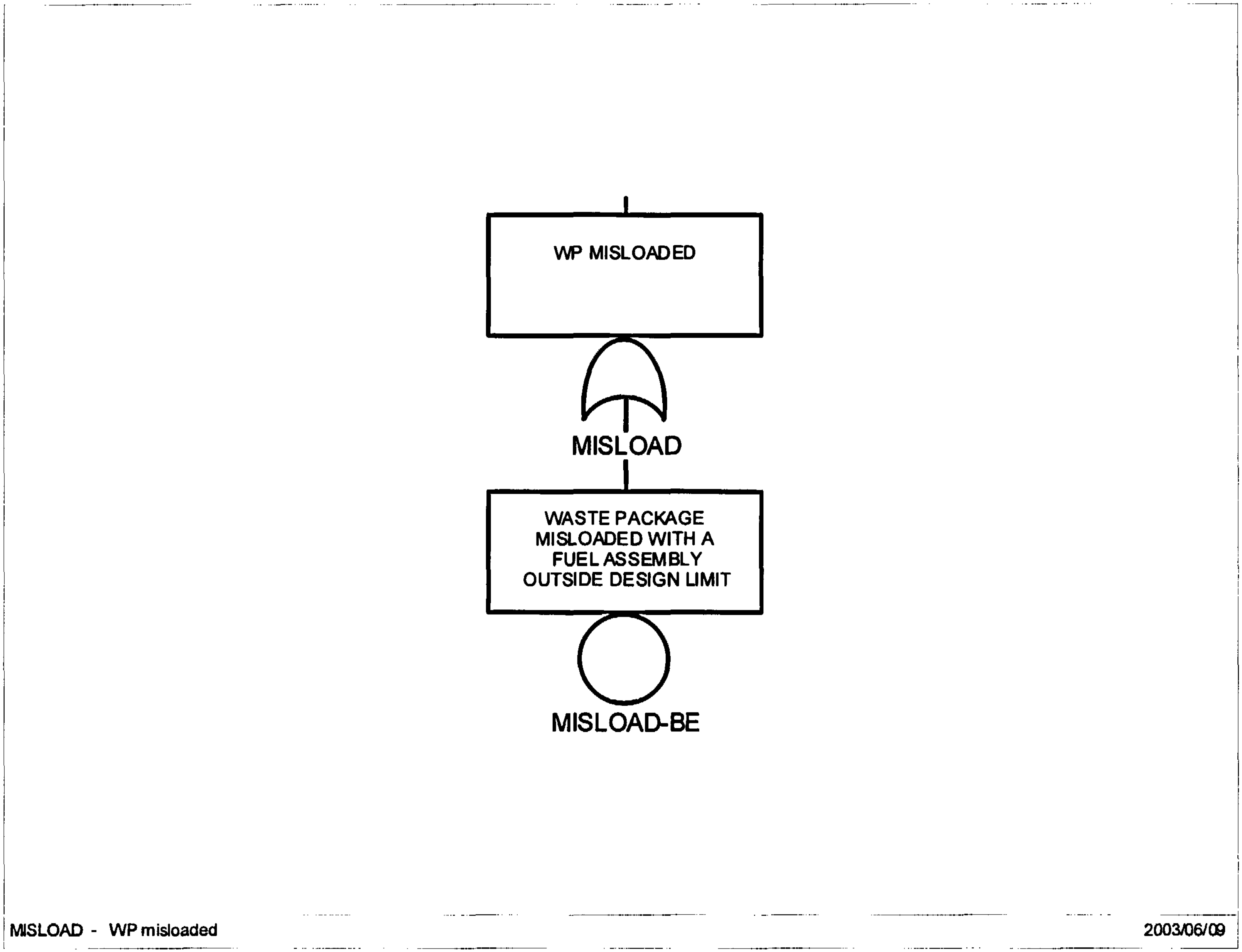


Figure II-10. Fault Tree MISLOAD, Waste Package Loaded with Fuel Assembly Outside Design Limits

ATTACHMENT III

CGM SAPHIRE MODEL RULES

ATTACHMENT III

CGM SAPHIRE MODEL RULES

The different rules used in the SAPHIRE CGM model are listed below. The rules include the top event substitution rules, time specific end state rules, and unrealistic process combination removal rules.

Top Event Substitution Rules:

```
if MS-IC-4*CONFIG-SCEN[1]*MS-IC-9 then
 /WF-TYPE = WF-TYPE-IP1A;
  WF-TYPE = WF-TYPE-IP1A;
 /CRIT-POT-FUEL = CRIT-POT-FUEL-IP1A;
  CRIT-POT-FUEL = CRIT-POT-FUEL-IP1A;

elsif MS-IC-4*CONFIG-SCEN[1]*MS-IC-11 then
 /WF-TYPE = WF-TYPE-IP1B;
  WF-TYPE = WF-TYPE-IP1B;
 /CRIT-POT-FUEL = CRIT-POT-FUEL-IP1B;
  CRIT-POT-FUEL = CRIT-POT-FUEL-IP1B;

elsif MS-IC-4*CONFIG-SCEN[2] then
 /WF-TYPE=WF-TYPE-IP2A;
  WF-TYPE=WF-TYPE-IP2A;
 /CRIT-POT-FUEL = CRIT-POT-FUEL-IP2A;
  CRIT-POT-FUEL = CRIT-POT-FUEL-IP2A;

elsif MS-IC-4*CONFIG-SCEN[3]*IP3-CON-CLASS[1] then
 /WF-TYPE = WF-TYPE-IP3A;
  WF-TYPE = WF-TYPE-IP3A;
 /CRIT-POT-FUEL = CRIT-POT-FUEL-IP3A;
  CRIT-POT-FUEL = CRIT-POT-FUEL-IP3A;

elsif MS-IC-4*CONFIG-SCEN[3]*IP3-CON-CLASS[2] then
 /WF-TYPE = WF-TYPE-IP3B;
  WF-TYPE = WF-TYPE-IP3B;
 /CRIT-POT-FUEL = CRIT-POT-FUEL-IP3B;
  CRIT-POT-FUEL = CRIT-POT-FUEL-IP3B;

elsif MS-IC-4*CONFIG-SCEN[3]*IP3-CON-CLASS[3] then
 /WF-TYPE = WF-TYPE-IP3C;
  WF-TYPE = WF-TYPE-IP3C;
 /CRIT-POT-FUEL = CRIT-POT-FUEL-IP3C;
  CRIT-POT-FUEL = CRIT-POT-FUEL-IP3C;

elsif MS-IC-4*CONFIG-SCEN[3]*IP3-CON-CLASS[4] then
```

```
 /WF-TYPE = WF-TYPE-IP3D;
  WF-TYPE = WF-TYPE-IP3D;
 /CRIT-POT-FUEL = CRIT-POT-FUEL-IP3D;
  CRIT-POT-FUEL = CRIT-POT-FUEL-IP3D;

elsif /MS-IC-4*CONFIG-SCEN[1]* IP4-CON-CLASS[1] then
 /WF-TYPE = WF-TYPE-IP4A;
  WF-TYPE = WF-TYPE-IP4A;
 /CRIT-POT-FUEL = CRIT-POT-FUEL-IP4A;
  CRIT-POT-FUEL = CRIT-POT-FUEL-IP4A;

elsif /MS-IC-4*CONFIG-SCEN[1]*IP4-CON-CLASS[2] then
 /WF-TYPE = WF-TYPE-IP4B;
  WF-TYPE = WF-TYPE-IP4B;
 /CRIT-POT-FUEL = CRIT-POT-FUEL-IP4B;
  CRIT-POT-FUEL = CRIT-POT-FUEL-IP4B;

elsif /MS-IC-4*CONFIG-SCEN[2] then
 /WF-TYPE = WF-TYPE-IP5A;
  WF-TYPE = WF-TYPE-IP5A;
 /CRIT-POT-FUEL = CRIT-POT-FUEL-IP5A;
  CRIT-POT-FUEL = CRIT-POT-FUEL-IP5A;

elsif /MS-IC-4*CONFIG-SCEN[3] then
 /WF-TYPE = WF-TYPE-IP6A;
  WF-TYPE = WF-TYPE-IP6A;
 /CRIT-POT-FUEL = CRIT-POT-FUEL-IP6A;
  CRIT-POT-FUEL = CRIT-POT-FUEL-IP6A;
endif

if TIME-STEP[1] then
 eventree(CNSF-21PWRABS) = True(HOUSE-10K);
elsif TIME-STEP[2] then
 eventree(CNSF-21PWRABS) = True(HOUSE-25K);
elsif TIME-STEP[3] then
 eventree(CNSF-21PWRABS) = True(HOUSE-50K);
endif

if /MS-IC-4 then
 CONFIG-SCEN[1] = CONFIG-SCEN4;
 CONFIG-SCEN[2] = CONFIG-SCEN5;
 CONFIG-SCEN[3] = CONFIG-SCEN6;

elsif MS-IC-4 then
 CONFIG-SCEN[1] = CONFIG-SCEN1;
 CONFIG-SCEN[2] = CONFIG-SCEN2;
```

```
 CONFIG-SCEN[3] = CONFIG-SCEN3;
endif

if always then
 ip3-con-class[1] = ip3-con-class1;
 ip3-con-class[2] = ip3-con-class2;
 ip3-con-class[3] = ip3-con-class3;
 ip3-con-class[4] = ip3-con-class4;
endif

if always then
 ip4-con-class[1] = ip4-con-class1;
 ip4-con-class[2] = ip4-con-class2;
endif

if always then
 TIME-STEP[1] = TIME-STEP-10K;
 TIME-STEP[2] = TIME-STEP-25K;
 TIME-STEP[3] = TIME-STEP-50K;
endif
```

Time Specific End State (Partition) Rules:

```
if SYSTEM(CONFIG-SCEN1) * SYSTEM(MS-IC-9) * SYSTEM(TIME-STEP-10K) then
 partition ="IP-1A-10k";
elsif SYSTEM(CONFIG-SCEN1) * SYSTEM(MS-IC-9)  * SYSTEM(TIME-STEP-25K) then
 partition ="IP-1A-25k";
elsif SYSTEM(CONFIG-SCEN1) * SYSTEM(MS-IC-9)  * SYSTEM(TIME-STEP-50K) then
 partition ="IP-1A-50k";
endif

if SYSTEM(CONFIG-SCEN1) * SYSTEM(MS-IC-11) * SYSTEM(TIME-STEP-10K) then
 partition ="IP-1B-10k";
elsif SYSTEM(CONFIG-SCEN1) * SYSTEM(MS-IC-11)  * SYSTEM(TIME-STEP-25K) then
 partition ="IP-1B-25k";
elsif SYSTEM(CONFIG-SCEN1) * SYSTEM(MS-IC-11)  * SYSTEM(TIME-STEP-50K) then
 partition ="IP-1B-50k";
endif

if SYSTEM(CONFIG-SCEN2) * SYSTEM(TIME-STEP-10K) then
 partition ="IP-2A-10k";
elsif SYSTEM(CONFIG-SCEN2) * SYSTEM(TIME-STEP-25K) then
 partition ="IP-2A-25k";
elsif SYSTEM(CONFIG-SCEN2) * SYSTEM(TIME-STEP-50K) then
 partition ="IP-2A-50k";
endif
```

```
if SYSTEM(CONFIG-SCEN3) * SYSTEM(IP3-CON-CLASS1) * SYSTEM(TIME-STEP-10K)
then
 partition ="IP-3A-10k";
elsif SYSTEM(CONFIG-SCEN3) * SYSTEM(IP3-CON-CLASS1) * SYSTEM(TIME-STEP-
25K) then
 partition ="IP-3A-25k";
elsif SYSTEM(CONFIG-SCEN3) * SYSTEM(IP3-CON-CLASS1) * SYSTEM(TIME-STEP-
50K) then
 partition ="IP-3A-50k";
endif

if SYSTEM(CONFIG-SCEN3) * SYSTEM(IP3-CON-CLASS2) * SYSTEM(TIME-STEP-10K)
then
 partition ="IP-3B-10k";
elsif SYSTEM(CONFIG-SCEN3) * SYSTEM(IP3-CON-CLASS2) * SYSTEM(TIME-STEP-
25K) then
 partition ="IP-3B-25k";
elsif SYSTEM(CONFIG-SCEN3) * SYSTEM(IP3-CON-CLASS2) * SYSTEM(TIME-STEP-
50K) then
 partition ="IP-3B-50k";
endif

if SYSTEM(CONFIG-SCEN3) * SYSTEM(IP3-CON-CLASS3) * SYSTEM(TIME-STEP-10K)
then
 partition ="IP-3C-10k";
elsif SYSTEM(CONFIG-SCEN3) * SYSTEM(IP3-CON-CLASS3) * SYSTEM(TIME-STEP-
25K) then
 partition ="IP-3C-25k";
elsif SYSTEM(CONFIG-SCEN3) * SYSTEM(IP3-CON-CLASS3) * SYSTEM(TIME-STEP-
50K) then
 partition ="IP-3C-50k";
endif

if SYSTEM(CONFIG-SCEN3) * SYSTEM(IP3-CON-CLASS4)* SYSTEM(TIME-STEP-10K)
then
 partition ="IP-3D-10k";
elsif SYSTEM(CONFIG-SCEN3) * SYSTEM(IP3-CON-CLASS4) * SYSTEM(TIME-STEP-
25K) then
 partition ="IP-3D-25k";
elsif SYSTEM(CONFIG-SCEN3) * SYSTEM(IP3-CON-CLASS4) * SYSTEM(TIME-STEP-
50K) then
 partition ="IP-3D-50k";
endif
```

if SYSTEM(CONFIG-SCEN4) * SYSTEM(IP4-CON-CLASS1) * SYSTEM(TIME-STEP-10K) then
 partition ="IP-4A-10k";
elsif SYSTEM(CONFIG-SCEN4) * SYSTEM(IP4-CON-CLASS1) * SYSTEM(TIME-STEP-25K) then
 partition ="IP-4A-25k";
elsif SYSTEM(CONFIG-SCEN4) * SYSTEM(IP4-CON-CLASS1) * SYSTEM(TIME-STEP-50K) then
 partition ="IP-4A-50k";
endif

if SYSTEM(CONFIG-SCEN4) * SYSTEM(IP4-CON-CLASS2) * SYSTEM(TIME-STEP-10K) then
 partition ="IP-4B-10k";
elsif SYSTEM(CONFIG-SCEN4) * SYSTEM(IP4-CON-CLASS2) * SYSTEM(TIME-STEP-25K) then
 partition ="IP-4B-25k";
elsif SYSTEM(CONFIG-SCEN4) * SYSTEM(IP4-CON-CLASS2) * SYSTEM(TIME-STEP-50K) then
 partition ="IP-4B-50k";
endif

if SYSTEM(CONFIG-SCEN5) * SYSTEM(TIME-STEP-10K) then
 partition ="IP-5A-10k";
elsif SYSTEM(CONFIG-SCEN5) * SYSTEM(TIME-STEP-25K) then
 partition ="IP-5A-25k";
elsif SYSTEM(CONFIG-SCEN5) * SYSTEM(TIME-STEP-50K) then
 partition ="IP-5A-50k";
endif

if SYSTEM(CONFIG-SCEN6) * SYSTEM(TIME-STEP-10K) then
 partition ="IP-6A-10k";
elsif SYSTEM(CONFIG-SCEN6) * SYSTEM(TIME-STEP-25K) then
 partition ="IP-6A-25k";
elsif SYSTEM(CONFIG-SCEN6) * SYSTEM(TIME-STEP-50K) then
 partition ="IP-6A-50k";
endif

Mutually Exclusive Combination Removal Rules:

if BE-WP-EARLY-F * BE-MS-IC-4 then
 DeleteEvent = BE-MS-IC-4;
Endif

if (BE-BATHTUB-10K + BE-BATHTUB-25K) * BE-MS-IC-4 then
 DeleteEvent = BE-MS-IC-4;

```
Endif

GENCORB=BE-BATHTUB-50K-GC;
GENCOR18= BE-MS-IC-18-50K-GC;
GENCOR19= BE-MS-IC-19-50K-GC;
GENCORSEEP= BE-SEEPAGE-50K-GC;
EFB= BE-BATHTUB-50K-EF;
EF18= BE-MS-IC-18-50K-EF;
EF19= BE-MS-IC-19-50K-EF;
EFSEEP= BE-SEEPAGE-50K-EF;

if BE-WP-EARLY-F * (GENCORB + GENCOR18 + GENCOR19 + GENCORSEEP) then
 DeleteRoot;
endif

GENCORWP = (BE-WP-GENCOR-10K + BE-WP-GENCOR-25K + BE-WP-GENCOR-50K);

if GENCORWP * (EFB + EF18 + EF19 + EFSEEP) then
 DeleteRoot;
endif
```

INTENTIONALLY LEFT BLANK

ATTACHMENT IV
SEEPAGE FLUX ABSTRACTION

ATTACHMENT IV

SEEPAGE FLUX ABSTRACTION

Modern Climate parameters from *Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000b, p. 3-29)

min = 0.4 m^3/yr
peak = 4.7 m^3/yr
max = 12 m^3/yr

Monsoon Climate parameters from *Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000b, p. 3-29)

min = 4.7 m^3/yr
peak = 13 m^3/yr
max = 20 m^3/yr

Glacial Transition Climate parameters from *Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000b, p. 3-29)

min = 2.2 m^3/yr
peak = 20 m^3/yr
max = 37 m^3/yr
median focus factors
min = 6.88
peak = 4.73
max = 3.11

Percolation flux based on focus factor times infiltration rate

Modern	Monsoon	Glacial Transition
min1 := 2.75 m^3/yr	min2 := 32.34 m^3/yr	min3 := 15.14 m^3/yr
peak1 := 22.2 m^3/yr	peak2 := 61.5 m^3/yr	peak3 := 94.6 m^3/yr
max1 := 37.32 m^3/yr	max2 := 62.2 m^3/yr	max3 := 115.1 m^3/yr

The following defines the probability distribution functions and cumulative distribution functions for the triangular distributions for the climates

Modern Climate

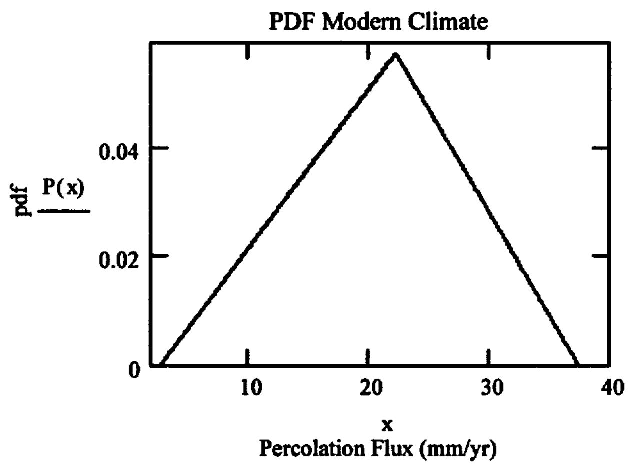
$$P1(x) := \frac{[2\cdot(x - min1)]}{(max1 - min1)\cdot(peak1 - min1)}$$

$$\mu := \frac{1}{3}\cdot(min1 + peak1 + max1)$$

$\mu = 20.757$ percolation flux mm/yr

$$P2(x) := \frac{[2\cdot(max1 - x)]}{(max1 - min1)\cdot(max1 - peak1)}$$

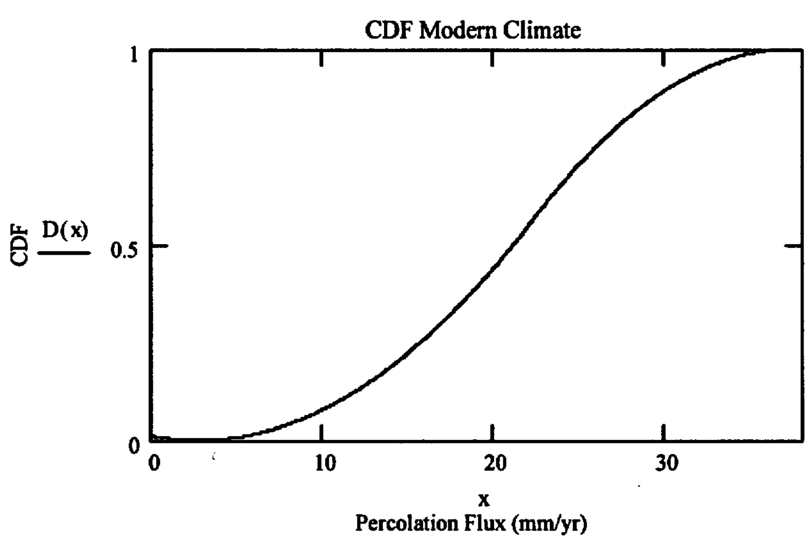
$$P(x) := if(x < peak1, P1(x), P2(x))$$



$$D1(x) := \frac{(x - min1)^2}{(max1 - min1)\cdot(peak1 - min1)}$$

$$D2(x) := 1 - \frac{(max1 - x)^2}{(max1 - min1)\cdot(max1 - peak1)}$$

$$D(x) := if(x < peak1, D1(x), D2(x))$$



Monsoon Climate

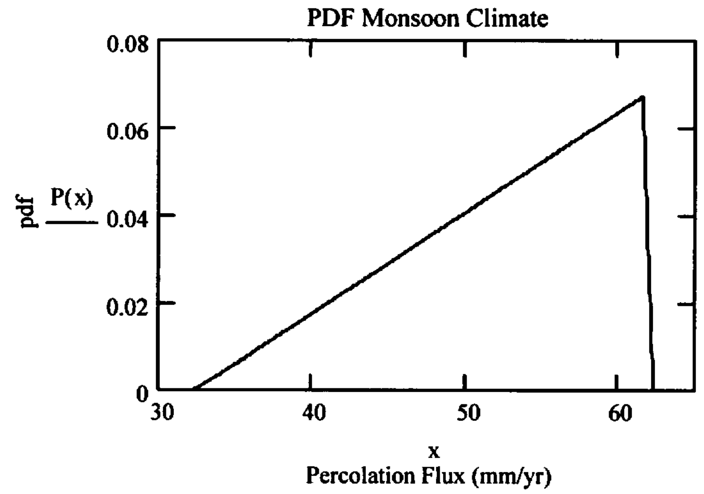
$$P1(x) := \frac{[2\cdot(x - min2)]}{(max2 - min2)\cdot(peak2 - min2)}$$

$$P2(x) := \frac{[2\cdot(max2 - x)]}{(max2 - min2)\cdot(max2 - peak2)}$$

$$\mu := \frac{1}{3}\cdot(min2 + peak2 + max2)$$

$\mu = 52.013$ percolation flux mm/yr

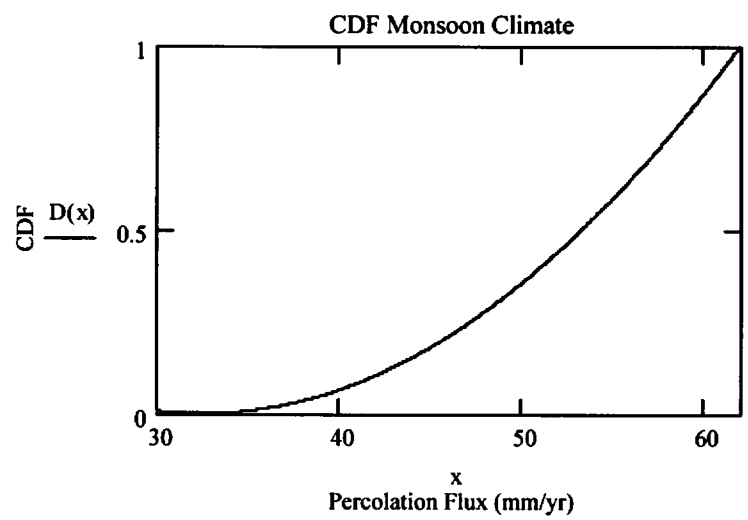
$P(x) := if(x < peak2, P1(x), P2(x))$



$$D1(x) := \frac{(x - min2)^2}{(max2 - min2)\cdot(peak2 - min2)}$$

$$D2(x) := 1 - \frac{(max2 - x)^2}{(max2 - min2)\cdot(max2 - peak2)}$$

$D(x) := if(x < peak2, D1(x), D2(x))$



Glacial Transition Climate

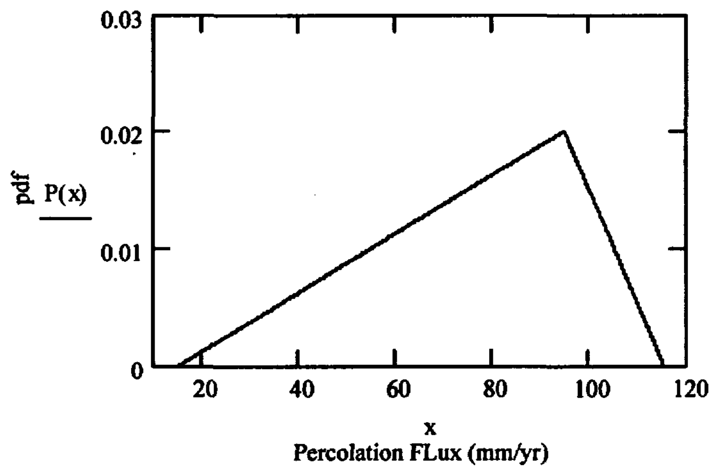
$$P1(x) := \frac{[2\cdot(x - min3)]}{(max3 - min3)\cdot(peak3 - min3)}$$

$$P2(x) := \frac{[2\cdot(max3 - x)]}{(max3 - min3)\cdot(max3 - peak3)}$$

$$\mu := \frac{1}{3}\cdot(min3 + peak3 + max3)$$

$\mu = 74.947$ percolation flux mm/yr

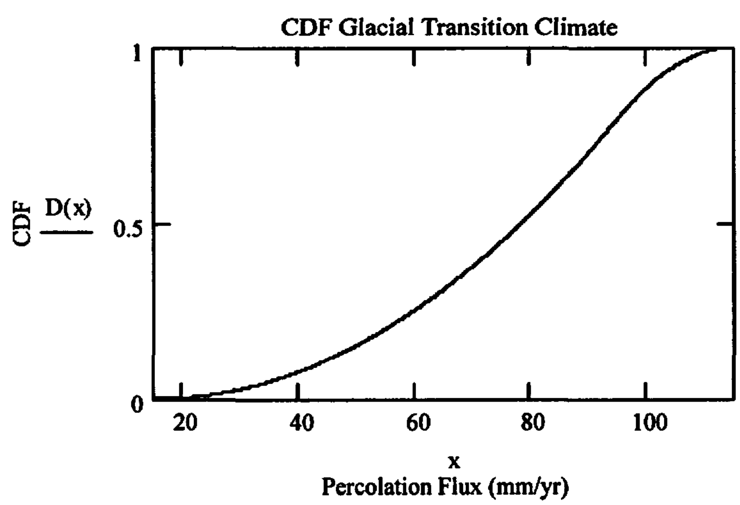
$P(x) := if(x < peak3, P1(x), P2(x))$



$$D1(x) := \frac{(x - min3)^2}{(max3 - min3)\cdot(peak3 - min3)}$$

$$D2(x) := 1 - \frac{(max3 - x)^2}{(max3 - min3)\cdot(max3 - peak3)}$$

$D(x) := if(x < peak3, D1(x), D2(x))$



Using mean percolation flux from Glacial Transition, obtain seepage fraction and seepage flux from Table 16, page 38 of *Abstraction of Drift Seepage* (CRWMS M&O 2001a).

$q := 74.95$ m^3/yr

Seepage Fraction

Seepage fraction requires the FF to be divided back into the seepage fraction for mass balance.

$min := 0.0066 \quad minsf := \frac{min}{6.88}$

$peak := 0.054 \quad peaksf := \frac{peak}{4.73}$

$max := 0.379 \quad maxsf := \frac{max}{3.11}$

$seepfracmean := \frac{1}{3} \cdot (minsf + peaksf + maxsf)$

$seepfracmean = 0.045$

$seepfracstd := \left[\frac{1}{18} \cdot \left(minsf^2 + peaksf^2 + maxsf^2 - minsf \cdot maxsf - minsf \cdot peaksf - peaksf \cdot maxsf\right)\right]^{0.5}$

$seepfracstd = 0.027$

Seepage Rate (m^3/yr)

$minmeansf := 0.493$

$peakmeansf := 0.502$

$maxmeansf := 0.91$

$meanseepflux := \frac{1}{3} \cdot (minmeansf + peakmeansf + maxmeansf)$

$meanseepflux = 0.635$ mean seepage rate (m^3/yr)

$meanseepfluxstd1 := \left(minmeansf^2 + peakmeansf^2 + maxmeansf^2\right)$

$meanseepfluxstd2 := (minmeansf \cdot maxmeansf + minmeansf \cdot peakmeansf + peakmeansf \cdot maxmeansf)$

$meanseepfluxstd := \left[\frac{1}{18} \cdot (meanseepfluxstd1 - meanseepfluxstd2)\right]^{0.5}$

$meanseepfluxstd = 0.097$ standard deviation of mean seepage rate

Standard Deviation of the Seepage Rate (m^3/yr)

$minstdsf := 0.0845$
$peakstdsf := 0.0845$
$maxstdsf := 1.067$

$$stdseepflux := \frac{1}{3}\cdot(minstdsf + peakstdsf + maxstdsf)$$

$stdseepflux = 0.412$ Standard Deviation of the seepage rate (m^3/yr)

$$stdseepfluxstd1 := \left(minstdsf^2 + peakstdsf^2 + maxstdsf^2\right)$$

$$stdseepfluxstd2 := (minstdsf\cdot maxstdsf + minstdsf\cdot peakstdsf + peakstdsf\cdot maxstdsf)$$

$$stdseepfluxstd := \left[\frac{1}{18}\cdot(stdseepfluxstd1 - stdseepfluxstd2)\right]^{0.5}$$

$stdseepfluxstd = 0.232$ Standard Deviation of the standard deviation seepage rate

Seepage rate will use a beta distribution with a mean of 0.635 and standard deviation of 0.412 with a maximum value of 4.12 m^3/yr. The maximum is based on 10 times standard deviation.

The beta-gt abstraction contains information about the seepage flux distribution used in the probability analysis. The beta-gt abstraction is discussed in the following sub-section. The Mathcad® file for the beta-gt abstraction, "beta-gt.mcd" is described in Attachment XI and included in Attachment XII.

Glacial Transition Beta Distribution

Using the mean and standard deviation obtained from the glacial transition climate information, the alpha and beta values are calculated. The calculated alpha and beta values will be used in the beta distribution for the probabilistic analysis.

$\mu := 0.635$ mean seepage flux (m^3/yr)
$\sigma := 0.412$ standard deviation seepage flux (m^3/yr)
$a := 0$ lower bound of beta distribution
$b := 4.12$ upper bound of beta distribution

$$c := \frac{(\mu - a)}{(b - a)}$$ Dummy variables used to obtain alpha and beta.

The variables are based on: (The variables are shown in Ang and Tang [1975, p. 131]).

$$d := \frac{c}{(1 - c)}$$

$$\mu x := a + \frac{\alpha}{\alpha + \beta}\cdot(b - a)$$ where μx and σx are the mean and standard deviation, respectively.

$$e := 1 + d$$

$$\sigma x := \frac{\alpha \cdot \beta}{(\alpha + \beta)^2 \cdot (\alpha + \beta + 1)} \cdot (b - a)^2$$

$$f := \frac{\sigma^2}{(b - a)^2}$$

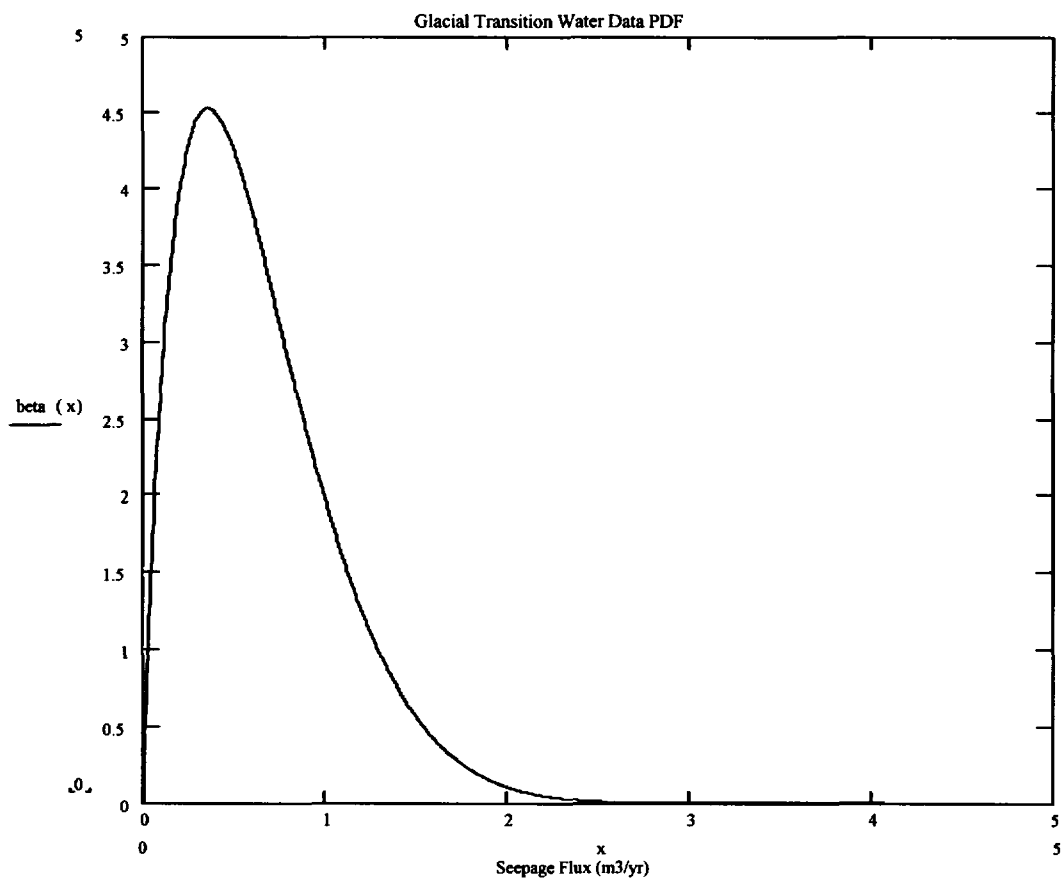
$$\beta := \frac{\left(d - f \cdot e^2\right)}{\left(f \cdot d \cdot e^2 + f \cdot e^2\right)}$$

$$\alpha := d \cdot \beta$$

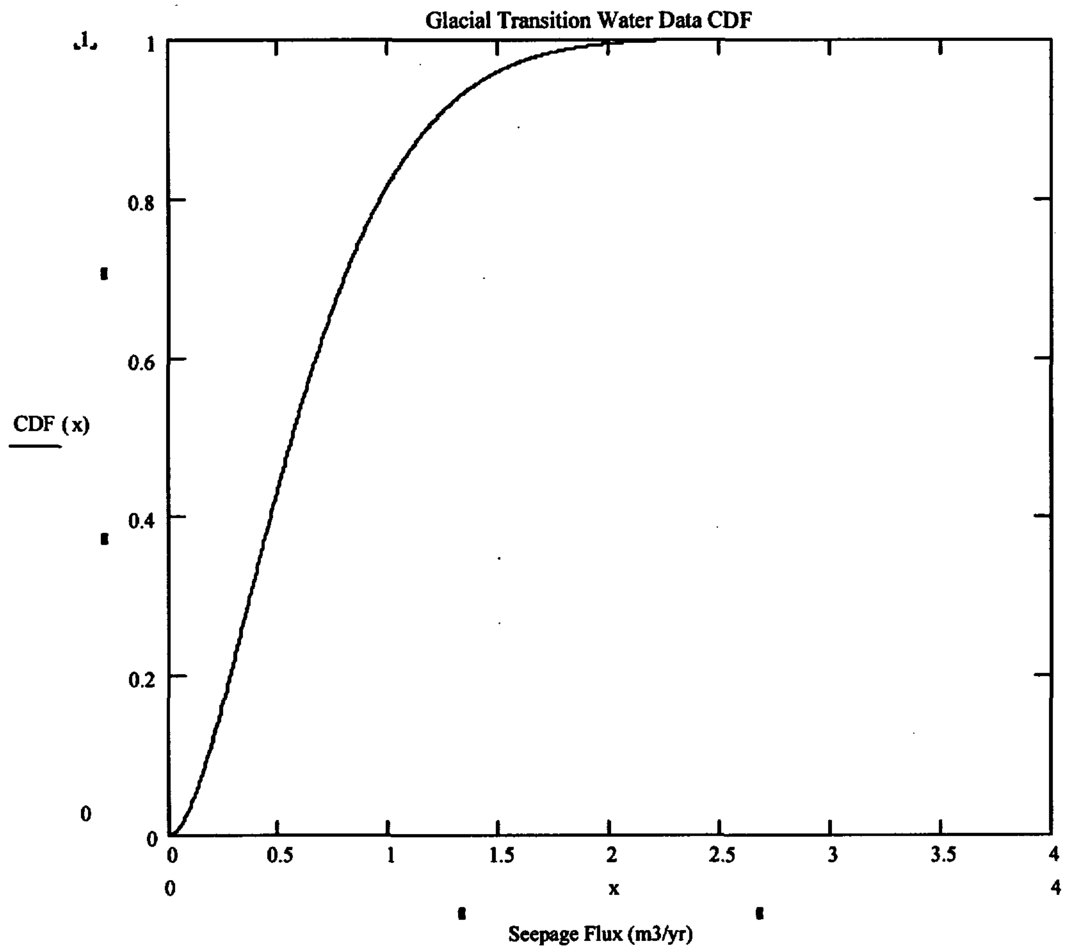
$\alpha = 1.855$ $\beta = 10.182$

Alpha and beta parameters used for probabilistic analysis. The parameters have been adjusted to bound the distribution between 0 and 4.12 m^3/yr.

$$\text{beta}(x) := \text{dbeta}\left(\frac{x}{4.12}, \alpha, \beta\right)$$



$$CDF(x) := pbeta\left(\frac{x}{4.12}, \alpha, \beta\right)$$



Probability equation used to calculate the probability that the seepage flux can be at or greater than the seepage noted on the bottom of the integral.

$$P(x) := \int_{2}^{\infty} dbeta\left(\frac{x}{4.12}, \alpha, \beta\right) dx$$

$Q := \frac{P(1)}{4.12}$ Q is used to re-normalize the beta distribution between 0 and 4.12 since beta distributions are bound between 0 and 1.

P(seepage flux > 2 m^3/yr) = Q

$Q = 5.557 \times 10^{-3}$

INTENTIONALLY LEFT BLANK

ATTACHMENT V
WASTE PACKAGE BATHTUB DURATION

ATTACHMENT V

WASTE PACKAGE BATHTUB DURATION

The bathtub duration is based on Case (2001) which took 100 realizations where each realization contained 400 waste package/drip shield failure times. The data set generated information that consists of positive waste package duration times. The positive waste package duration times are used to determine how long a waste package can be in a bathtub configuration. The data also set the negative times (i.e., times when the bottom of the waste package breached prior to the top) to zero. All of the positive times were collated and sorted from the smallest to the largest and then fit to a two-parameter Weibull distribution. The Weibull parameters obtained from the fit were alpha of 16,861.5 and beta of 1.1143 (Modarres 1993, p. 109). The probability of being in a bathtub duration time was also calculated using the data set. To obtain the probability that a waste package will be in a bathtub duration time, the total number of positive times was divided by all possible times. Based on all of the data times the probability is 0.486 (19,458/40,000). All of the data and information used to obtain the Weibull parameters and probability of being in a bathtub configuration is listed in the Excel spreadsheet "freqhist_bathtub.xls" (Attachment XII).

ATTACHMENT VI
STEEL CORROSION RATE ABSTRACTION

ATTACHMENT VI

STEEL CORROSION RATE ABSTRACTION

VI.1 CARBON STEEL 516 CORROSION RATE

The corrosion rate data of Carbon Steel Type 516 is obtained from DTN: MO0303SPAMCRAQ.000 and given as follows:

$t_1 := 29.53$	$t_{14} := 68.90$
$t_2 := 42.42$	$t_{15} := 70.45$
$t_3 := 43.65$	$t_{16} := 74.29$
$t_4 := 45.19$	$t_{17} := 76.96$
$t_5 := 45.91$	$t_{18} := 84.02$
$t_6 := 48.30$	$t_{19} := 87.65$
$t_7 := 50.17$	$t_{20} := 88.68$
$t_8 := 55.97$	$t_{21} := 89.41$
$t_9 := 58.08$	$t_{22} := 107.46$
$t_{10} := 63.58$	$t_{23} := 130.02$
$t_{11} := 65.04$	$t_{24} := 180.42$
$t_{12} := 65.73$	$t_{13} := 66.27$

$n := 24$

where t_i is the corrosion rate data in (μm/yr) and n = 24 data points. The data were fitted to three types of distributions, a lognormal, a normal, and a Weibull. The Mathcad® files for the Carbon Steel Type 516 corrosion rate probability calculations described in Attachment XI and included in Attachment XII are, "516cs_corr_info_lnorm.mcd", "516cs_corr_info_norm.mcd", and "516cs_corr_info_weib.mcd" , respectively.

VI.1.1 Carbon Steel 516 Corrosion Rates Fit to a Lognormal Distribution

$$\lambda := \frac{\left(\sum_{i=1}^{n} \ln(t_i)\right)}{n}$$

$\lambda = 4.204$ λ is the mean for a lognormal distribution

$$\varsigma 2 := \frac{\left[\sum_{i=1}^{n} \left(\ln(t_i) - \lambda\right)^2\right]}{n}$$

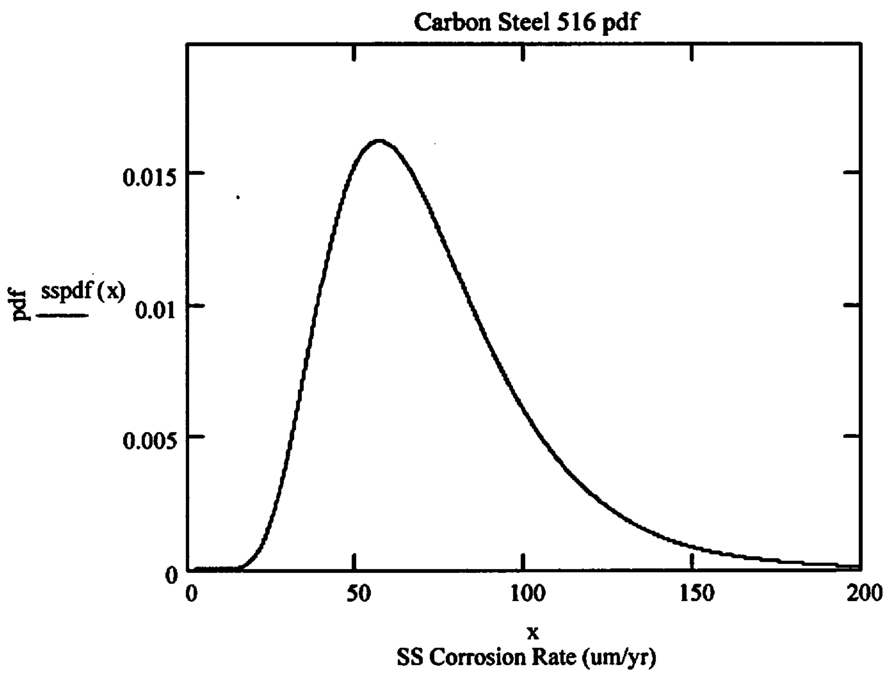
$\zeta 2 = 0.149$

$\zeta := \sqrt{\zeta 2}$

$\zeta = 0.386$ ζ is the standard deviation for the lognormal distribution

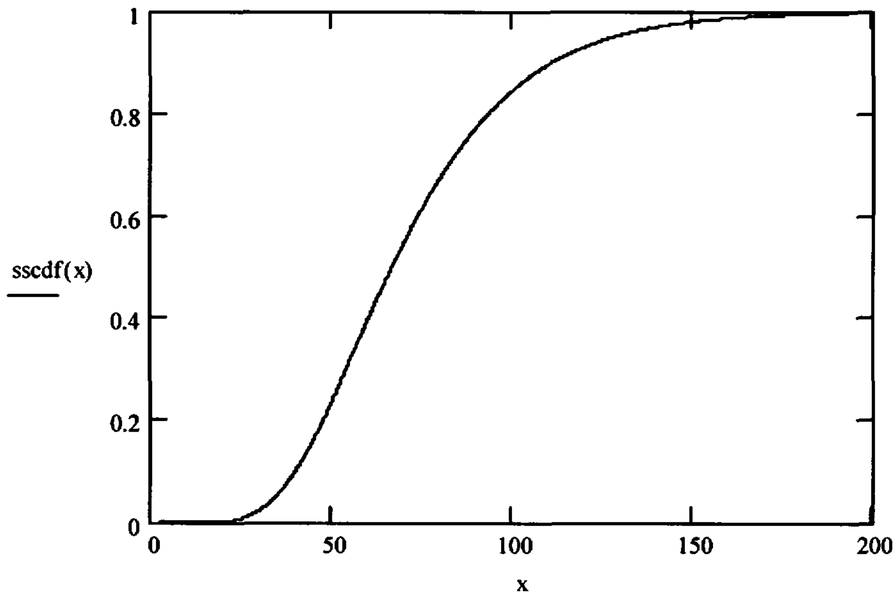
sspdf(x) is the probability distribution function of Carbon Steel Type 516 using a lognormal distribution.

sspdf (x) := dlnorm(x, λ, ζ)



sscdf(x) is the cumulative distribution function of the Carbon Steel Type 516 data fit to a lognormal distribution.

sscdf (x) := plnorm(x, λ, ζ)

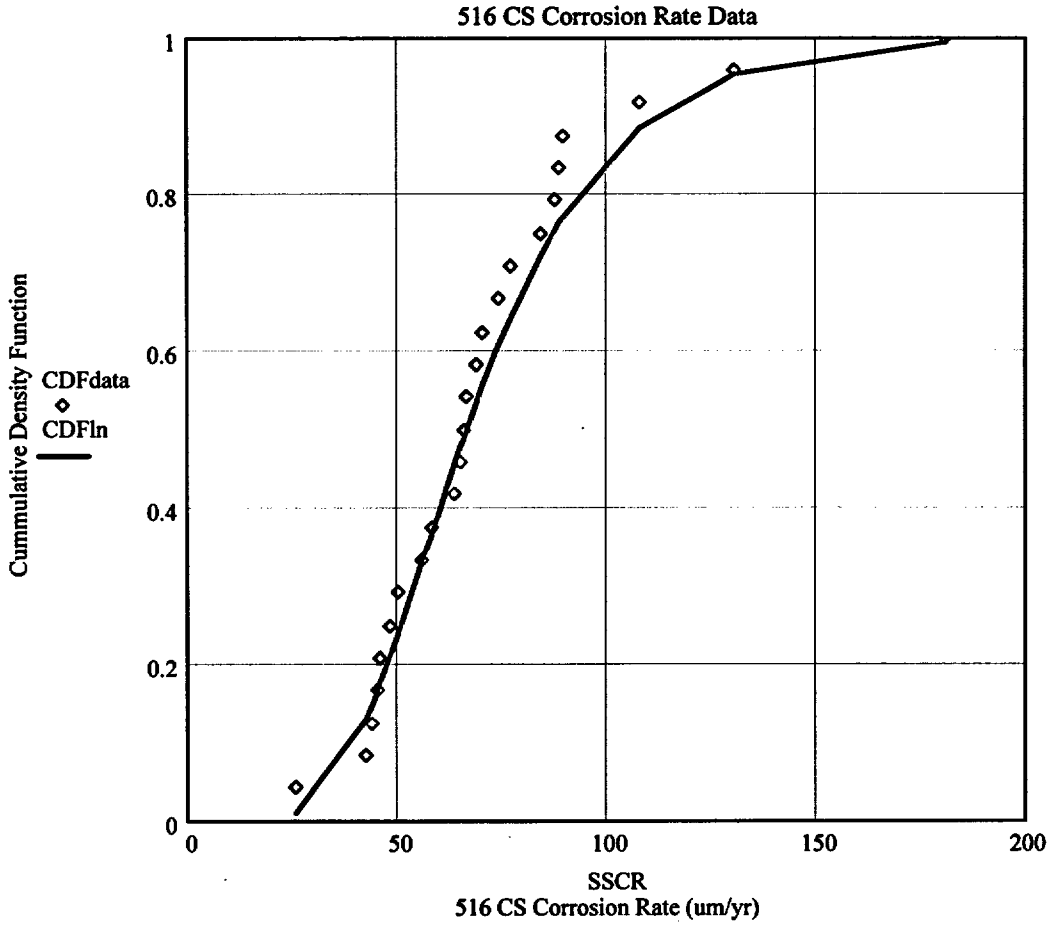


The probability of the corrosion rate can be obtained using the equation below at any range or point.

$$\text{sscdf1}(x) := \int_{50}^{\infty} \text{dlnorm}(x, \lambda, \zeta)\, dx$$

sscdf1 (0) = 0.775

The raw data was plotted together with the lognormal distribution.



The lognormal distribution was checked for its fit against the raw data. The Anderson-Darling Test was used to check for goodness-of-fit. The Anderson-Darling Test is used because it is designed for use with few data points and is more appropriate versus the Kolmogorov-Smirnov Test.

$w_i := \text{plnorm}(t_i, \lambda, \zeta)$ w is the standard lognormal cumulative distribution function of the fitted corrosion rate.

$A2 := -n - \left(\frac{1}{n}\right)\cdot\sum_{i=1}^{n}(2\cdot i - 1)\cdot\left(\ln\left(w_i\right) + \ln\left(1 - w_{n-i+1}\right)\right)$ A2 is the test equation for the Anderson-Darling test (D'Agostino and Stephens 1986, p. 101).

$A2 = 0.244$

$A2m := A2\cdot\left(1 + \frac{0.75}{n} + \frac{2.25}{n^2}\right)$ A2m is used to adjust the test limit due to a small amount of data (D'Agostino and Stephens 1986, Table 4-7, p. 123).

A2m = 0.253

The Anderson-Darling test for 5 percent rejection significance for a null test requires the test value to be less than critical limit based on a small amount of data points and a significant level of 0.05.

Anderson-Darling critical limit for 0.05 is 0.752 from *Goodness-Of-Fit Techniques* (D'Agostino and Stephens 1986, Table 4-7, p. 123).

A2m < Anderson-Darling critical limit; therefore, the lognormal distribution can be used to represent the data (D'Agostino and Stephens 1986, Table 4.7, p. 123).

VI.1.2 Carbon Steel 516 Corrosion Rate Fit to a Normal Distribution

$$\mu := \frac{\left(\sum_{i=1}^{n} t_i\right)}{n}$$

$\mu = 72.421$ μ is the sample mean obtained from the data that will be used in a normal distribution.

$$\sigma2 := \frac{1 \cdot \sum_{i=1}^{n} \left(t_i - \mu\right)^2}{n}$$

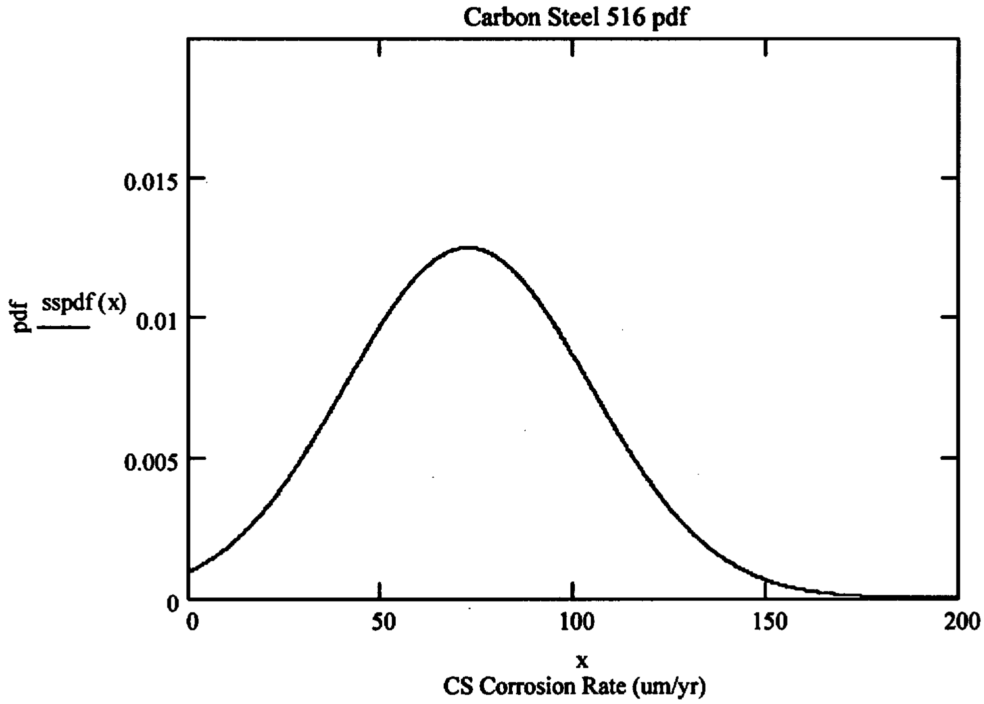
$\sigma2 = 997.887$

$\sigma := \sqrt{\sigma2}$

$\sigma = 31.589$ σ is the standard deviation for the normal distribution.

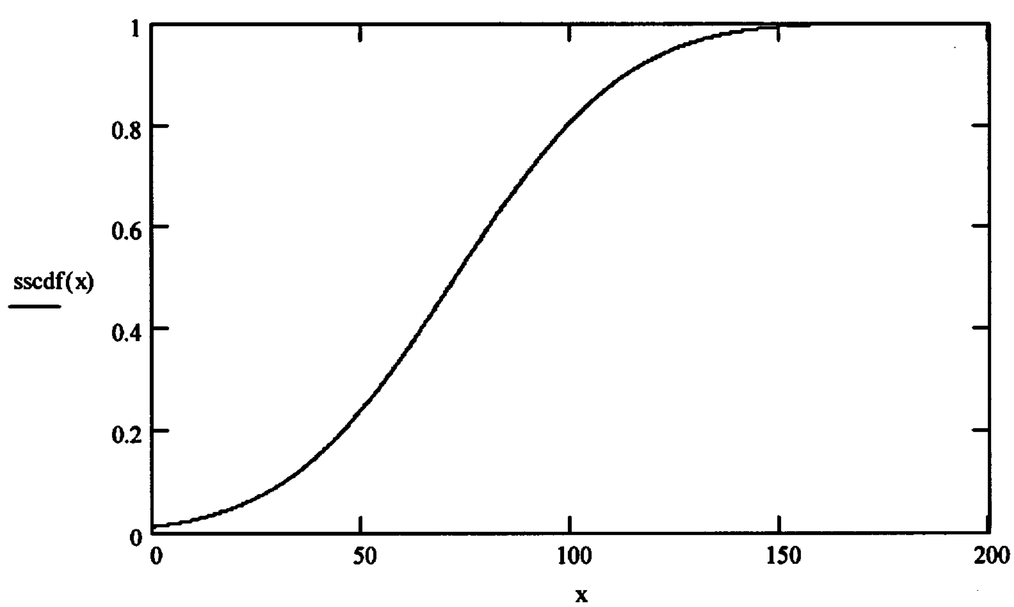
sspdf(x) is the probability distribution function for a normal distribution using the mean and standard deviation calculated from the data.

$\text{sspdf}(x) := \text{dnorm}(x, \mu, \sigma)$



sscdf(x) is the cumulative distribution function of the normal distribution using the mean and standard deviation calculated using the data.

$sscdf(x) := pnorm(x, \mu, \sigma)$

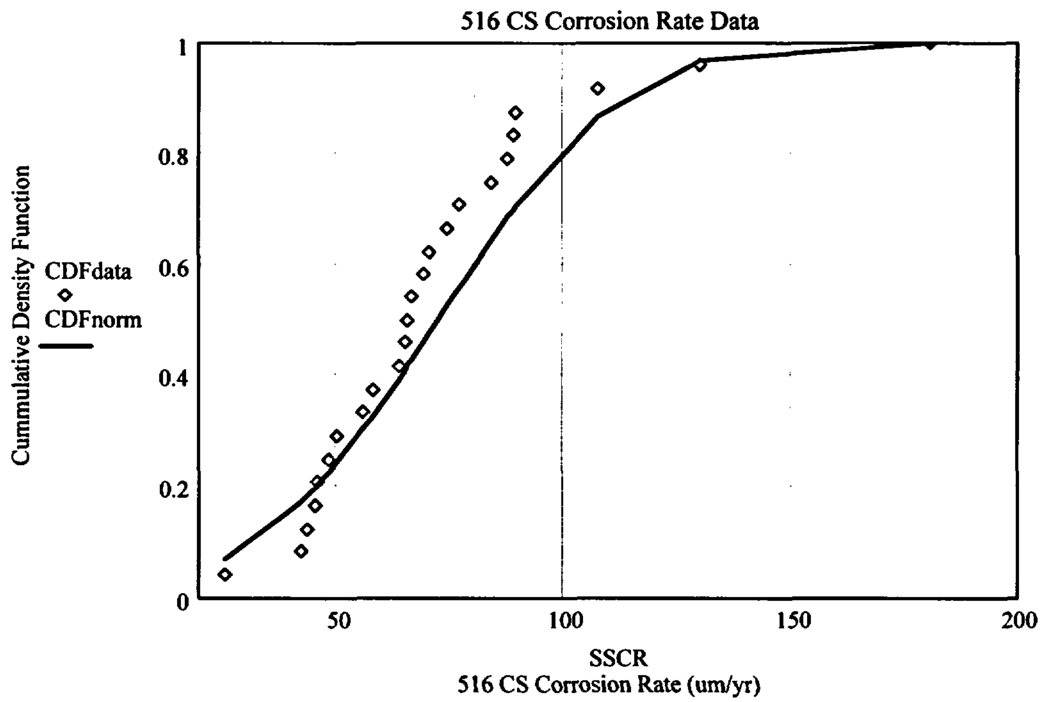


The probability of the corrosion rate can be obtained using the equation below at any range or point.

$$\text{sscdfl}(x) := \int_{50}^{\infty} \text{dnorm}(x, \mu, \sigma)\, dx$$

sscdfl (1) = 0.761

The data is plotted versus normal distribution using the calculated mean and standard deviation.



The normal distribution was checked for its fit against the raw data. The Anderson-Darling Test was used to check for goodness-of-fit. The Anderson-Darling Test is used because it is designed for use with few data points and is more appropriate versus the Kolmogorov-Smirnov Test.

$w_i := \text{pnorm}(t_i, \mu, \sigma)$ w is the standard normal cumulative distribution function of the fitted corrosion rate.

$$A2 := -n - \left(\frac{1}{n}\right) \cdot \sum_{i=1}^{n} (2 \cdot i - 1) \cdot \left(\ln(w_i) + \ln(1 - w_{n-i+1})\right)$$

A2 is the test equation for the Anderson-Darling test (D'Agostino and Stephens 1986, Table 4-7, p. 101).

$A2 = 1.021$

$$A2m := A2 \cdot \left(1 + \frac{0.75}{n} + \frac{2.25}{n^2}\right)$$

A2m is used to adjust the test limit due to the small amount of data points (D'Agostino and Stephens 1986, Table 4-7, p. 123).

$A2m = 1.057$

The Anderson-Darling test for five percent rejection significance for a null test requires the test value to be less than critical limit based on a small amount of data points and a significant level of 0.05.

Anderson-Darling critical limit for 0.05 is 0.752 (D'Agostino and Stephens 1986, Table 4-7, p. 123).

A2m > Anderson-Darling critical limit; therefore, the normal distribution should not be used to represent the data (D'Agostino and Stephens 1986, Table 4.7, p. 123)

VI.1.3 Carbon Steel 516 Corrosion Rate Fit to a Weibull Distribution

The following equations are from Modarres (1993, p. 109).

Solve for α and β:

The equations need to be solved by numerical interpolation. The value of β is determined when parameters y = z.

$$z := \left(\frac{1}{n}\right) \cdot \sum_{i=1}^{n} \ln(t_i)$$

$\beta := 2.38$ Select a value of β and solve for y, check to see if y = z, if not select a new value for β.

$$y := \frac{\left[\sum_{i=1}^{n} (t_i)^{\beta} \cdot \ln(t_i)\right]}{\sum_{i=1}^{n} (t_i)^{\beta}} - \left(\frac{1}{\beta}\right)$$

$y = 4.204$ $z = 4.204$

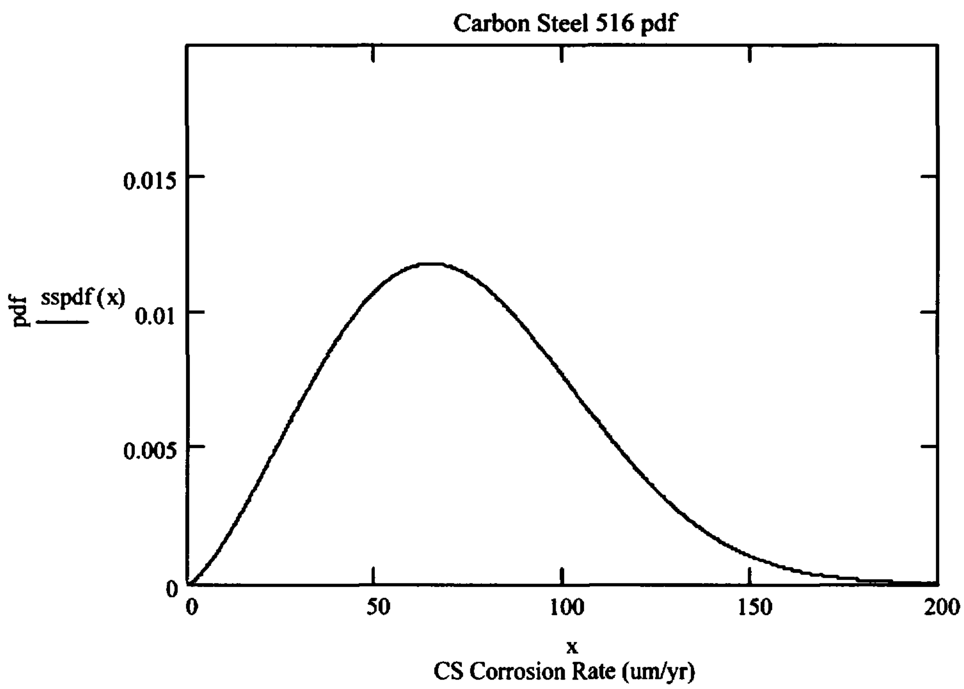
When y = z then calculate the corresponding value for α.

$$\alpha := \left[\frac{\sum_{i=1}^{n} (t_i)^{\beta}}{n}\right]^{\frac{1}{\beta}}$$

$\alpha = 81.812$

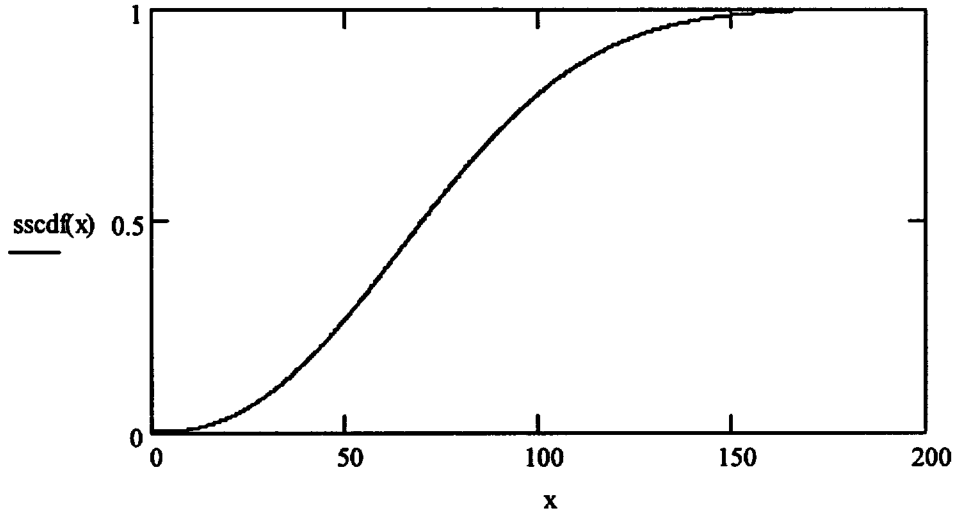
sspdf(x) is the probability distribution function of Carbon Steel Type 516 using a Weibull distribution.

$$sspdf(x) := \left[\frac{\beta \cdot x^{(\beta-1)}}{\alpha^{\beta}}\right] \cdot \exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right]$$



sscdf(x) is the cumulative distribution function of the Carbon Steel Type 516 data fit to a Weibull distribution.

$$sscdf(x) := 1 - \exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right]$$

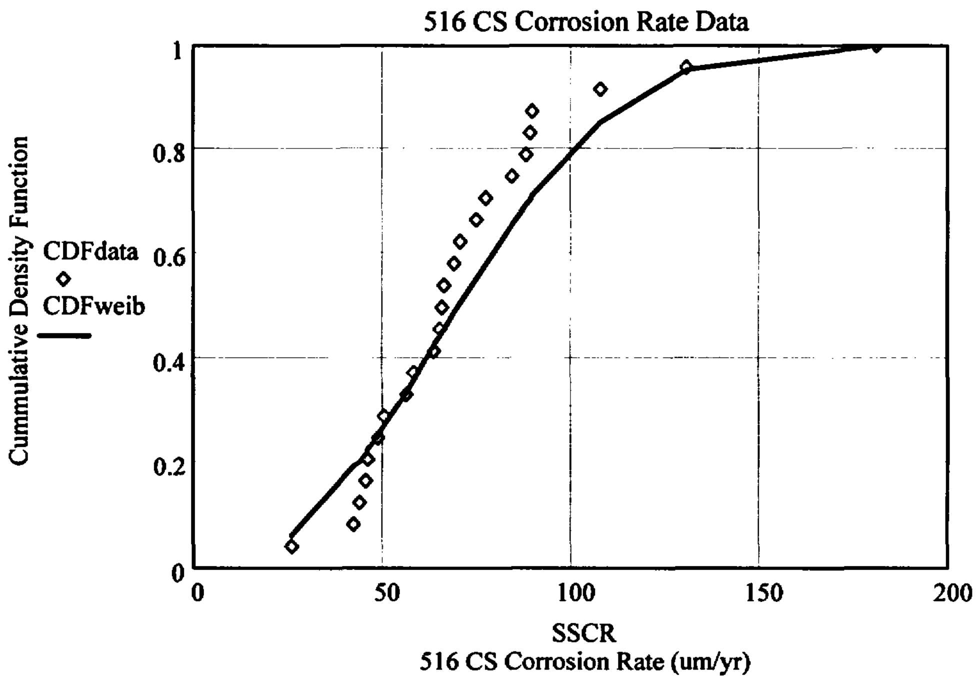


The probability of the corrosion rate can be obtained using the equation at any range or point.

$$cdf(x) := \exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right]$$

$cdf(50) = 0.734$

Plot of raw data versus Weibull distribution



The Weibull distribution was checked for its fit against the raw data. The Anderson-Darling Test was used to check for goodness-of-fit. The Anderson-Darling Test (D'Agostino and Stephens 1986, Table 4-7, p. 101) is used because it is designed for use with a small number of data points and is more appropriate vis-a-vis the Kolmogorov-Smirnov Test.

$w_i := 1 - \exp\left[-\left(\frac{t_i}{\alpha}\right)^{\beta}\right]$ w is the Weibull cumulative distribution function of the fitted corrosion rate.

$A2 := -n - \left(\frac{1}{n}\right)\cdot\sum_{i=1}^{n}(2\cdot i - 1)\cdot\left(\ln\left(w_i\right) + \ln\left(1 - w_{n-i+1}\right)\right)$ A2 is the test equation for the Anderson-Darling test (D'Agostino and Stephens 1986, Table 4-7, p. 101).

$A2 = 0.864$

$A2m := A2\cdot\left(1 + \frac{0.75}{n} + \frac{2.25}{n^2}\right)$ A2m is used to adjust the test limit due to a small amount of data (D'Agostino and Stephens 1986, Table 4-3, p. 123).

$A2m = 0.895$

The Anderson-Darling test for five percent rejection significance for a null test requires the test value to be less than critical limit based on a small amount of data points and a significant level of 0.05.

Anderson-Darling critical limit for 0.05 is 0.752 (D'Agostino and Stephens 1986, Table 4-7, p. 123).

A2m > Anderson-Darling critical limit; therefore, the Weibull distribution should not be used to represent the data (D'Agostino and Stephens 1986, Table 4.7, p. 123).

VI.2 STAINLESS STEEL 304 CORROSION RATE

The Stainless Steel Type 304 corrosion rate data is obtained from DTN: MO0303SPAMCRAQ.000 and given as follows:

$c := 1$

$t_1 := .02 \cdot c$	$t_{14} := .08 \cdot c$	$t_{27} := .14 \cdot c$	$t_{40} := .283 \cdot c$
$t_2 := .02 \cdot c$	$t_{15} := .0811 \cdot c$	$t_{28} := .1524 \cdot c$	$t_{41} := .285 \cdot c$
$t_3 := .0254 \cdot c$	$t_{16} := .085 \cdot c$	$t_{29} := .1524 \cdot c$	$t_{42} := .37 \cdot c$
$t_4 := .04 \cdot c$	$t_{17} := .09 \cdot c$	$t_{30} := .15 \cdot c$	$t_{43} := .57 \cdot c$
$t_5 := .04 \cdot c$	$t_{18} := .09 \cdot c$	$t_{31} := .151 \cdot c$	
$t_6 := .05 \cdot c$	$t_{19} := .1016 \cdot c$	$t_{32} := .2032 \cdot c$	
$t_7 := .05 \cdot c$	$t_{20} := .116 \cdot c$	$t_{33} := .2032 \cdot c$	
$t_8 := .05 \cdot c$	$t_{21} := .12 \cdot c$	$t_{34} := .2032 \cdot c$	
$t_9 := .06 \cdot c$	$t_{22} := .123 \cdot c$	$t_{35} := .2286 \cdot c$	
$t_{10} := .06 \cdot c$	$t_{23} := .127 \cdot c$	$t_{36} := .2286 \cdot c$	
$t_{11} := .07 \cdot c$	$t_{24} := .13 \cdot c$	$t_{37} := .242 \cdot c$	
$t_{12} := .07 \cdot c$	$t_{25} := .13 \cdot c$	$t_{38} := .249 \cdot c$	
$t_{13} := .072 \cdot c$	$t_{26} := .133 \cdot c$	$t_{39} := .25 \cdot c$	

$n := 43$

where t_i is the corrosion rate data in (μm/yr) and n = 43 data points. The data were fitted to three types of distributions, a lognormal, a normal, and a Weibull. The Mathcad® files for the Stainless Steel Type 304 304 corrosion rate probability calculations described in Attachment XI and included in Attachment XII are, respectively, "304cs_corr_info_lnorm.mcd", "304cs_corr_info_norm.mcd", and "304cs_corr_info_weib.mcd".

VI.2.1 Stainless Steel 304 Corrosion Rate Fit to a Lognormal Distribution

$$\lambda := \frac{\left(\sum_{i=1}^{n} \ln(t_i)\right)}{n}$$

λ is the mean for a lognormal distribution

$$\lambda = -2.213$$

$$\varsigma 2 := \frac{\left[\sum_{i=1}^{n} \left(\ln(t_i) - \lambda\right)^2\right]}{n}$$

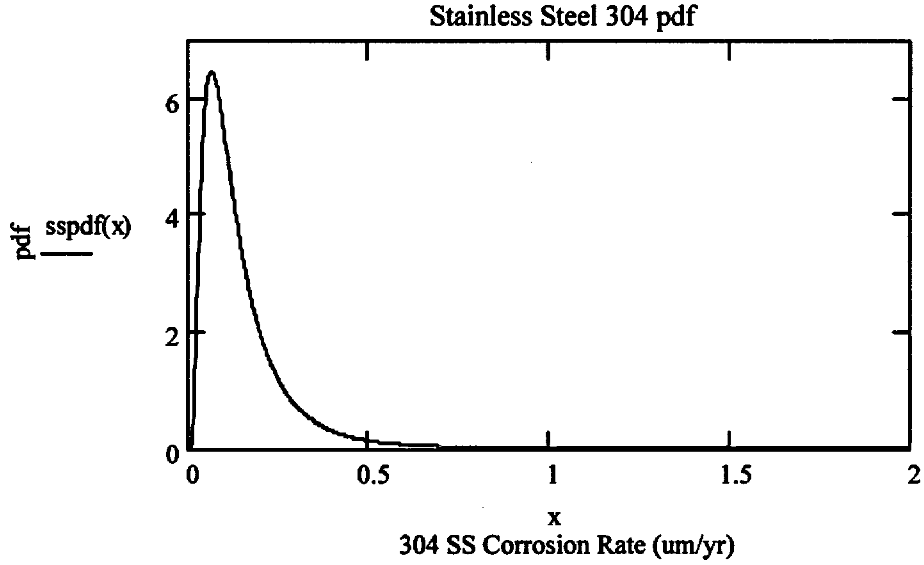
$$\varsigma 2 = 0.565$$

$$\zeta := \sqrt{\varsigma 2}$$

$$\zeta = 0.752$$

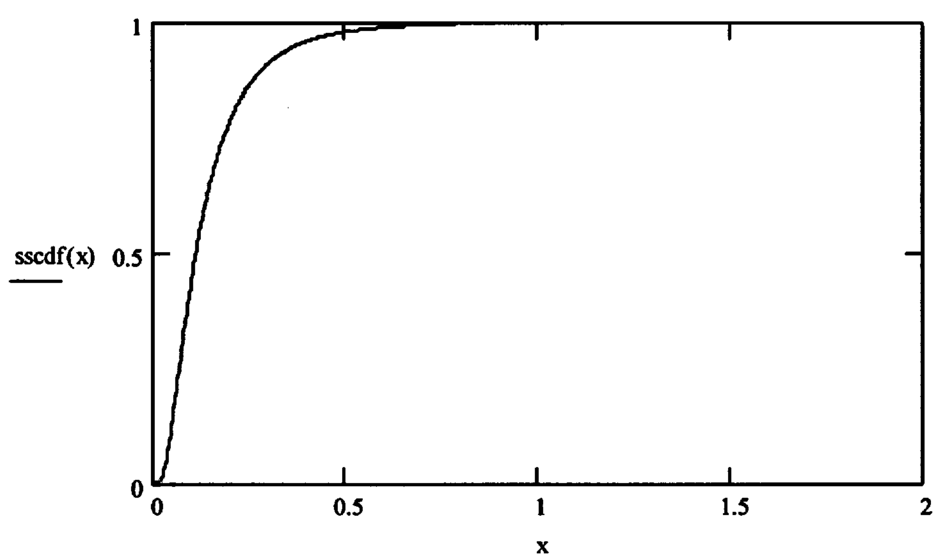
ζ is the standard deviation for the lognormal distribution sspdf(x) is the probability distribution function of Stainless Steel Type 304 using a lognormal distribution.

sspdf (x) := dlnorm(x, λ, ζ)



sscdf(x) is the cumulative distribution function of the Stainless Steel Type 304 data fit to a lognormal distribution.

sscdf (x) := plnorm(x, λ, ζ)

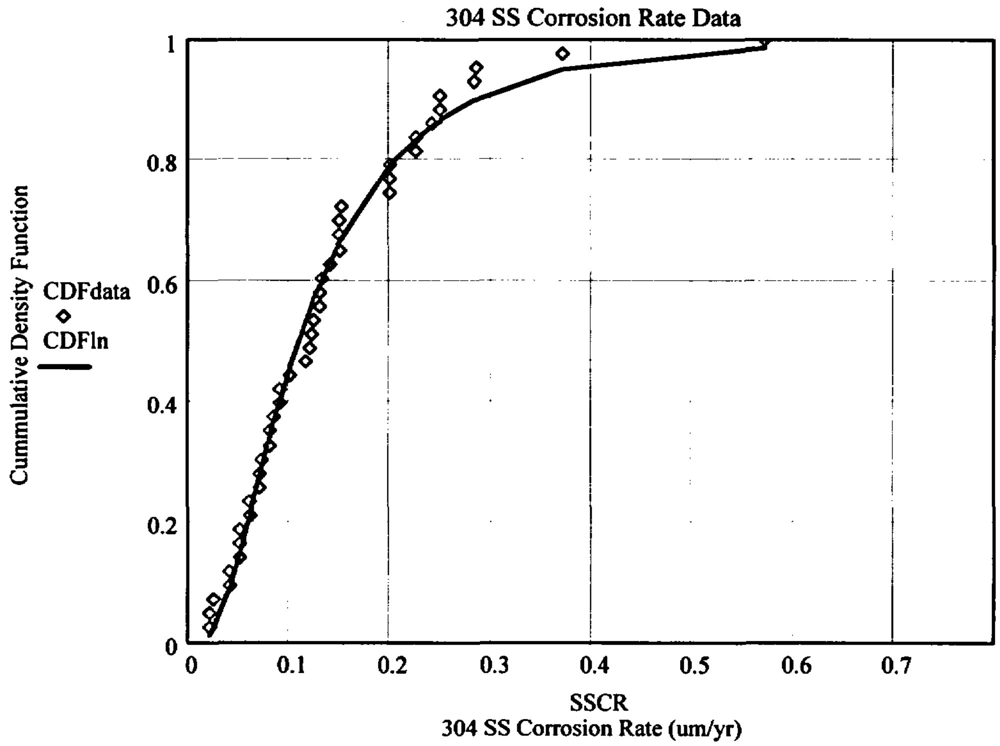


The probability of the corrosion rate can be obtained using the equation at any range or point.

$$sscdf1\,(x) := \int_{.1}^{\infty} dlnorm(x, \lambda, \zeta)\, dx$$

$sscdf1\,(0) = 0.548$

Plot raw data versus lognormal distribution



The lognormal distribution was checked for its fit against the raw data. The Anderson-Darling Test was used to check for goodness-of-fit. The Anderson-Darling Test is used because it is designed for use with few data points and is more appropriate versus the Kolmogorov-Smirnov Test.

$w_i := plnorm(t_i, \lambda, \zeta)$ w is the standard lognormal cumulative distribution function of the fitted corrosion rate.

$$A2 := -n - \left(\frac{1}{n}\right)\cdot\sum_{i=1}^{n} (2\cdot i - 1)\cdot\left(\ln(w_i) + \ln(1 - w_{n-i+1})\right)$$

A2 is the test equation for the Anderson-Darling test (D'Agostino and Stephens 1986, Table 4-7, p. 101).

$A2 = 0.299$

$$A2m := A2\cdot\left(1+\frac{0.75}{n}+\frac{2.25}{n^2}\right)$$ A2m is used to adjust the test limit due to a small amount of data (D'Agostino and Stephens 1986, Table 4-7, p. 123)

$A2m = 0.305$

The Anderson-Darling test for five percent rejection significance for a null test requires the test value to be less than critical limit based on a small amount of data points and a significant level of 0.05.

Anderson-Darling critical limit for 0.05 is 0.752 (D'Agostino and Stephens 1986, Table 4-7, p. 123).

A2m < Anderson-Darling critical limit; therefore, the lognormal distribution can be used to represent the data (D'Agostino and Stephens 1986, Table 4.7, p. 123).

VI.2.2 Stainless Steel 304 Corrosion Rate Fit to a Normal Distribution

$$\mu := \frac{\left(\sum_{i=1}^{n} t_i\right)}{n}$$

$\mu = 0.142$ μ is the sample mean obtained from the data that will be used in a normal distribution.

$$\sigma2 := \frac{1\cdot\sum_{i=1}^{n}\left(t_i-\mu\right)^2}{n}$$

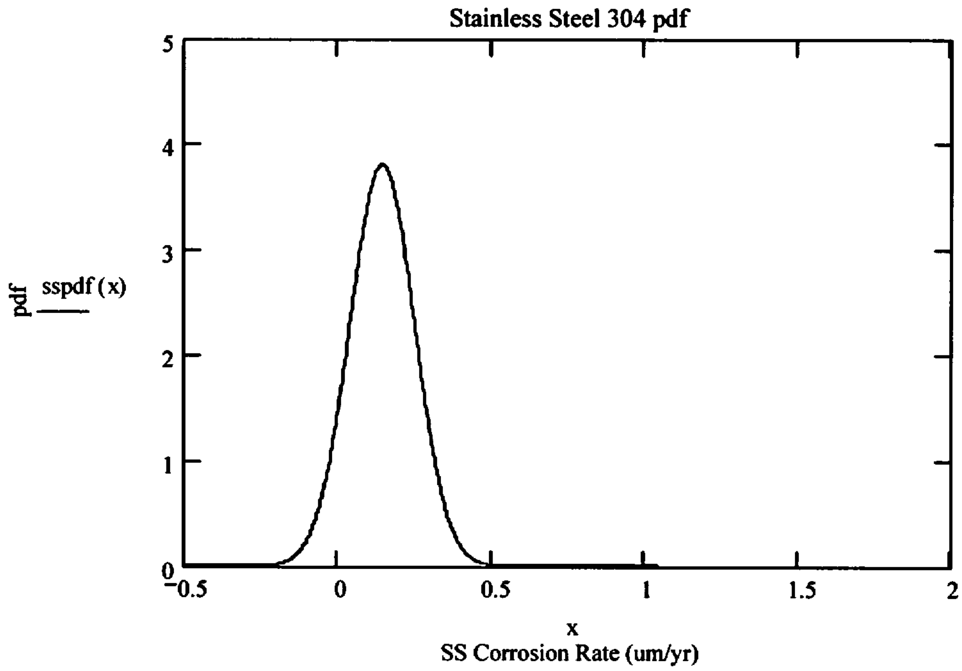
$\sigma2 = 0.011$

$\sigma := \sqrt{\sigma2}$ σ is the standard deviation for the normal distribution

$\sigma = 0.105$

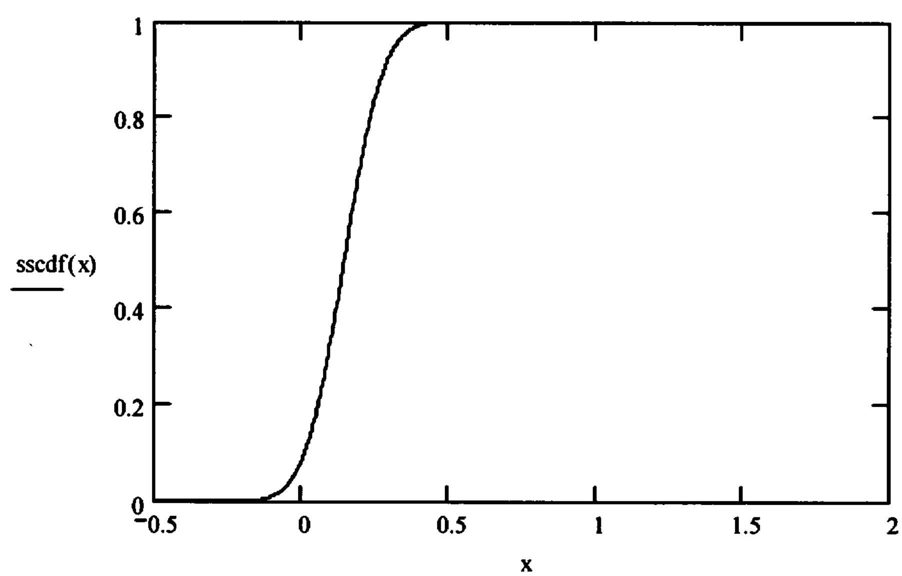
sspdf(x) is the probability distribution function for a normal distribution using the mean and standard deviation calculated from the data.

$sspdf(x) := dnorm(x, \mu, \sigma)$



sscdf(x) is the cumulative distribution function of the normal distribution using the mean and standard deviation calculated using the data.

$sscdf(x) := pnorm(x, \mu, \sigma)$

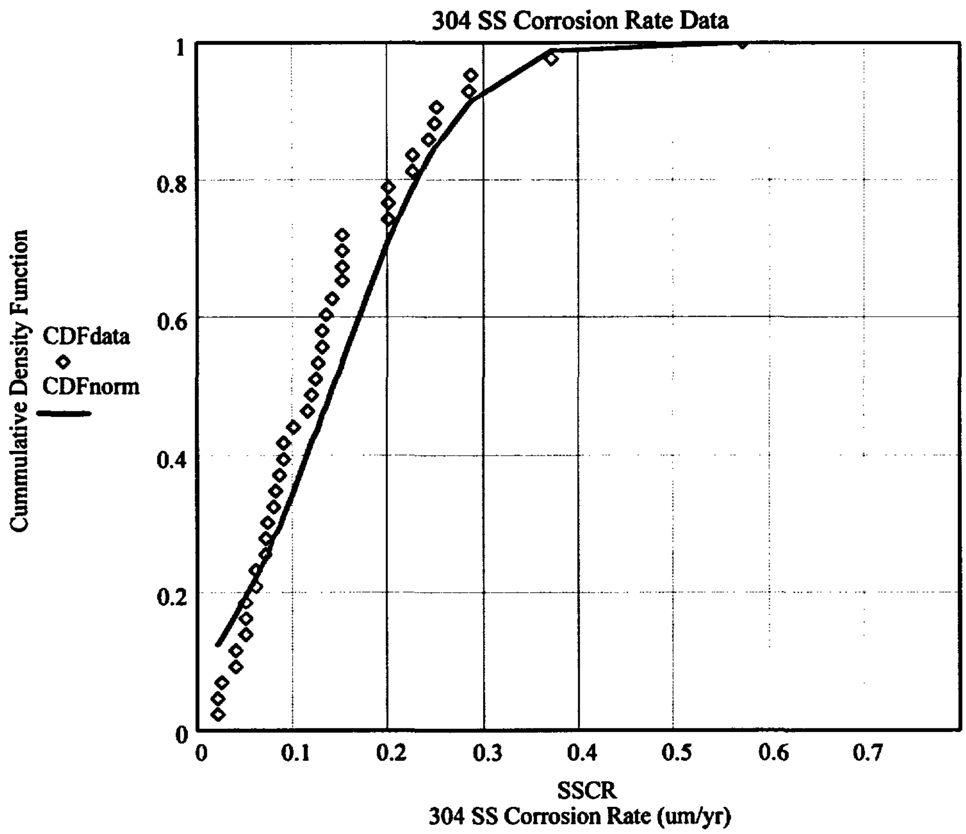


The probability of the corrosion rate can be obtained using the equation at any range or point

$$sscdf1(x) := \int_{0.1}^{\infty} dnorm(x, \mu, \sigma)\, dx$$

$sscdf1(0) = 0.655$

The data is plotted versus normal distribution using the calculated mean and standard deviation.



The normal distribution was checked for its fit against the raw data. The Anderson-Darling Test was used to check for goodness-of-fit. The Anderson-Darling Test is used because it is designed for use with few data points and is more appropriate versus the Kolmogorov-Smirnov Test.

$w_i := \mathrm{pnorm}(t_i, \mu, \sigma)$ w is the standard normal cumulative distribution function of the fitted corrosion rate.

$$A2 := -n - \left(\frac{1}{n}\right) \cdot \sum_{i=1}^{n} (2 \cdot i - 1) \cdot \left(\ln(w_i) + \ln(1 - w_{n-i+1})\right)$$ A2 is the test equation for the

Anderson-Darling test (D'Agostino and Stephens 1986, Table 4-7, p. 101).

$A2 = 1.461$

$A2m := A2\cdot\left(1+\frac{0.75}{n}+\frac{2.25}{n^2}\right)$ A2m is used to adjust the test limit due to the small amount of data (D'Agostino and Stephens 1986, Table 4-7, p. 123).

$A2m = 1.488$

The Anderson-Darling test for five percent rejection significance for a null test requires the test value to be less than critical limit based on a small amount of data points and a significant level of 0.05.

Anderson-Darling critical limit for 0.05 is 0.752 (D'Agostino and Stephens 1986, Table 4-7, p. 123).

A2m > Anderson-Darling critical limit; therefore, the normal distribution should not be used to represent the data (D'Agostino and Stephens 1986, Table 4-7, p. 123).

VI.2.3 Stainless Steel 304 Corrosion Rate Fit to a Weibull Distribution

The following equations are from Modarres (1993, p. 109).

Solve the following equations to obtain α and β:

The equations need to be solved by numerical interpolation. The value of β is determined when parameters y = z.

$$z := \left(\frac{1}{n}\right)\cdot\sum_{i=1}^{n} \ln(t_i)$$

$\beta := 1.460$ Select a value of β and solve for y, check to see if y = z, if not select a new value for β.

$$y := \frac{\left[\sum_{i=1}^{n} (t_i)^{\beta}\cdot\ln(t_i)\right]}{\sum_{i=1}^{n} (t_i)^{\beta}} - \left(\frac{1}{\beta}\right)$$

$y = -2.213$ $z = -2.213$

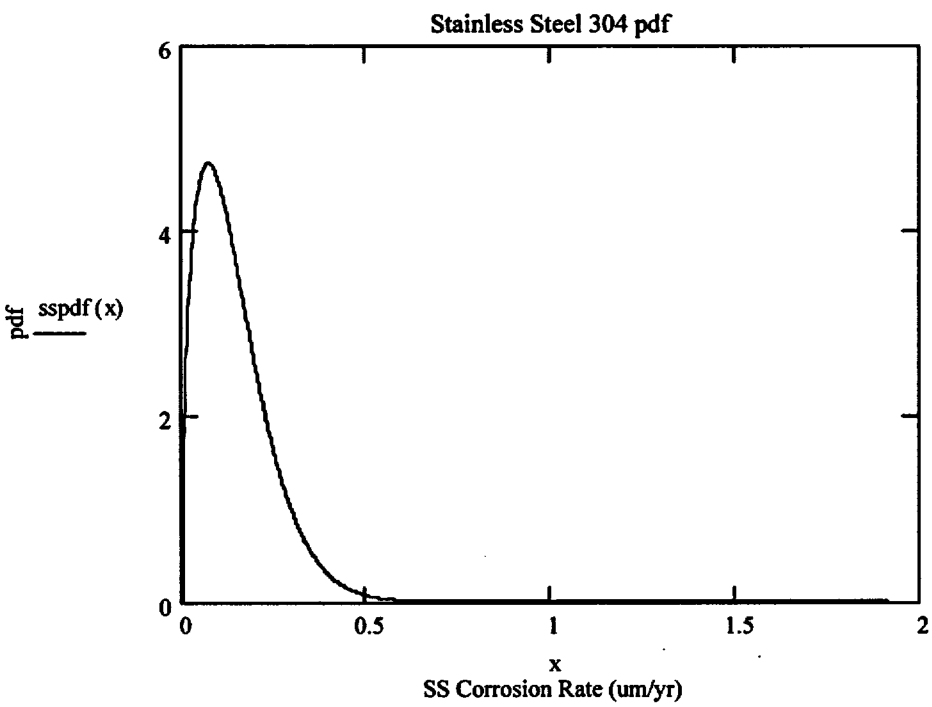
When y = z then calculate the corresponding value for α.

$$\alpha := \left[\frac{\sum_{i=1}^{n} (t_i)^{\beta}}{n}\right]^{\frac{1}{\beta}}$$

$\alpha = 0.157$

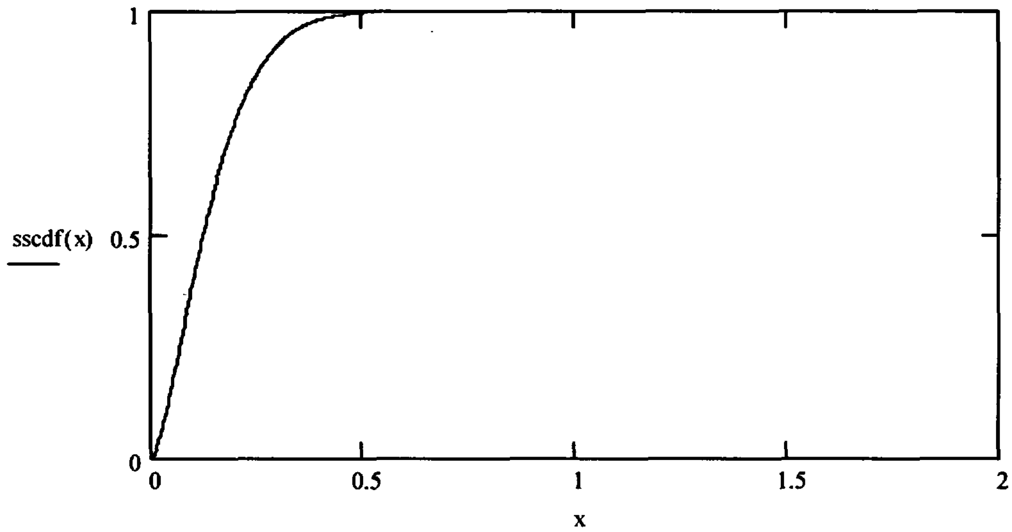
sspdf(x) is the probability distribution function of Stainless Steel Type 304 using a Weibull distribution.

$$\text{sspdf}(x) := \left[\frac{\beta \cdot x^{(\beta-1)}}{\alpha^{\beta}}\right] \cdot \exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right]$$



sscdf(x) is the cumulative distribution function of the Stainless Steel Type 304 data fit to a Weibull distribution.

$$\text{sscdf}(x) := 1 - \exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right]$$

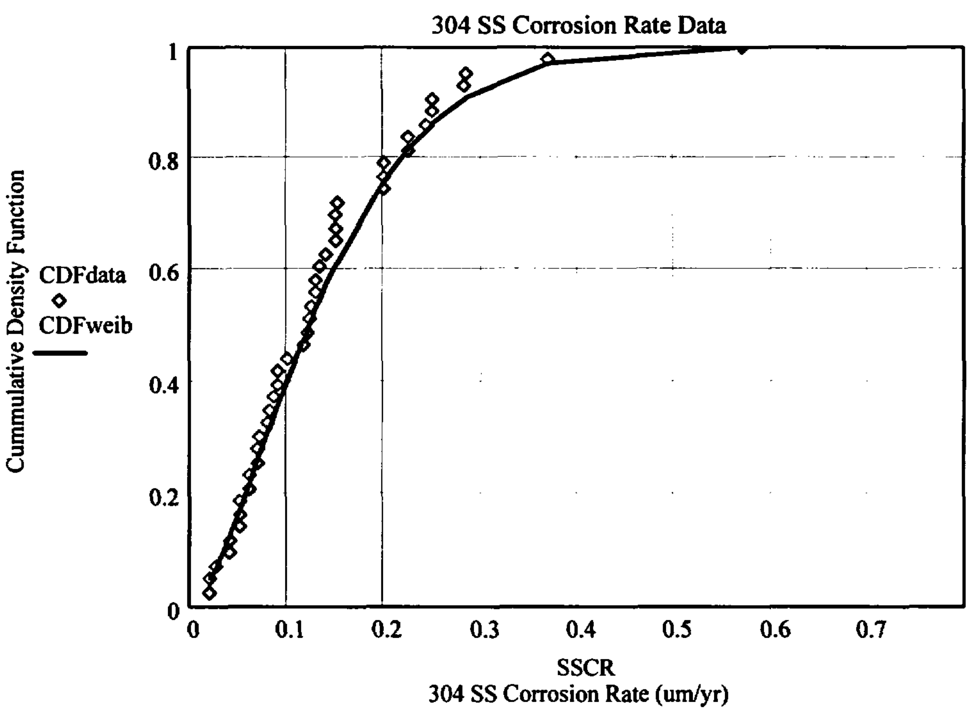


The probability of the corrosion rate can be obtained using the equation at any range or point.

$$cdf(x) := \exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right]$$

cdf(.1) = 0.597

Plot of raw data versus Weibull distribution



The Weibull distribution was checked for its fit against the raw data. The Anderson-Darling Test was used to check for goodness-of-fit. The Anderson-Darling Test is used because it is designed for use with few data points and is more appropriate vis-a-vis the Kolmogorov-Smirnov Test.

$w_i := 1 - \exp\left[-\left(\frac{t_i}{\alpha}\right)^\beta\right]$ w is the Weibull cumulative distribution function of the fitted corrosion rate.

$A2 := -n - \left(\frac{1}{n}\right) \cdot \sum_{i=1}^{n} (2 \cdot i - 1) \cdot \left(\ln(w_i) + \ln(1 - w_{n-i+1})\right)$ A2 is the test equation for the Anderson-Darling test (D'Agostino and Stephens 1986, Table 4-7, p. 101).

$A2 = 0.322$

$A2m := A2 \cdot \left(1 + \frac{0.75}{n} + \frac{2.25}{n^2}\right)$ A2m is used to adjust the test limit due to a small amount of data (D'Agostino and Stephens 1986, Table 4-7, p. 123).

$A2m = 0.328$

The Anderson-Darling test for five percent rejection significance for a null test requires the test value to be less than critical limit based on a small amount of data points and a significant level of 0.05.

Anderson-Darling critical limit for 0.05 is 0.752 (D'Agostino and Stephens 1986, Table 4-7, p. 123).

A2m < Anderson-Darling critical limit; therefore, the Weibull distribution can be used to represent the data (D'Agostino and Stephens 1986, Table 4.7, p. 123).

VI.3 STAINLESS STEEL 316 CORROSION RATE

The Stainless Steel Type 316 corrosion rate data is obtained from DTN: MO0303SPAMCRAQ.000 and given as follows:

$c := 2.5$ c is assumed to be the median boron degradation factor increase for Neutronit versus Stainless Steel Type 316 (based on CRWMS M&O 1999b, Sections 3.4 and 5.14). The boron increase factor is assumed to range between 1 and 4.

$t_1 := .037 \cdot c$ $t_2 := .102 \cdot c$

$t_3 := .109 \cdot c$ $t_4 := .152 \cdot c$

$t_5 := .154 \cdot c$ $\quad t_6 := .178 \cdot c$

$t_7 := .203 \cdot c$ $\quad t_8 := .229 \cdot c$

$t_9 := .229 \cdot c$ $\quad t_{10} := .254 \cdot c$

$t_{11} := .254 \cdot c$ $\quad t_{12} := .254 \cdot c$

$t_{13} := .279 \cdot c$

$n := 13$

where t_i is the corrosion rate data in (μm/yr) and n = 13 data points. The data were fitted to three types of distributions, a lognormal, a normal, and a Weibull. The Mathcad® files for the Stainless Steel Type 316 corrosion rate probability calculations described in Attachment XI and included in Attachment XII are, respectively, "316cs_corr_info_lnorm.mcd", "316cs_corr_info_norm.mcd", and "316cs_corr_info_weib.mcd".

VI.3.1 Stainless Steel 316 Corrosion Rate Fit to a Normal Distribution

$$\mu := \frac{\left(\sum_{i=1}^{n} t_i\right)}{n}$$

μ is the sample mean obtained from the data that will be used in a normal distribution.

$\mu = 0.468$

$$\sigma 2 := \frac{1 \cdot \sum_{i=1}^{n} \left(t_i - \mu\right)^2}{n}$$

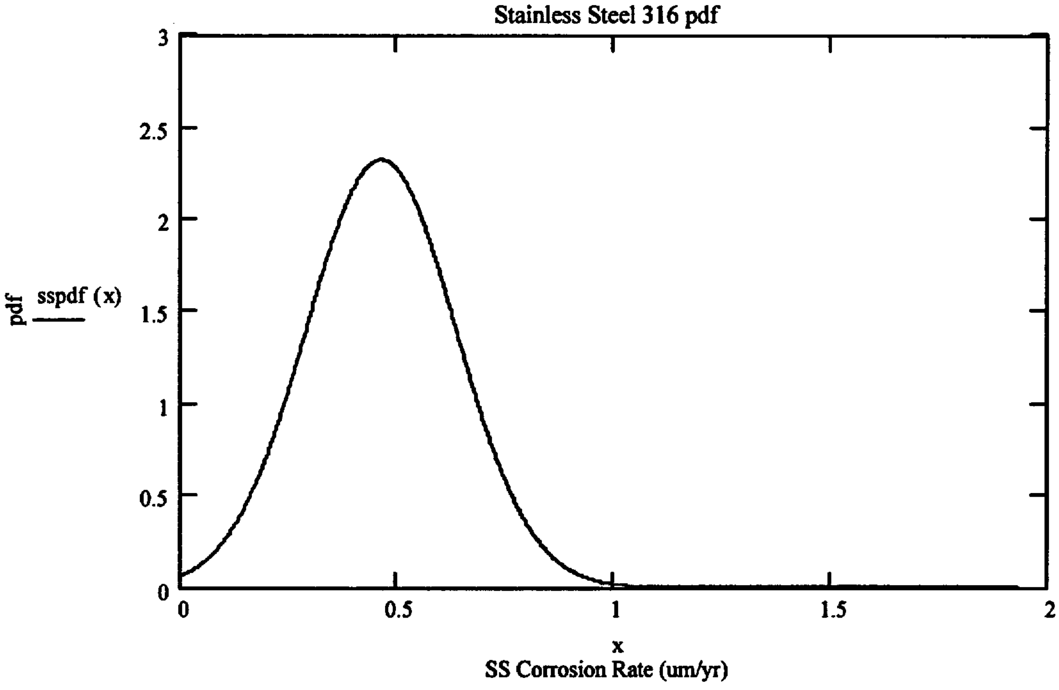
$\sigma 2 = 0.031$

$\sigma := \sqrt{\sigma 2}$ $\quad$ σ is the standard deviation for the normal distribution.

$\sigma = 0.175$

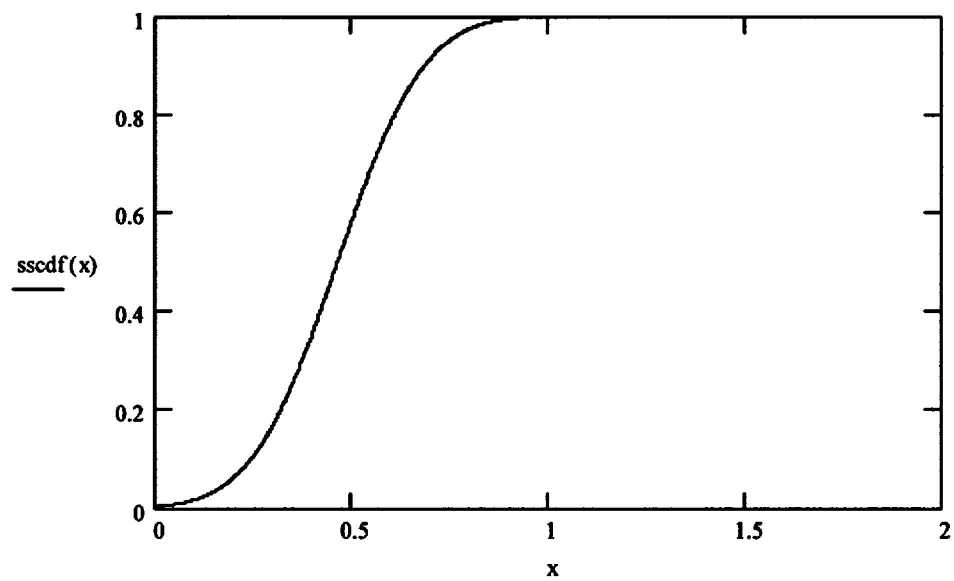
sspdf(x) is the probability distribution function for a normal distribution using the mean and standard deviation calculated from the data.

$sspdf(x) := dnorm(x, \mu, \sigma)$



sscdf(x) is the cumulative distribution function of the normal distribution using the mean and standard deviation calculated using the data.

$sscdf(x) := pnorm(x, \mu, \sigma)$

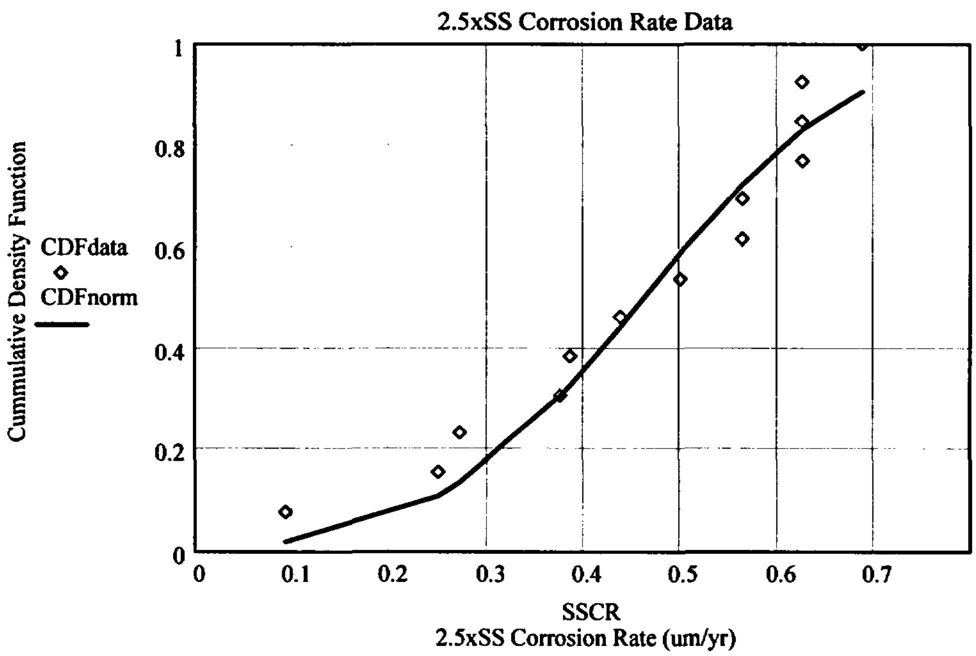


The probability of the corrosion rate can be obtained using the equation at any range or point.

$$sscdf1(x) := \int_{0.5}^{\infty} dnorm(x, \mu, \sigma)\, dx$$

$sscdf1(0.5) = 0.428$

The data is plotted versus normal distribution using the calculated mean and standard deviation.



The normal distribution was checked for its fit against the raw data. The Anderson-Darling Test (D'Agostino and Stephens 1986, Table 4-7, p. 123) was used to check for goodness-of-fit. The Anderson-Darling Test is used because it is designed for use with few data points and is more appropriate versus the Kolmogorov-Smirnov Test.

$w_i := pnorm(t_i, \mu, \sigma)$ w is the standard normal cumulative distribution function of the fitted corrosion rate.

$$A2 := -n - \left(\frac{1}{n}\right) \cdot \sum_{i=1}^{n} (2 \cdot i - 1) \cdot \left(\ln(w_i) + \ln(1 - w_{n-i+1})\right)$$

A2 is the test equation for the Anderson-Darling test (D'Agostino and Stephens 1986, Table 4-7, p. 101).

$A2 = 0.417$

$$A2m := A2 \cdot \left(1 + \frac{0.75}{n} + \frac{2.25}{n^2}\right)$$

A2m is used to adjust the test limit due to the small number of data points (D'Agostino and Stephens 1986, Table 4-7, p. 123).

$A2m = 0.447$

The Anderson-Darling test for five percent rejection significance for a null test requires the test value to be less than critical limit based on a small amount of data points and a significance level of 0.05.

Anderson-Darling critical limit for 0.05 is 0.752 (D'Agostino and Stephens 1986, Table 4-7, p. 123).

A2m < Anderson-Darling critical limit; therefore, the normal distribution can be used to represent the data (D'Agostino and Stephens 1986, Table 4-7, p. 123).

VI.3.2 Stainless Steel 316 Corrosion Rate Fit to a Weibull Distribution

The following equations are from Modarres (1993, p. 109).

The following equations are solved for α and β.

The equations need to be solved by numerical interpolation. The value of β is determined when parameters y = z.

$$z := \left(\frac{1}{n}\right) \cdot \sum_{i=1}^{n} \ln(t_i)$$

$\beta := 3.025$ Select a value of β and solve for y, check to see if y = z, if not select a new value for β.

$$y := \frac{\left[\sum_{i=1}^{n} (t_i)^{\beta} \cdot \ln(t_i)\right]}{\sum_{i=1}^{n} (t_i)^{\beta}} - \left(\frac{1}{\beta}\right)$$

$y = -0.869$ $z = -0.869$

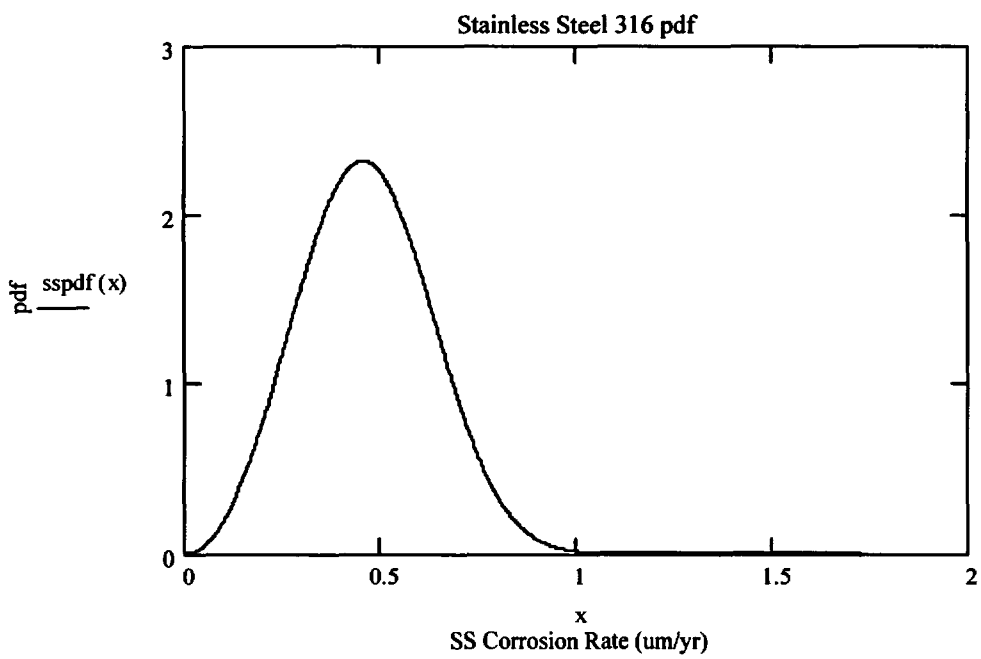
When y = z then calculate the corresponding value for α.

$$\alpha := \left[\frac{\sum_{i=1}^{n} (t_i)^{\beta}}{n}\right]^{\frac{1}{\beta}}$$

$\alpha = 0.523$

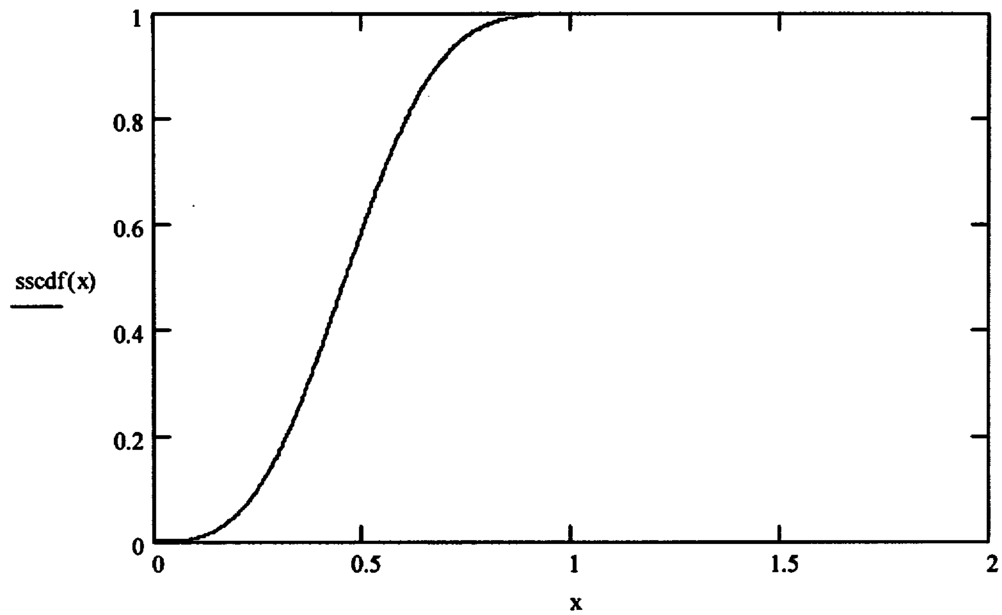
sspdf(x) is the probability distribution function of Stainless Steel Type 316 using a Weibull distribution.

$$\mathrm{sspdf}(x) := \left[\frac{\beta \cdot x^{(\beta-1)}}{\alpha^{\beta}}\right] \cdot \exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right]$$



sscdf(x) is the cumulative distribution function of the Stainless Steel Type 316 data fit to a Weibull distribution.

$$\mathrm{sscdf}(x) := 1 - \exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right]$$

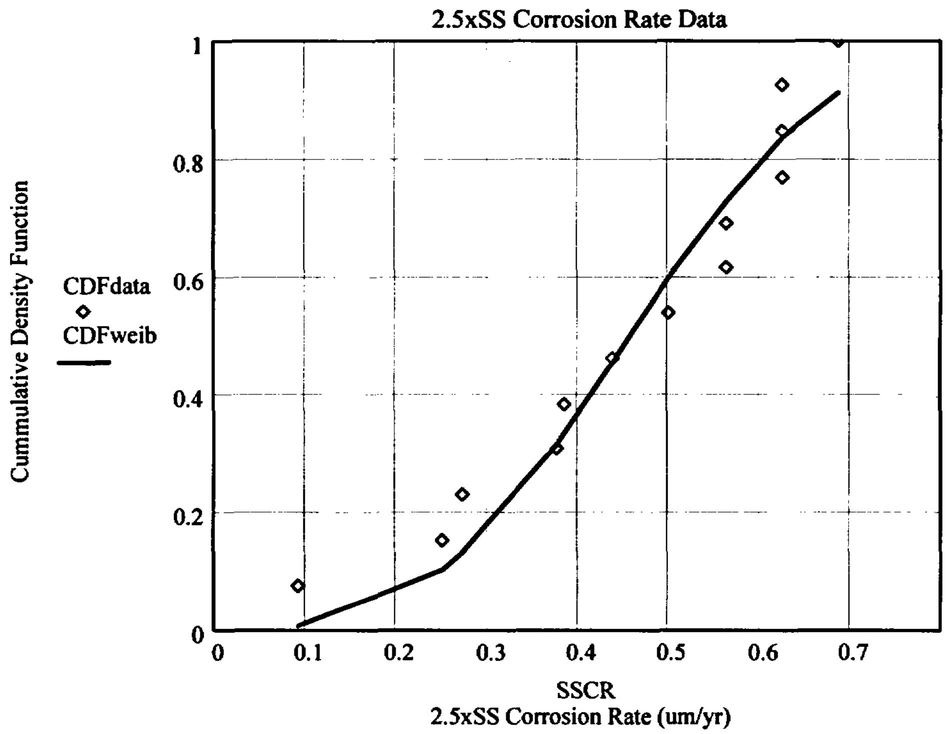


The probability of the corrosion rate can be obtained using the equation at any range or point.

$$cdf(x) := \exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right]$$

$cdf(.5) = 0.417$

Plot of raw data versus Weibull distribution



The Weibull distribution was checked for its fit against the raw data. The Anderson-Darling Test was used to check for goodness-of-fit. The Anderson-Darling Test is used because it is designed for use with few data points and is more appropriate vis-a-vis the Kolmogorov-Smirnov Test.

$w_i := 1 - \exp\left[-\left(\frac{t_i}{\alpha}\right)^{\beta}\right]$ w is the Weibull cumulative distribution function of the fitted corrosion rate.

$A2 := -n - \left(\frac{1}{n}\right)\cdot\sum_{i=1}^{n} (2\cdot i - 1)\cdot\left(\ln\left(w_i\right) + \ln\left(1 - w_{n-i+1}\right)\right)$ A2 is the test equation for the Anderson-Darling test (D'Agostino and Stephens 1986, Table 4-7, p. 101).

$A2 = 0.516$

$$A2m := A2\cdot\left(1 + \frac{0.75}{n} + \frac{2.25}{n^2}\right)$$

A2m is used to adjust the test limit due to a small amount of data (D'Agostino and Stephens 1986, Table 4-7, p. 123).

$A2m = 0.552$

The Anderson-Darling test for five percent rejection significance for a null test requires the test value to be less than critical limit based on a small number of data points and a significant level of 0.05.

Anderson-Darling critical limit for 0.05 is 0.752 (D'Agostino and Stephens 1986, Table 4-7, p. 123).

A2m < Anderson-Darling critical limit; therefore, the Weibull distribution can be used to represent the data (D'Agostino and Stephens 1986, Table 4-7, p. 123).

VI.3.3 Stainless Steel 316 Corrosion Rate Fit to a Lognormal Distribution

$$\lambda := \frac{\left(\sum_{i=1}^{n} \ln\left(t_i\right)\right)}{n}$$

$\lambda = -0.869$ λ is the mean for a lognormal distribution

$$\zeta 2 := \frac{\left[\sum_{i=1}^{n} \left(\ln\left(t_i\right) - \lambda\right)^2\right]}{n}$$

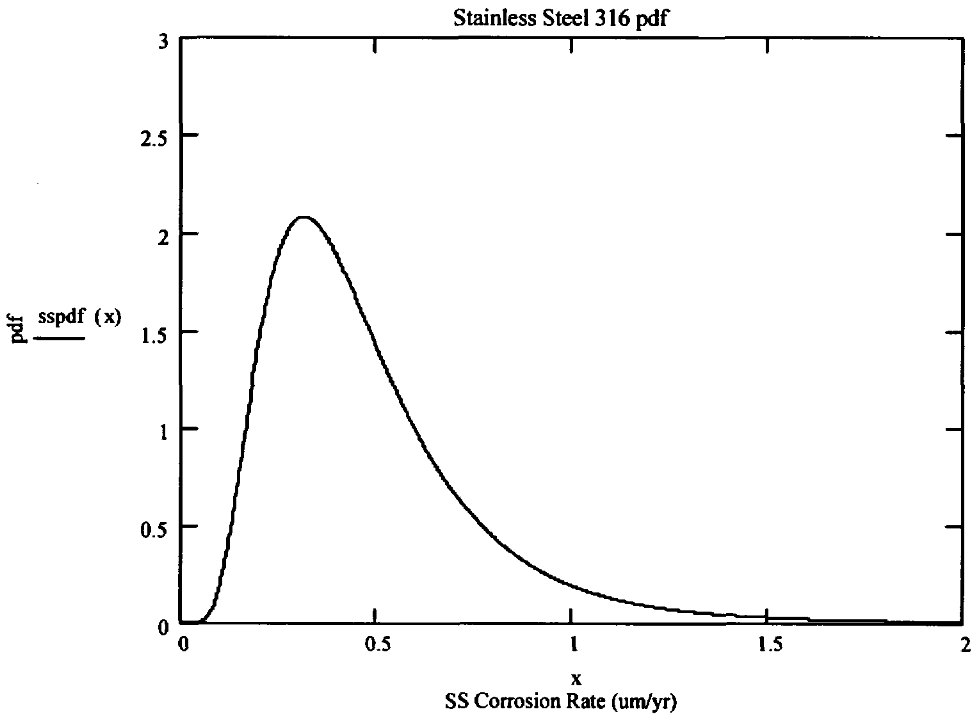
$\zeta 2 = 0.288$

$\zeta := \sqrt{\zeta 2}$ ζ is the standard deviation for the lognormal distribution

$\zeta = 0.537$

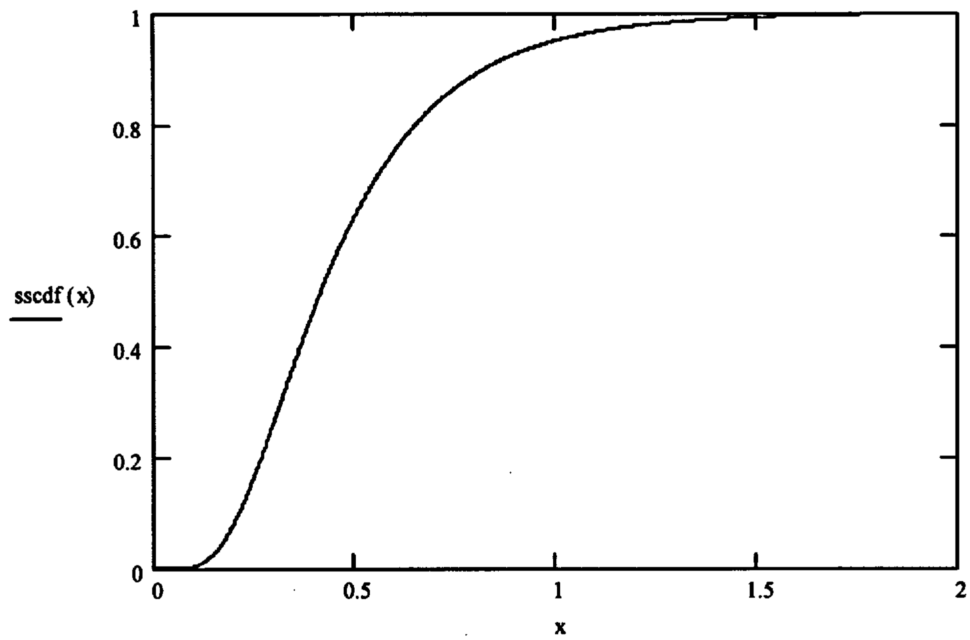
sspdf(x) is the probability distribution function of Stainless Steel Type 316 using a lognormal distribution.

$$sspdf(x) := dlnorm(x, \lambda, \zeta)$$

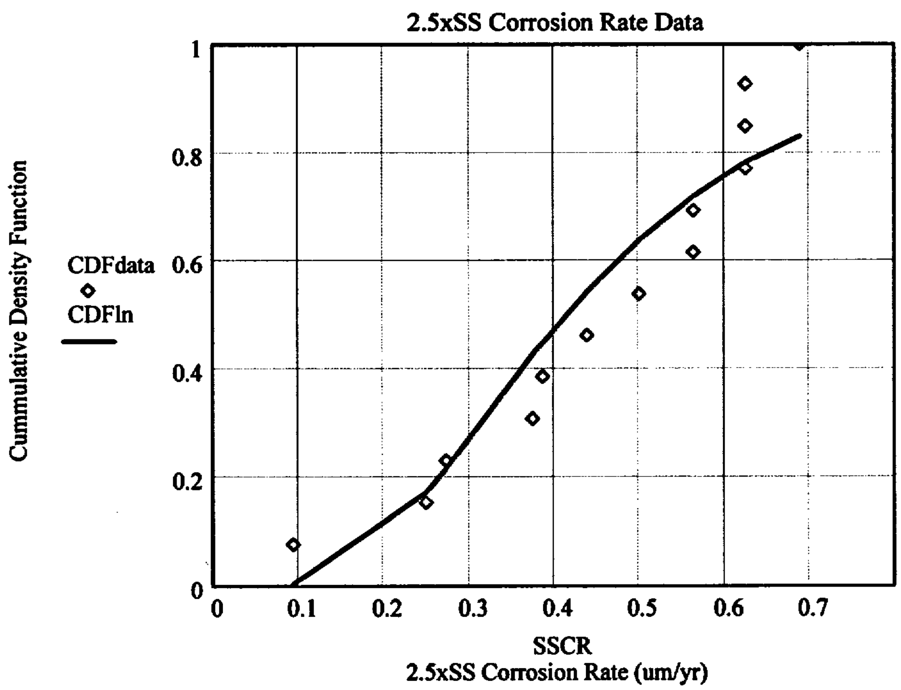


sscdf(x) is the cumulative distribution function of the Stainless Steel Type 316 data fit to a lognormal distribution.

$$sscdf(x) := plnorm(x, \lambda, \zeta)$$



Plot raw data versus lognormal distribution



The lognormal distribution was checked for its fit against the raw data. The Anderson-Darling Test was used to check for goodness-of-fit. The Anderson-Darling Test is used because it is designed for use with few data points and is more appropriate versus the Kolmogorov-Smirnov Test.

$w_i := \text{plnorm}(t_i, \lambda, \zeta)$ w is the standard lognormal cumulative distribution function of the fitted corrosion rate.

$$A2 := -n - \left(\frac{1}{n}\right) \cdot \sum_{i=1}^{n} (2 \cdot i - 1) \cdot \left(\ln(w_i) + \ln(1 - w_{n-i+1})\right)$$

A2 is the test equation for the Anderson-Darling test (D'Agostino and Stephens 1986, p. 101).

$A2 = 0.891$

$$A2m := A2 \cdot \left(1 + \frac{0.75}{n} + \frac{2.25}{n^2}\right)$$

A2m is used to adjust the test limit due to a small amount of data (D'Agostino and Stephens 1986, Table 4-7, p. 123).

$A2m = 0.954$

The Anderson-Darling test for five percent rejection significance for a null test requires the test value to be less than critical limit based on a small amount of data points and a significant level of 0.05.

Anderson-Darling critical limit for 0.05 is 0.752 (D'Agostino and Stephens 1986, Table 4-7, p. 123).

A2m > Anderson-Darling critical limit; therefore, the lognormal distribution should not be used to represent the data (D'Agostino and Stephens 1986, Table 4-7, p. 123).

ATTACHMENT VII
ZIRCALOY CLADDING CREEP FAILURE

ATTACHMENT VII

ZIRCALOY CLADDING CREEP FAILURE

Cladding failure due to creep strain can occur during dry storage, during transportation, or after emplacement in the repository provided the cladding temperature is high enough. The parameters of a triangular distribution for the fraction of rods perforated from creep as a function of peak waste package surface temperature have been derived in *Clad Degradation – Summary and Abstraction* (CRWMS M&O 2001c, p. 36). The minimum, maximum, and mode values of the triangular distributions for different waste-package peak temperature conditions are listed in Table VII-1.

Table VII-1. Fraction of Rods Perforated from Creep as a Function of Peak Waste Package Surface Temperature

Waste Package Peak Temperature (°C)	Maximum	Mode	Minimum
≤177	0.0000	0.0000	0.0000
227	0.0000	0.0001	0.0000
277	0.0001	0.0001	0.0000
302	0.0005	0.0002	0.0000
327	0.0039	0.0019	0.0000
352	0.0325	0.0127	0.0001
377	0.1495	0.0540	0.0009
427	0.5638	0.2802	0.0617
477	0.8991	0.6113	0.3418
502	0.9683	0.7499	0.5067
527	0.9980	0.8516	0.6727
≥547	0.9980	0.9050	0.7841

Source: CRWMS M&O 2001c, p. 36.

The peak waste package temperature is determined in the thermal hydrologic model and provided in *Abstraction of NFE Drift Thermodynamic Environment and Percolation Flux* (CRWMS M&O 2001b, p. 50). Table VII-2 presents the minimum, mean, and maximum values of the peak waste package temperatures.

Table VII-2. The Minimum, Mean, and Maximum of the Peak Waste Package Temperature

Infiltration Bin (mm/yr)	Infiltration Flux Map	HLW			CSNF		
		Min (°C)	Mean (°C)	Max (°C)	Min (°C)	Mean (°C)	Max (°C)
0-3	High	N/A	N/A	N/A	N/A	N/A	N/A
	Mean	159	159	160	173	173	173
	Low	129	151	170	140	162	184
3-10	High	131	149	156	141	162	169
	Mean	136	149	161	145	160	174
	Low	133	153	172	143	163	186
10-20	High	130	146	156	140	157	170
	Mean	131	144	161	141	154	175
	Low	N/A	N/A	N/A	N/A	N/A	N/A
20-60	High	127	141	156	138	151	170
	Mean	132	147	160	142	157	173
	Low	N/A	N/A	N/A	N/A	N/A	N/A
60+	High	137	144	154	146	154	166
	Mean	155	156	156	169	169	170
	Low	N/A	N/A	N/A	N/A	N/A	N/A
Overall	High	127	143	156	138	153	170
	Mean	131	146	161	141	157	175
	Low	129	152	172	140	162	186
Overall	Overall	127	147	172	138	157	186

Source: CRWMS M&O 2001b, p. 50.

INTENTIONALLY LEFT BLANK

ATTACHMENT VIII
TRIANGULAR DISTRIBUTION DERIVATION

ATTACHMENT VIII

TRIANGULAR DISTRIBUTION DERIVATION

Derivation of the distribution function for a random variable, Q, distributed according to a triangular distribution with a minimum, peak, and maximum of q_l, q_p, and q_u, respectively.

$$f_Q(q) = \begin{cases} a_1 q + a_0 & q_l \le q \le q_p \\ b_1 q + b_0 & q_p \le q \le q_u \\ 0 & \text{elsewhere} \end{cases} \qquad \text{(Eq. VIII-1)}$$

Since $f_Q(q)$ is a probability distribution function, the area of the triangle is equal to unity, that is,

$$(q_u - q_l) \cdot f_Q(q_p)/2 = 1 \qquad \text{(Eq. VIII-2)}$$

The coefficients a_0, a_1, b_0, and b_1 of Equation VIII-1 are derived from the following system of four linear equations, which results from the properties of a triangular density function including Equation VIII-2.

$$\begin{cases} a_1 \cdot q_l + a_0 = 0 \\ b_1 \cdot q_u + b_0 = 0 \\ a_1 \cdot q_p + a_0 = f_Q(q_p) \\ b_1 \cdot q_p + b_0 = f_Q(q_p) \end{cases} \Rightarrow \begin{cases} a_0 = \dfrac{2 \cdot q_l}{(q_l - q_u) \cdot (q_p - q_l)} \\ a_1 = \dfrac{2}{(q_u - q_l) \cdot (q_p - q_l)} \\ b_0 = \dfrac{2 \cdot q_u}{(q_l - q_u) \cdot (q_p - q_u)} \\ b_1 = \dfrac{2}{(q_u - q_l) \cdot (q_p - q_u)} \end{cases} \qquad \text{(Eq. VIII-3)}$$

Substituting the expressions for the coefficients a_0, a_1, b_0, and b_1 in Equation VIII-1, the probability distribution function f_Q becomes

$$f_Q(q) = \begin{cases} \dfrac{2}{(q_u - q_l) \cdot (q_p - q_l)} \cdot q + \dfrac{2 \cdot q_l}{(q_l - q_u) \cdot (q_p - q_l)} & q_l \le q \le q_p \\ \dfrac{2}{(q_u - q_l) \cdot (q_p - q_u)} \cdot q + \dfrac{2 \cdot q_u}{(q_l - q_u) \cdot (q_p - q_u)} & q_p \le q \le q_u \\ 0 & \text{elsewhere} \end{cases} \qquad \text{(Eq. VIII-4)}$$

The distribution function of the random variable Q is obtained from the integration of Equation VIII-4, as shown below.

$$F_Q(q)=\begin{cases}0 & q<q_l\\ \int_{q_l}^{q}(a_1\cdot x+a_0)dx & q_l\le q\le q_p\\ \int_{q_l}^{q_p}(a_1x+a_0)dx+\int_{q_p}^{q}(b_1\cdot x+b_0)dx & q_p\le q\le q_u\\ 1 & q>q_u\end{cases}$$

$$=\begin{cases}0 & q<q_l\\ \left(a_1\cdot\frac{x^2}{2}+a_0\cdot x\right)\Big|_{q_l}^{q} & q_l\le q\le q_p\\ \left(a_1\cdot\frac{x^2}{2}+a_0\cdot x\right)\Big|_{q_l}^{q_p}+\left(b_1\cdot\frac{x^2}{2}+b_0\cdot x\right)\Big|_{q_p}^{q} & q_p\le q\le q_u\\ 1 & q>q_u\end{cases}$$

$$=\begin{cases}0 & q<q_l\\ \frac{a_1}{2}\cdot\left(q^2-q_l^2\right)+a_0\cdot\left(q-q_l\right) & q_l\le q\le q_p\\ \frac{b_1}{2}\cdot\left(q^2-q_p^2\right)+b_0\cdot\left(q-q_p\right)+\frac{a_1}{2}\cdot\left(q_p^2-q_l^2\right)+a_0\cdot\left(q_p-q_l\right) & q_p\le q\le q_u\\ 1 & q>q_u\end{cases} \qquad \text{(Eq. VIII-5)}$$

After substituting the expressions for the coefficients a_0, a_1, b_0, and b_1 in Equation VIII-5, the cumulative distribution function F_Q becomes

$$F_Q(q)=\begin{cases}0 & q<q_l\\ \frac{(q^2-q_l^2)}{(q_u-q_l)\cdot(q_p-q_l)}+\frac{2\cdot q_l\cdot(q-q_l)}{(q_l-q_u)\cdot(q_p-q_l)} & q_l\le q\le q_p\\ \frac{(q^2-q_p^2)}{(q_u-q_l)\cdot(q_p-q_u)}+\frac{2\cdot q_u\cdot(q-q_p)}{(q_l-q_u)\cdot(q_p-q_u)}+\frac{q_p-q_l}{q_u-q_l} & q_p\le q\le q_u\\ 1 & q>q_u\end{cases} \qquad \text{(Eq. VIII-6)}$$

INTENTIONALLY LEFT BLANK

ATTACHMENT IX
PROBABILITY OF DRIP SHIELD FAILURE DUE TO ROCK FALL

ATTACHMENT IX

PROBABILITY OF DRIP SHIELD FAILURE DUE ROCK FALL

This attachment provides a calculation of the probability of a rock greater than 4 metric tons falling on the drip shield. The calculation is based on *Rock Fall on Drip Shield* (CRWMS M&O 2000p).

Probability that a waste package will be located under a drip shield failed due to stress corrosion cracking following rock fall:

1. Context

   a. The drip shield is considered to fail by stress corrosion cracking after being hit by a rock of mass greater than 1 metric ton.

   b. More precisely, the length of the drip shield affected by stress corrosion cracking corresponds to the length of the key block that has fallen, increased by the length of the zone where the stresses in the drip shield change sufficiently to be impacted by SCC. This additional length is assumed to be 2 m.

   c. Based on the number of key blocks expected in the repository on the one hand, and the expected length of drip shield that would be affected by the fall of each of these key blocks on the other hand, the total length of drip shield impacted by stress corrosion cracking is calculated. The ratio of this length to the total length of the emplacement drifts yields the probability that a given waste package will be located under a failed drip shield.

2. Inputs

   a. The predicted lengths of the key blocks in the repository, as a function of mass, are from *Drift Degradation Analysis* (BSC 2001j, Table IX-2). They are summarized in Table IX-1.

Table IX-1. Lengths of Key Blocks

Block Size (metric tons)	Length (meters)
1	2.44
2	3.30
4	4.23
5	5.38
8	7.82
15	13.65
19	15.96
30	24.79
36	28.94
52	40.49

b. The length of the 70,000 MTHM repository is estimated at 60,227 m (BSC 2001a, p. 9).

c. The features of the key blocks and of the surrounding environment (rock units Tptpln, Tptpll, Tptpmn) are given in Table IX-2. The key block mass has a lognormal distribution. The inputs are from *Expected Number of Key Blocks Throughout the Emplacement Drifts as a Function of Block Size* (CRWMS M&O 2000p, Sections 5.5 and 6).

Table IX-2. Key Block and Rock Unit Features

Rock unit	Tptpll	Tptpln	Tptpmn
Percentage in Repository	80.4%	11.1%	8.5%
Key Block Frequency (/m)	2×10^{-3}	1.2×10^{-2}	3.2×10^{-2}
Lognormal Parameter (Mean of Related Normal Distribution)	-1.891	-1.105	-1.494
Lognormal Parameter (Standard Deviation of Related Normal Distribution)	1.333	1.952	1.628

3. Calculation

a. First, the total number of key blocks of mass *m* present in the repository is calculated based on the inputs from Table IX-2 and the total length of drift. Only the key blocks of mass greater than 4 metric tons are considered.

b. Then, based on inputs from Table IX-1, the predicted length of a key block of mass *m* is calculated by linear interpolation and extrapolation, over the range extending from 4 to 140 metric tons, with mass increments of 1 metric tons. The upper value of 140 metric has been chosen because it is slightly greater than the greatest key block size estimated in *Drift Degradation Analysis* (BSC 2001j, Table 25) (a key block of about 2025 ft^3 was obtained in the Monte Carlo simulations modeling of the Tptpln rock unit; this corresponds to about 138 metric tons).

c. Multiplying the number of key blocks of mass *m* by their expected length, and summing up on all the *m* (greater than 4 metric tons), yields the total length of drip shield directly hit by rock fall greater than 4 metric tons. A length of about 159 m is found.

d. In addition, the length corresponding to the zone where the stresses in the drip shield change significantly to enhance SCC after a rock fall is calculated as 2 m multiplied by the total number of expected key blocks of mass greater than 4 metric tons. A length of about 30 m is found.

e. Summing these two lengths yields the total length of drip shield expected to fail (i.e., 159 + 30 = 189 m).

f. The probability that a given waste package will be located under a failed portion of the drip shield is the ratio of this length over the total length of the emplacement drifts (60,227 m). This makes a probability of 189/60,227 = 3.13×10^{-3}. The Excel spreadsheet "prob of rockfall on WO-4MT.xls" (Attachment XII) contains the information used to calculate the probability.

ATTACHMENT X
BORON LOSS ABSTRACTION

ATTACHMENT X
BORON LOSS ABSTRACTION

The degraded boron does goes into solution and does not form any minerals within the waste package. Boron's solubility is independent of pH; therefore, the amount of boron in the system is equal to the amount of boron in the intact Neutronit plus the amount of boron in solution from the degraded Neutronit (BSC 2002b). The equations below are based on mass balance in the waste package system as discussed in (BSC 2002b, p. 88 and Attachment V). The two equations calculate the amount of boron remaining in the waste package system at any given time based on drip rate and corrosion rate of Neutronit.

Input parameters from abstraction

$dr := 0.008$ dr is drip rate in m^3/yr

$nf := 4969$ nf is the normalizing factor (volume of waste package)

$con := 1000$ con is conversion from m^3 to liter

$time := 365.25 \cdot 24 \cdot 60 \cdot 60$ time is conversion from year to sec

$time = 3.156\times 10^{7}$

$cr := 1$ cr is corrosion rate in μm/yr

$neutronit := 4.5$ initial moles of Neutronit

$boron := 0.115$ moles boron per mole of Neutronit

$sa := 112.9$ surface area of Neutronit

$Vr := 1$ volume of the waste package (liter)

$drip := dr \cdot \left(\frac{1}{nf} \cdot con \cdot \frac{1}{time}\right)$ drip is moles/sec

$drip = 5.102\times 10^{-11}$

$deg := cr \cdot \left(\frac{1}{10000}\right) \cdot \left(\frac{1}{time}\right) \cdot \frac{8}{100}$ degradation of Neutronit in moles

$deg = 2.535\times 10^{-13}$

$timedeg := \left(neutronit \cdot \frac{1}{deg}\right) \cdot \left(\frac{1}{sa}\right) \cdot \left(\frac{1}{time}\right)$ time when Neutronit is degraded

$timedeg = 4.982\times 10^{3}$

$D := deg \cdot sa \cdot boron \cdot time$ moles of B release from Neutronit per year

$D = 1.039 \times 10^{-4}$

$v := drip \cdot time$ volumetric drip rate (liter/y)

$v = 1.61 \times 10^{-3}$

$bi := neutronit \cdot boron$ initial moles of B in the waste package

$bi = 0.518$

Boron Loss Equations

While Neutronit degrading (t < timedeg)

$$NBt(t) := nf \cdot \left[\left[\frac{(Vr \cdot D)}{v} \right] \cdot \left(1 - \exp\left(-t \cdot \frac{v}{Vr} \right) \right) + bi - D \cdot t \right]$$

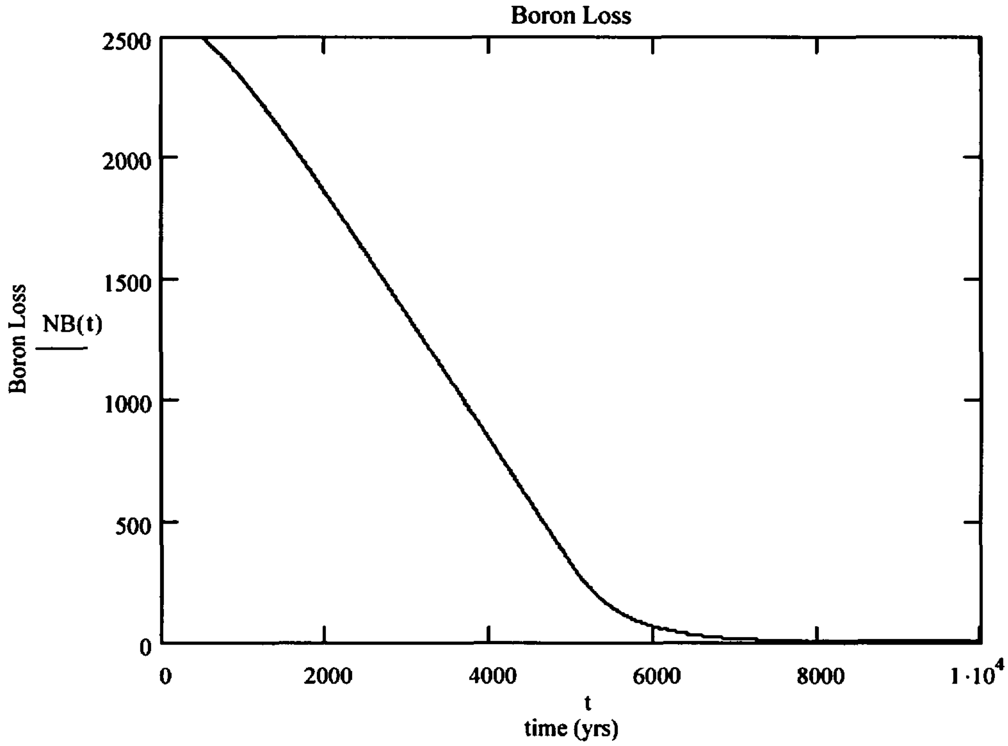
$NBt(timedeg) = 320.47$

After Neutronit degraded (t > timedeg)

$$NBtb(t) := nf \cdot \left(Vr \cdot \frac{D}{v} \right) \cdot \left(1 - \exp\left(-timedeg \cdot \frac{v}{Vr} \right) \right) \cdot \exp\left[\frac{-v \cdot (t - timedeg)}{Vr} \right]$$

$NBtb(9000) = 0.497$

$NB(t) := if(t < timedeg, NBt(t), NBtb(t))$



The Mathcad® file for the boron loss abstraction, "boronloss.mcd" is described in Attachment XI and included in Attachment XII.

ATTACHMENT XI

LIST OF THE ELECTRONIC FILES IN ATTACHMENT XII

ATTACHMENT XI

LIST OF THE ELECTRONIC FILES IN ATTACHMENT XII

The directory of files on the electronic media (compact disk, Attachment XII) for this model and analysis is given in Table XI-1. File names, their size in bytes, and the date and time of last update as given in the directory on the originating PC hardware are listed in Table XI-1. The file, "saph-config-gen.zip", referenced in the "config-gen-model" block is in a compressed format and contains the SAPHIRE binary data files. Moving the compressd file into a local directory, expanding the files, and removing the "read only" attribute will restore them to a useable form. Files referenced in the "ds-wp-files" block are all in Excel spreadsheet format and files referenced in the "mathcad files" block are Mathcad® output files.

Table XI-1. List of the Electronic Files in Attachment XII

Directory			
config-gen-model			
File Name	**File Size**	**Date of Last Update**	**Time**
saph-config-gen.zip	140,735	06/09/2003	02:50p
ds-wp-files			
prob of rockfall on WP-4MT.xls	109,056	09/09/2002	09:40a
DSAvgPat.xls	228,352	09/11/2002	07:11a
DSFail.xls	231,936	09/11/2002	09:55a
Freqhist_bathtub.xls	12,530,176	09/11/2002	10:28a
WPAvgPat.xls	210,944	09/11/2002	09:54a
WPFailPat.xls	216,064	09/11/2002	09:33a
mathcad files			
304cs_corr_info_lnorm.mcd	41,270	11/18/2002	10:56a
304cs_corr_info_norm.mcd	41,436	11/18/2002	10:57a
304cs_corr_info_weib.mcd	39,654	11/18/2002	11:01a
316cs_corr_info_lnorm.mcd	24,536	11/18/2002	11:03a
316cs_corr_info_norm.mcd	25,405	11/18/2002	11:04p
316cs_corr_info_weib.mcd	26,984	11/18/2002	11:05a
516cs_corr_info_lnorm.mcd	30,072	11/18/2002	10:53a
516cs_corr_info_norm.mcd	30,144	11/18/2002	10:52a
516cs_corr_info_weib.mcd	30,488	11/18/2002	10:53a
beta-gt.mcd	14,301	8/29/2002	04:24p
boronloss.mcd	16,742	10/30/2002	09:07a