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BECHTEL SAIC COMPANY LLC

WAPDEG Analysis of Waste Package and Drip Shield Degradation

Prepared for:
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11. Remarks

For TSPA-LA.

Kevin Mon is responsible for the entire document.

Bryan Bullard and Alda Behie made significant contributions.

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Change History

12. Revision No.	13. Description of Change
00	Initial Issue.
00 / 01	Interim Change to incorporate changes due to the removal of backfill and new/revised upstream inputs. Names of Alloy 22 outer barrier lids changed to outer closure lid and middle closure lid. Discussion added for recommended versus used uncertainty models Section 6.1.
01	Revision to incorporate changes for TSPA-LA. Incorporate changes in upstream process models. Conform to AP-SIII.10Q. The entire model documentation was revised because the changes were too extensive to use Step 5.8d) of AP-SIII.10Q
02	Revision to incorporate changes for regulatory integration. The entire scientific analysis documentation was revised and the changes were too extensive to use change bars. The previous revision was prepared as a model report. This revision does not contain model development and is prepared as a scientific analysis.

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ACRONYMS

AP	absorber plate
CDF	cumulative distribution function
CDSP	codisposal
CFR	Code of Federal Regulations
CPP	cyclic potentiodynamic polarization
CSNF	commercial spent nuclear fuel
DHLW	defense high-level radioactive waste
DLL	dynamic link library
DOE	U.S. Department of Energy
DTN	Data Tracking Number
EBS	engineered barrier system
EPRI	Electric Power Research Institute
FEPs	features, events, and processes
HAZ	heat-affected zone
HLW	high-level waste
IMARC	Integrated Multiple Assumptions and Release Code
IWPD	Integrated Waste Package Degradation
LA	License Application
LC	localized corrosion
LTCTF	Long Term Corrosion Test Facility
NDE	nondestructive evaluation
NRC	U.S. Nuclear Regulatory Commission
RH	relative humidity
SC	Safety Category
sd	standard deviation
SMR	Software Management Report
SNF	spent nuclear fuel
SR	Site Recommendation
TMRB	Technical Management Review Board
TPA	Total-system Performance Assessment
TSPA	Total System Performance Assessment
YS	yield strength

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1. PURPOSE

As directed by *Technical Work Plan for: Regulatory Integration Modeling and Analysis of the Waste Form and Waste Package* (BSC 2004 [DIRS 171583]), an analysis of the degradation of the engineered barrier system (EBS) drip shields and waste packages at the Yucca Mountain repository is developed. The purpose of this activity is to provide the TSPA with inputs and methodologies used to evaluate waste package and drip shield degradation as a function of exposure time under exposure conditions anticipated in the repository. This analysis provides information useful to satisfy *Yucca Mountain Review Plan, Final Report* (NRC 2003 [DIRS 163274]) requirements. Several features, events, and processes (FEPs) are also discussed (Section 6.2, Table 15).

The previous revision of this report was prepared as a model report in accordance with AP-SIII.10Q*, Models*. Due to changes in the role of this report since the site recommendation, it no longer contains model development. This revision is prepared as a scientific analysis in accordance with AP-SIII.9Q, *Scientific Analyses* and uses models previously validated in (1) *Stress Corrosion Cracking of the Drip Shield, the Waste Package Outer Barrier, and the Stainless Steel Structural Material* (BSC 2004 [DIRS 169985]); (2) *General Corrosion and Localized Corrosion of Waste Package Outer Barrier* (BSC 2004 [DIRS 169984]); and (3) *General Corrosion and Localized Corrosion of Drip Shield* (BSC 2004 [DIRS 169845]). The integrated waste package degradation (IWPD) analysis presented in this report treats several implementation-related issues, such as defining the number and size of patches per waste package that undergo stress corrosion cracking; recasting the weld flaw analysis in a form as implemented in the Closure Weld Defects (CWD) software; and, general corrosion rate manipulations (e.g., change of scale in Section 6.3.4). The weld flaw portion of this report takes input from an engineering calculation (BSC 2004 [DIRS 170024]) and uses standard mathematical methods to enable easier implementation. The IWPD analysis also provides guidance on implementation of early failures (importance sampling and multinomial distribution usage). These manipulations are evident from standard scientific practices, approaches, or methods and do not require changes to the previously validated models.

The IWPD analysis itself (Section 6.4), not the resultant curves from executing the IWPD analysis presented in Section 6.5 (which are for illustrative purposes), is used directly in total system performance assessment (TSPA). The IWPD analysis simulates general corrosion and stress corrosion cracking of the waste package outer barrier and general corrosion of the drip shield. The effects of igneous and seismic events and localized corrosion on drip shield and waste package performance are not evaluated in this report. The outputs of this report are inputs and methodologies used by TSPA to evaluate waste package and drip shield degradation as a function of exposure time under exposure conditions anticipated in the repository. The analyses presented in this report are for the current repository design (BSC 2004 [DIRS 168489]).

Analysis outputs presented in Section 6.5 are for illustrative purposes only and do not represent output for use in TSPA nor should they be used to evaluate repository performance. The drip shield and waste package degradation profiles presented in Section 6.5 result from the use of representative thermal hydrologic history files (Section 6.4.5) produced to allow the IWPD analysis to be exercised in this report. The drip shield and waste package degradation profiles generated in TSPA-LA will make use of the thermal hydrologic history files appropriate for the repository. Also, the results of the localized corrosion (pitting and crevice corrosion) are not presented in this report because evaluation of this degradation mode would require (in addition to of the actual thermal hydrologic history files appropriate for the repository) in-drift geochemical inputs, which will only be available to TSPA. Therefore, localized corrosion is implemented directly in TSPA. The drip shield and waste package degradation profiles presented in Section 6.5 provide evidence that the IWPD analysis implementation functions properly over a range of input parameter values.

The IWPD analysis applies to degradation of Titanium Grade 7 and Alloy 22. The limitations on the IWPD analysis result from the models implemented within it. The corrosion models developed in *General Corrosion and Localized Corrosion of the Drip Shield* are intended to apply to the Titanium Grade 7 alloy used for the drip shield plates (BSC 2004 [DIRS 169845], Section 1.2). The treatment of stress corrosion cracking is restricted to the waste package outer barrier. Degradation of the Stainless Steel Type 316 waste package inner vessel is not analyzed.

The following scientific analyses or models reports provide direct or indirect inputs to this report: *Analysis of Mechanisms for Early Waste Package/Drip Shield Failure*, *General Corrosion and Localized Corrosion of the Drip Shield*, *General Corrosion and Localized Corrosion of Waste Package Outer Barrier*, and *Stress Corrosion Cracking of the Drip Shield, the Waste Package Outer Barrier, and the Stainless Steel Structural Material*. This report provides direct or indirect inputs to the following scientific analyses or models reports: *Screening Analysis for Criticality Features, Events, and Processes for License Application*, *FEPs Screening of Processes and Issues in Drip Shield and Waste Package Degradation*, *Features, Events, and Processes: System Level*, and *Total System Performance Assessment (TSPA) Model/Analysis for the License Application*.

2. QUALITY ASSURANCE

The quality assurance program applies to the development of this technical product. *Technical Work Plan for: Regulatory Integration Modeling and Analysis of the Waste Form and Waste Package* (BSC 2004 [DIRS 171583]) determined that this activity is subject to *Quality Assurance Requirements and Description* (QARD) (DOE 2004 [DIRS 171539]) requirements. All waste package configurations have been determined to be important to waste isolation in accordance with AP-2.22Q and, therefore, are classified as Safety Category (SC) in *Q-List* (BSC 2004 [DIRS 168361], Appendix A; BSC 2004 [DIRS 170992]). The drip shields have been determined to be important to waste isolation in accordance with AP-2.22Q and, therefore, are classified as Safety Category (SC) in *Q-List* (BSC 2004 [DIRS 168361], Appendix A; BSC 2004 [DIRS 170992]).

The inputs to this report are documented according to AP-3.15Q, *Managing Technical Product Inputs*. The methods used to control the electronic management of data as required by AP-SV.1Q, *Control of the Electronic Management of Information*, were accomplished in accordance with the technical work plan. The process for control of the electronic management of information on evaluation of work activities, processes, or process functions (AP-SV.1Q, Section 5.0) is followed to ensure accuracy, completeness, and security of information and data used in preparation of this report. Examples of process controls mentioned in AP-SV.1Q are (a) access to the information contained on personal computer is password protected; (b) secured backup copies are appropriately labeled and stored before changes are made and kept until the changes are confirmed and correct; (c) physical electronic media (tape, diskette, CD-ROM, etc.) are appropriately labeled; and (d) for nonphysical electronic media, transport mechanisms can be e-mail, TCP/IP, NetBios, etc. and methods of receipt verification may include visual inspection, transmission verification settings, check sums, application information integrity check, etc.

This document was prepared in accordance with AP-SIII.9Q, *Scientific Analyses,* and reviewed in accordance with AP-2.14Q, *Document Review.*

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3. USE OF SOFTWARE

3.1 EXCEL 97 SR-2

Excel 97 SR-2 is a commercial off-the-shelf software program used in this report. The computations performed using Excel in this report use only standard functions and are documented in sufficient detail to allow an independent technical reviewer to reproduce or verify the results by visual inspection or hand calculation without recourse to the originator. The formulas or algorithms used and a listing of inputs to and outputs from the formulas or algorithms are sufficiently documented to allow results to be reproduced. Therefore, this software is exempt from LP-SI.11Q-BSC, *Software Management*. Excel 97 SR-2 is appropriate for its intended use because it offers the mathematical and graphical functionality necessary to perform and document the numerical manipulations used in this report. Excel 97 SR-2 was executed on an Optiplex GX260 Workstation (CRWMS M&O tag 152849, located in the Summerlin Offices, Las Vegas, Nevada) equipped with the Windows 2000 operating system.

3.2 SIGMAPLOT 8.0

SigmaPlot 8.0 is a commercial off-the-shelf software program used in this report. No computations are performed in this report using SigmaPlot 8.0; therefore, this software is exempt from LP-SI.11Q-BSC, *Software Management*. SigmaPlot 8.0 is appropriate for its intended use because it offers the graphical functionality necessary to perform and document the plots used in this report. SigmaPlot 8.0 was executed on an Optiplex GX260 Workstation (CRWMS M&O tag 152849, located in the Summerlin Offices, Las Vegas, Nevada) equipped with the Windows 2000 operating system.

3.3 MATHCAD 2001i PROFESSIONAL

MathCad 2001i Professional is a commercial off-the-shelf software program used in this report. The computations performed using MathCad 2001i Professional in this report use only standard functions and are documented in sufficient detail to allow an independent technical reviewer to reproduce or verify the results by visual inspection or hand calculation without recourse to the originator. The formulas or algorithms used and a listing of inputs to and outputs from the formulas or algorithms are sufficiently documented to allow results to be reproduced. Therefore, this software is exempt from LP-SI.11Q-BSC, *Software Management*. MathCad 2001i Professional is appropriate for its intended use because it offers the mathematical and graphical functionality necessary to perform and document the numerical manipulations used in this report. MathCad 2001i Professional was executed on an Optiplex GX260 Workstation (CRWMS M&O tag 152849, located in the Summerlin Offices, Las Vegas, Nevada) equipped with the Windows 2000 operating system.

3.4 WAPDEG V. 4.07

WAste Package DEGradation (WAPDEG) (WAPDEG V4.07, STN: 10000-4.07-00 [DIRS 161240]) is developed software used in this report, in accordance with LP-SI.11Q-BSC, *Software Management*, to calculate drip shield and waste package degradation profiles. The WAPDEG software is qualified. The following information is used to identify the WAPDEG software:

- Software Title: WAPDEG
- Software Tracking Number: 10000-4.07-00
- Version Number: 4.07

This software was obtained from the software configuration manager in accordance with appropriate procedures. WAPDEG was executed on an Optiplex GX260 Workstation (CRWMS M&O tag 152849, located in the Summerlin Offices, Las Vegas, Nevada) equipped with the Windows 2000 operating system. WAPDEG Version 4.07 was selected for this application, because it was specifically designed to calculate drip shield and waste package failure profiles. There are no limitations on outputs due to the software selected. The use of the software was consistent with its intended use and within its range of validation.

3.5 CWD V. 2.0

Closure Weld Defects (CWD) (CWD V2.0, 10363-2.0-00 [DIRS 162809]) is developed software used in this report, in accordance with LP-SI.11Q-BSC, *Software Management*, to calculate the probability of the occurrence and size of weld flaws in the closure-lid welds of the Alloy 22 waste package outer barrier. The CWD software is qualified. The following information is used to identify the CWD software:

- Software Title: CWD
- Software Tracking Number: 10363-2.0-00
- Version Number: 2.0

This software was obtained from the software configuration manager in accordance with appropriate procedures. CWD was executed on an Optiplex GX260 Workstation (CRWMS M&O tag 152849, located in the Summerlin Offices, Las Vegas, Nevada) equipped with the Windows 2000 operating system. This software was selected for this application because it was developed to calculate the probability of the occurrence and size of weld flaws in the closure-lid welds of the Alloy 22 waste package outer barrier. There are no limitations on outputs due to the software selected. The use of the software was consistent with its intended use and within its range of validation.

3.6 SCCD V. 2.01

Stress Corrosion Cracking Dissolution (SCCD) (SCCD V2.01, STN: 10343-2.01-00 [DIRS 161757]) is developed software used in this report, in accordance with LP-SI.11Q-BSC, *Software Management*, to calculate the stress and stress intensity factor profiles in the closure-lid welds of the Alloy 22 waste package outer barrier. The SCCD software routine is qualified. The following information is used to identify the SCCD software:

- Software Title: SCCD
- Software Tracking Number: 10343-2.01-00
- Version Number: 2.01

This software was obtained from the Software Configuration Manager in accordance with appropriate procedures. SCCD was executed on an Optiplex GX260 Workstation (CRWMS M&O tag 152849, located in the Summerlin Offices, Las Vegas, Nevada) equipped with the Windows 2000 operating system. This software was selected for this application because it was developed to calculate the stress and stress intensity factor profiles in the closure-lid welds of the Alloy 22 waste package outer barrier. There are no limitations on outputs due to the software selected. The use of the software was consistent with its intended use and within its range of validation.

3.7 GOLDSIM V. 7.50.100

GoldSim (GoldSim V7.50.100, STN: 10344-7.50.100-00 [DIRS 161572]) is acquired software controlled in accordance with LP-SI.11Q-BSC, *Software Management*. GoldSim was used to pass input to the developed software listed in this Section. The GoldSim software is qualified. The following information is used to identify the GoldSim software:

- Software Title: GoldSim
- Software Tracking Number: 10344-7.50.100-00
- Version Number: 7.50.100

This software was obtained from the software configuration manager in accordance appropriate procedures. GoldSim was executed on an Optiplex GX260 Workstation (CRWMS M&O tag 152849, located in the Summerlin Offices, Las Vegas, Nevada) equipped with the Windows 2000 operating system. This software was selected for this application because it has the capabilities to interface with external software routines and was specifically configured to call the developed software discussed in this section. There are no limitations on outputs due to the software selected. The use of the software was consistent with its intended use and within its range of validation.

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4. INPUTS

This section describes the direct inputs used to construct the integrated waste package degradation (IWPD) analysis, the criteria and codes and standards applied in this analysis. Treatment of uncertainties in inputs will be discussed in this section and in Section 6.

4.1 DIRECT INPUTS

Since the time to waste package breach due to stress corrosion cracking (SCC) and general corrosion is well beyond the regulatory period, and the waste package design may further change as the design matures, it is appropriate and justified to use the waste package dimensions and weld volumes from the IED identified in *Design and Engineering, D&E/PA/C IED Typical Waste Package Components Assembly 1 of 9* (BSC 2003 [DIRS 165406]) and the documents listed on this IED, based on TMRB decision 2004-066 (BSC 2004 [DIRS 171478]).

Table 1. Summary of IWPD Analysis Inputs

Input Name	Input Source	DTN	Input Value
21 PWR Waste Package Configuration Dimensions	*Repository Design, Waste Package, Project 21-PWR Waste Package with Absorber Plates, Sheet 1 of 3, Sheet 2 of 3, and Sheet 3 of 3* (BSC 2001 [DIRS 157812])	N/A	See Section 4.1.1
5 HLW/1 DOE Short Waste Package Configuration Dimensions	*Repository Design, Waste Package Project 5 DHLW/DOE SNF - Short Waste Package, Sheet 1 of 3, Sheet 2 of 3, and Sheet 3 of 3* (BSC 2001 [DIRS 157817])	N/A	See Section 4.1.1
5 HLW/1 DOE Long Waste Package Configuration Dimensions	*Repository Design, Waste Package Project 5 DHLW/DOE SNF - Long Waste Package, Sheet 1 of 3, Sheet 2 of 3, and Sheet 3 of 3* (BSC 2001 [DIRS 157818])	N/A	See Section 4.1.1
Drip Shield Thickness	*Repository Design Project, Repository/PA IED Interlocking Drip Shield and Emplacement Pallet.* (BSC 2004 [DIRS 169220], Table 5)	N/A	See Section 4.1.1
Waste Package Inventory Information	*Repository Design Project, RDP/PA IED Typical Waste Package Components Assembly (2).* (BSC 2003 [DIRS 163855], Table 11)	N/A	See Section 4.1.1

Table 1. Summary of IWPD Analysis Inputs (Continued)

Input Name	Input Source	DTN	Input Value
Weld Volumes	*Repository Design Project, RDP/PA IED Typical Waste Package Components Assembly (5).* (BSC 2003 [DIRS 164610], Table 18 and 19)	N/A	See Section 4.1.4
Drip shield general corrosion rate (Titanium Grade 7)	*General Corrosion and Localized Corrosion of the Drip Shield* (BSC 2004 [DIRS 169845], Section 6.5.5)	MO0408MWDGLCDS.002 [DIRS 171486]	See Section 4.1.2
Alloy 22 waste package outer barrier general corrosion inputs	*General Corrosion and Localized Corrosion of Waste Package Outer Barrier* (BSC 2004 [DIRS 169984], Section 6.4.3)	MO0409MWDUGCMW.000 [DIRS 171714]	See Section 4.1.3
Weld flaw analysis inputs	BSC 2004 [DIRS 170024] BSC 2004 [DIRS 169985] BSC 2001 [DIRS 157812] BSC 2001 [DIRS 157817] BSC 2001 [DIRS 157818]	LL030607012251.065 [DIRS 163968]	See Section 4.1.4
Stress intensity factor (K_I) vs depth	*Stress Corrosion Cracking of the Drip Shield, the Waste Package Outer Barrier, and the Stainless Steel Structural Material* (BSC 2004 [DIRS 169985])	LL030607012251.065 [DIRS 163968]	See Section 4.1.5
Stress coefficients for outer and middle closure lids	*Stress Corrosion Cracking of the Drip Shield, the Waste Package Outer Barrier, and the Stainless Steel Structural Material* (BSC 2004 [DIRS 169985])	LL030607012251.065 [DIRS 163968]	See Section 4.1.5
Yield strength, YS (various temperatures)	N/A	MO0003RIB00071.000 [DIRS 148850]	See Section 4.1.5
Slip dissolution inputs	*Stress Corrosion Cracking of the Drip Shield, the Waste Package Outer Barrier, and the Stainless Steel Structural Material* (BSC 2004 [DIRS 169985])	LL030607012251.065 [DIRS 163968]	See Section 4.1.6
Waste package outer barrier microbial induced corrosion inputs	*General Corrosion and Localized Corrosion of Waste Package Outer Barrier* (BSC 2004 [DIRS 169984], Section 6.4.5)	MO0409MWDUGCMW.000 [DIRS 171714]	See Section 4.1.7
Waste package early failure inputs	*Analysis of Mechanisms for Early Waste Package/Drip Shield Failure* (BSC 2004 [DIRS 170024])	N/A	See Section 4.1.8

4.1.1 Waste Package and Drip Shield Design Input

In this report, as in TSPA-SR (CRWMS M&O 2000 [DIRS 153246], Table 4.1-1), two nominal waste package configurations are considered. The first is referred to as the commercial spent nuclear fuel (CSNF) waste package configuration (CRWMS M&O 2000 [DIRS 153246], Table 4.1-1) for which the 21-PWR AP waste package configuration parameters are used (BSC 2001 [DIRS 157812]). The second configuration is the codisposal (CDSP) waste package configuration (CRWMS M&O 2000 [DIRS 153246], Table 4.1-1) whose length is considered to be the average length of the 5 HLW/1 DOE SNF long (BSC 2001 [DIRS 157818]) and short (BSC 2001 [DIRS 157817]) waste package configurations. The waste package inventory information for the repository is shown in Table 2. Note that commercial spent nuclear fuel-containing waste package configurations (e.g., 21-PWR AP) and naval fuel-containing waste package configurations (i.e., naval short and long) are represented by the CSNF waste package configuration and HLW-containing waste package configurations (e.g., 5 HLW long only) are represented by the CDSP waste package configuration.

Table 2. Waste Package Inventory Information

Waste Package Configuration	Nominal Quantity for LA	Nominal Waste Package Configuration
21-PWR AP	4,299	CSNF
21-PWR CR	95	CSNF
12-PWR AP Long	163	CSNF
44-BWR AP	2,831	CSNF
24-BWR AP	84	CSNF
5 IPWF	0	N/A
5 HLW Short/1 DOE SNF Short	1,147	CDSP
5 HLW Long/1 DOE SNF Long	1,406	CDSP
2 MCO/2 HLW	149	CDSP
5 HLW Long/1 DOE SNF Short	31	CDSP
5 HLW Long Only	679	CDSP
Naval Short	144	CSNF
Naval Long	156	CSNF

Source: BSC 2003 [DIRS 163855], Table 11.

Based on Table 2, the total number of waste packages represented by the CSNF and CDSP waste package configurations in the repository are 7,772 and 3,412, respectively.

The 21-PWR waste package configuration is an appropriate representation of the CSNF waste package configuration since the 21-PWR AP waste package is the most common configuration in the repository (BSC 2003 [DIRS 163855], Table 11). The 5 HLW/1 DOE SNF (codisposal) long and short waste package configurations are appropriate representations of the CDSP waste package configuration since these are the most common High-Level Waste (HLW) waste package configurations in the repository (BSC 2003 [DIRS 163855], Table 11).

Relevant waste package and drip shield dimensions were obtained from information exchange drawings (IED) (BSC 2003 [DIRS 165406]; BSC 2004 [DIRS 169220]) or design products listed on IEDs (BSC 2003 [DIRS 165406]) and are presented in Table 3.

Table 3. Waste Package and Drip Shield Dimensions

Input Name	Input Source	Input Value
21-PWR Waste Package Outer Barrier (Shell) Outer Diameter (OD)	BSC 2001 [DIRS 157812] Sheet 2 of 3	1,564 mm
21-PWR Waste Package Inner Barrier Length	BSC 2001 [DIRS 157812] Sheet 2 of 3	4,775 mm
21-PWR AP Waste Package Outer Barrier Thickness	BSC 2001 [DIRS 157812] Sheet 3 of 3	20 mm
5 HLW/1 DOE SNF Short Waste Package Outer Barrier (Shell) Outer Diameter (OD)	BSC 2001 [DIRS 157817] Sheet 2 of 3	2,030 mm
5 HLW/1 DOE SNF Short Waste Package Outer Barrier (Shell) Nominal Outer Diameter	BSC 2001 [DIRS 157817] Sheet 1 of 3	2,110 mm
5 HLW/1 DOE SNF Short Waste Package Inner Barrier Length	BSC 2001 [DIRS 157817] Sheet 2 of 3	3,200 mm
5 HLW/1 DOE SNF Short Waste Package Outer Barrier Thickness	BSC 2001 [DIRS 157817] Sheet 3 of 3	25 mm
5 HLW/1 DOE SNF Long Waste Package Outer Barrier (Shell) Outer Diameter (OD)	BSC 2001 [DIRS 157818] Sheet 2 of 3	2,030 mm
5 HLW/1 DOE SNF Long Waste Package Inner Barrier Length	BSC 2001 [DIRS 157818] Sheet 2 of 3	4,827 mm
5 HLW/1 DOE SNF Long Waste Package Outer Barrier Thickness	BSC 2001 [DIRS 157818] Sheet 3 of 3	25 mm
Drip Shield Plate Thickness	BSC 2004 [DIRS 169220], Table 5	15 mm

The waste package outer barrier (shell) outer diameter and waste package inner barrier length are used to calculate the waste package surface area for use in determining the fraction of area subject to stress corrosion cracking. The waste package outer barrier thickness is used indirectly in the formulation of inputs to the analysis (see Section 6.3.2), while the drip shield thickness is used directly in the WAPDEG_Inputs element of the IWPD analysis (Section 6.3.1 and Table I-1, Row 40). Because these are design-related parameters, there is no uncertainty treatment for these parameters.

The information listed in Table 3 are design-related parameters which were obtained from controlled and confirmed sources and, thus, do not require data tracking numbers.

4.1.2 Drip Shield General Corrosion Model Inputs

Details of the general corrosion rate distributions used for the under side and top side of the drip shield are developed in *General Corrosion and Localized Corrosion of the Drip Shield* (BSC 2004 [DIRS 169845], Section 6.5.5) and are tracked with DTN: MO0408MWDGLCDS.002 [DIRS 171486]. These inputs are qualified. Also, see Section 6.3.3 for a discussion of the drip shield general corrosion model and Section 6.4.6 for discussion of its implementation. The general corrosion rate cumulative distribution function applicable to the under side of the drip shield is shown in Table 4. The general corrosion rate cumulative distribution function applicable to the top side of the drip shield is shown in Table 5.

Table 4. Cumulative Distribution Function for General Corrosion Rates for Under Side of the Drip Shield

Sample	Rate (mm/yr)	Cumulative Distribution Function
1	0.00000000E+00	0.0000
2	7.90540100E-06	0.2500
3	7.90899600E-06	0.3125
4	7.91733600E-06	0.3750
5	7.99205500E-06	0.4375
6	1.59679640E-05	0.5000
7	1.60740360E-05	0.5625
8	2.35658240E-05	0.6250
9	2.37302160E-05	0.6875
10	2.40329080E-05	0.7500
11	3.99976910E-05	0.8125
12	7.14961090E-05	0.8750
13	7.91641200E-05	0.9375
14	1.12788228E-04	1.0000

Source: BSC 2004 [DIRS 169845], Section 6.5.5;
DTN: MO0408MWDGLCDS.002 [DIRS 171486].

Table 5. Cumulative Distribution Function for General Corrosion Rates for the Top Side of the Drip Shield

Sample	Rate (mm/yr)	Cumulative Distribution Function
1	0.00000000E+00	0.00000000E+00
2	4.18430800E-06	1.42857143E-01
3	7.90540100E-06	1.78571429E-01
4	7.90899600E-06	2.14285714E-01
5	7.91733600E-06	2.50000000E-01
6	7.99205500E-06	2.85714286E-01
7	1.59679640E-05	3.21428571E-01
8	1.60740360E-05	3.57142857E-01
9	1.65389750E-05	3.92857143E-01
10	2.10450870E-05	4.28571429E-01
11	2.35658240E-05	4.64285714E-01
12	2.37302160E-05	5.00000000E-01
13	2.40329080E-05	5.35714286E-01
14	2.52784890E-05	5.71428571E-01
15	3.99976910E-05	6.07142857E-01
16	4.26207080E-05	6.42857143E-01
17	4.28647310E-05	6.78571429E-01
18	5.15303020E-05	7.14285714E-01
19	6.33683700E-05	7.50000000E-01
20	6.49668830E-05	7.85714286E-01
21	7.14961090E-05	8.21428571E-01
22	7.91641200E-05	8.57142857E-01
23	8.22028960E-05	8.92857143E-01
24	1.11563286E-04	9.28571429E-01
25	1.12788228E-04	9.64285714E-01
26	3.19409704E-04	1.00000000E+00

Source: BSC 2004 [DIRS 169845], Section 6.5.5;
DTN: MO0408MWDGLCDS.002 [DIRS 171486].

These inputs are appropriate for their intended use because they were developed for this purpose while providing a reasonable estimate of the general corrosion behavior of Titanium Grade 7 subjected to the exposure conditions in the repository.

DTN: MO0408MWDGLCDS.002 [DIRS 171486] contains the file, 1_Year_CDFs.pdf, that contains the general corrosion rates for the top and under sides of the drip shield used in this report.

The variation in these inputs is entirely due to uncertainty (BSC 2004 [DIRS 169845], Section 6.5.5). Therefore, a single general corrosion rate is sampled from each distribution and applied to all drip shields in the repository. The general corrosion rate sampled for the outside surface of the drip shield is independent of the general corrosion rate sampled for the inner surface of the drip shield because the environments above and below the drip shield are not significantly correlated (BSC 2004 [DIRS 169845], Section 6.5.5).

4.1.3 Alloy 22 Waste Package Outer Barrier General Corrosion Model Inputs

4.1.3.1 Primary Alloy 22 General Corrosion Rate Distribution

In *General Corrosion and Localized Corrosion of Waste Package Outer Barrier* (BSC 2004 [DIRS 169984], Section 6.4.3; DTN: MO0409MWDUGCMW.000 [DIRS 171714]), general corrosion rates determined from 5-year weight-loss samples with the crevice geometry were used to generate a cumulative distribution function for the general corrosion rate (R_o) used in the IWPD analysis at an exposure temperature of 60°C (333.15 K). *General Corrosion and Localized Corrosion of Waste Package Outer Barrier* (BSC 2004 [DIRS 169984], Section 6.4.3) states that R_o (nm/yr) is given by a Weibull distribution (Evans et al. 1993 [DIRS 112115], Chapter 41) with scale parameter, α, equal to 8.88 nm/yr, shape parameter, β, equal to 1.62, and location parameter, θ, equal to 0. This is a two-parameter Weibull distribution since the location parameter, θ, is zero. The parameters are summarized in Table 6.

Table 6. Primary General Corrosion Rate Distribution

Input Name	Input Value	Units
Weibull Scale, α	8.88	nm/yr
Weibull Shape, β	1.62	N/A

Source: BSC 2004 [DIRS 169984], Section 6.4.3;
DTN: MO0409MWDUGCMW.000 [DIRS 171714].

The cumulative distribution function for a two-parameter Weibull distribution is given by (Evans et al. 1993 [DIRS 112115], Chapter 41):

$$CDF(x) = 1 - \exp\left(-\left(\frac{x}{\alpha} \right)^{\beta} \right) \quad \text{(Eq. 1)}$$

See Section 6.3.4 for a discussion of waste package general corrosion and Section 6.4.7 for discussion of implementation.

These inputs are appropriate for their intended use because they were developed for this purpose and provide a reasonable estimate of the general corrosion behavior of Alloy 22 subjected to the exposure conditions in the repository.

DTN: MO0409MWDUGCMW.000 [DIRS 171714] contains the file Base Case GC Rate CDF.xls that contains the Weibull scale (identified as s = 8.88) and Weibull shape (identified as b = 1.62) parameters.

These general corrosion rates are applied to the Alloy 22 waste package outer barrier surfaces when the exposure temperature is 60°C (333.15 K). The variation in the primary general corrosion rate distribution used for the Alloy 22 waste package outer barrier is entirely due to variability on the surface of the waste packages (BSC 2004 [DIRS 169984], Section 6.4.3) (i.e., the general corrosion rate distribution is used in the IWPD analysis. As discussed in *General Corrosion and Localized Corrosion of Waste Package Outer Barrier* (BSC 2004 [DIRS 169984], Section 6.4.3), the uncertainty in the general corrosion rate is contained in its temperature-dependent terms presented in the next section.

4.1.3.2 Temperature Dependence of Alloy 22 General Corrosion

The Alloy 22 general corrosion rate is considered a function of exposure temperature. The temperature dependence follows an Arrhenius relationship, i.e.:

$$R = \exp\left[C_o - \frac{C_1}{T}\right] \qquad \text{(Eq. 2)}$$

where

R = general-corrosion rate
T = temperature (Kelvin)
C_o = intercept term
C_1 = slope term (Kelvin)

The intercept term (C_o) is determined from the relationship between Equations 1 and 2 evaluated when the exposure temperature is 60°C (333.15 K). The variation in the general corrosion rate intercept term is entirely due to variability. Also, see Section 6.3.4 for a discussion of the Alloy 22 general corrosion model and Section 6.4.7 for discussion of implementation.

The slope term (C_1) is sampled from a truncated (at ±3 standard deviations) normal distribution with a mean of 3,116.47 K and a standard deviation of 296.47 K (BSC 2004 [DIRS 169984], Section 6.4.3) (DTN: MO0409MWDUGCMW.000 [DIRS 171714]). Note that the sign of the slope term in this report is negative with respect to the slope term in *General Corrosion and Localized Corrosion of Waste Package Outer Barrier* (BSC 2004 [DIRS 169984], Section 6.4.3) to be consistent with the input requirements of the WAPDEG.

Table 7. General Corrosion Slope Term (C_1) Distribution

Input Name	Input Value	Units
Normal mean[a]	3,116.47	K
Normal standard deviation[a]	296.47	K
Truncation[b]	±3 standard deviations	N/A

Source: [a] BSC 2004 [DIRS 169984], Section 6.4.3;
DTN: MO0409MWDUGCMW.000 [DIRS 171714].
[b] BSC 2004 [DIRS 169984], Section 6.4.3.

These inputs are appropriate for its intended use because they were developed for this purpose and provide a reasonable estimate of the temperature variation in the general corrosion behavior of Alloy 22 subjected to the exposure conditions in the repository.

DTN: MO0409MWDUGCMW.000 [DIRS 171714] contains a file called GC_TempDep_Reg.xls that contains the normal mean and standard deviation for the general corrosion temperature dependence slope term, C_1.

The variation in the general corrosion rate slope term is entirely due to uncertainty (BSC 2004 [DIRS 169984], Section 6.4.3). For each realization of the integrated waste package degradation analysis, a single general corrosion rate slope term is sampled and applied to the Alloy 22 waste package outer barrier surfaces to represent variation in the Alloy 22 general corrosion rate with exposure temperature. Spatial and temporal variability of the exposure temperature in the repository lead to spatial and temporal variability in Alloy 22 general corrosion rates.

4.1.4 Weld Flaw Inputs

The design information inputs to the integrated waste package degradation (IWPD) analysis of weld flaws in the Alloy 22 waste package outer barrier (or outer shell) closure-lid welds can be found in *Analysis of Mechanisms for Early Waste Package/Drip Shield Failure* (BSC 2004 [DIRS 170024]). The fraction of embedded weld flaws to propagate can be found in *Stress Corrosion Cracking of the Drip Shield, the Waste Package Outer Barrier, and the Stainless Steel Structural Material* (BSC 2004 [DIRS 169985], Table 8-1).

This design information was obtained from controlled sources. Weld flaws and their relation to stress corrosion cracking are discussed in Section 6.3.5.2.

Table 8. Manufacturing Defect Analysis Inputs and Their Sources

Description	Input Source	Input Value	Units
Fraction of embedded weld flaws to propagate (Depth of plate to be included for embedded flaws)	BSC 2004 [DIRS 169985], Table 8-1 DTN: LL030607012251.065 [DIRS 163968]	0.25	N/A
Fraction of weld flaws capable of propagation based on orientation	BSC 2004 [DIRS 170024], Table 12	0.008	N/A
Characteristic weld flaw size for PND (location parameter)	BSC 2004 [DIRS 170024], Table 11	2.5	mm
Shape factor for PND	BSC 2004 [DIRS 170024], Table 11	3	N/A
Lower limit for PND (detection threshold)	BSC 2004 [DIRS 170024], Table 11	0.005	N/A
Cumulative volume of sample welds, V_f	BSC 2004 [DIRS 170024], Appendix I, p. I-26 Identified as "total volume of weld in the 16 specimen rings"	18610540.3277924	mm^3
Number of sample welds	BSC 2004 [DIRS 170024], Section 6.2.1.1.2	16	N/A
Number of weld flaws, n_f	BSC 2004 [DIRS 170024], Table 11	7	N/A
Cumulative size of weld flaws S_f	BSC 2004 [DIRS 170024], Appendix I, p. I-3	31.75	mm
Flaw size parameter	BSC 2004 [DIRS 170024], Equation 2	Gamma distribution with a mean of n_f /S_f and a standard deviation of sqrt(n_f)/S_f [(a)]	mm^{-1}
Flaw density parameter	BSC 2004 [DIRS 170024], Equation 12	Gamma distribution with a mean of (n_f + ½)/ V_f and a standard deviation of sqrt(n_f + ½)/ V_f [(a)]	mm^{-3}
CSNF waste package outer closure lid weld volume	BSC 2003 [DIRS 164610], Table 19	1,350,189	mm^3
CSNF waste package middle closure lid weld volume	BSC 2003 [DIRS 164610], Table 18	490,478	mm^3
CDSP waste package outer closure lid weld volume	BSC 2003 [DIRS 164610], Table 19	1,753,091	mm^3
CDSP waste package middle closure lid weld volume	BSC 2003 [DIRS 164610], Table 18	639,901	mm^3
Weld Thickness (*th*)	BSC 2001 [DIRS 157812]; BSC 2001 [DIRS 157817]; and BSC 2001 [DIRS 157818], Sheet 3 of 3	25 for outer closure lid 10 for middle closure lid (same for CSNF and CDSP waste packages)	mm

NOTE: [a] Equations 2 and 12 in BSC 2004 [DIRS 170024] are probability density functions of gamma distributions (Evans et al. [DIRS 112115], Section 18.

4.1.5 Stress and Stress Intensity Factor Profile Inputs

Inputs to this analysis include stress and stress intensity factor profiles (stress or stress intensity factor versus depth) and slip dissolution parameters appropriate for both the outer closure and middle closure lids of the waste package outer barrier. Table 9 summarizes these inputs, their sources, data tracking numbers (DTNs), and table numbers. Most of these parameters can be found in *Stress Corrosion Cracking of the Drip Shield, the Waste Package Outer Barrier, and the Stainless Steel Structural Material* (BSC 2004 [DIRS 169985], Tables 8-1, 8-2, and 8-3).

Table 9. Stress and Stress Intensity Factor Profile Inputs and Their Sources

Input Name	Input Source	Input Value
Stress Profile Equation	BSC 2004 [DIRS 169985], Table 8-1 DTN: LL030607012251.065 [DIRS 163968]	Equation 3
Stress Profile Coefficients	BSC 2004 [DIRS 169985], Table 8-1 DTN: LL030607012251.065 [DIRS 163968]	See Table 10
Stress Intensity Factor Profiles	BSC 2004 [DIRS 169985], Table 8-2 and Table 8-3 DTN: LL030607012251.065 [DIRS 163968]	See Table 11
Yield strength, YS (various temperatures)	DTN: MO0003RIB00071.000 [DIRS 148850]	338 MPa at 366 K 283 MPa at 477 K
Stress variation with angle	BSC 2004 [DIRS 169985], Table 8-1 DTN: LL030607012251.065 [DIRS 163968]	Equation 4
Stress intensity factor variation with angle	BSC 2004 [DIRS 169985], Table 8-1 DTN: LL030607012251.065 [DIRS 163968]	Equation 5
Uncertain scaling factor for stress and stress intensity factor profiles, *z*	BSC 2004 [DIRS 169985], Table 8-1 DTN: LL030607012251.065 [DIRS 163968]	Truncated normal (at ±3 sd) with a mean of 0 and a standard deviation (sd) of 5% of YS

These inputs are qualified.

The hoop stress (σ in MPa) as a function of depth (x in mm) in the closure weld regions of the Alloy 22 waste package outer barrier is given by a third-order polynomial equation of the form (BSC 2004 [DIRS 169985], Table 8-1; DTN: LL030607012251.065 [DIRS 163968]):

$$\sigma(x,0) = A_0 + A_1 \cdot x + A_2 \cdot x^2 + A_3 \cdot x^3 \qquad \text{(Eq. 3)}$$

where the values of the coefficient(s) (A_i) are given in Table 10. The variation in the stress profile with depth is variability. The second argument in the stress function is used to represent angular variation as discussed later in this section.

Table 10. Stress Coefficients Used in the IWPD Analysis for the Outer and Middle Closure Lids of Waste Package Outer Barrier in Metric Units (i.e., stress in MPa)

Stress Coefficient	Outer Closure Lid Laser Peened	Middle Closure Lid As-Welded	Units
A_0	-292.607	219.908	MPa
A_1	178.277	56.494	MPa/mm
A_2	-14.135	-20.848	MPa/mm^2
A_3	0.320	1.083	MPa/mm^3

Source: BSC 2004 [DIRS 169985], Table 8-1; DTN: LL030607012251.065 [DIRS 163968]).

Table 11 lists the stress intensity factor versus depth profiles for the outer and middle closure lids of the Alloy 22 waste package outer barrier. The stress intensity factor is a scale factor defining the magnitude of the crack tip stress field. The variation in the stress intensity factor profile with depth is variability. As these are the results of intermediate calculations, as many digits as possible are retained to avoid round-off errors.

Table 11. Stress Intensity Factor (K_I) Vs. Depth Tables (due to Sz Hoop Stress) for the Outer and Middle Closure-Lids of Waste Package Outer Barrier

Outer Closure Lid		**Middle Closure Lid**	
K_I (MPa•m^{½})[a]	**Depth (mm)[b]**	**K_I (MPa•m^{½})[c]**	**Depth (mm)[d]**
-5.6943	0.3988	7.5754	0.1593
-6.4965	0.8001	10.9665	0.3203
-6.1528	1.1989	13.7144	0.4797
-5.1372	1.6002	16.1330	0.6407
-3.6697	1.9990	18.3358	0.8000
-1.8824	2.4003	20.3775	0.9593
0.1212	2.7991	22.3816	1.1203
2.2821	3.2004	24.3197	1.2797
4.5533	3.5992	26.1726	1.4407
6.8939	3.9980	27.9459	1.6000
9.2702	4.3993	29.6433	1.7593
11.6543	4.7981	31.2668	1.9203
14.0165	5.1994	32.8922	2.0797
16.3364	5.5982	34.5292	2.2407
18.6024	5.9995	36.1060	2.4000
20.8003	6.3983	37.6220	2.5593
22.9177	6.7970	39.0762	2.7203
24.9441	7.1984	40.4676	2.8797
26.9023	7.5971	41.8264	3.0407
28.8612	7.9985	43.2168	3.2000
30.7287	8.3972	44.5479	3.3593
32.5008	8.7986	45.8181	3.5203
34.1745	9.1973	47.0265	3.6797
35.7479	9.5987	48.1718	3.8407
37.2200	9.9974	49.2531	4.0000
38.4530	10.3962	50.3451	4.1593
39.5674	10.7975	51.3729	4.3203
40.5636	11.1963	52.3351	4.4797
41.4432	11.5976	53.2313	4.6407
42.2086	11.9964	54.0602	4.8000
42.8627	12.3977	54.8214	4.9593
43.4439	12.7965	55.4811	5.1203
43.9342	13.1978	56.0586	5.2797
44.3269	13.5966	56.5637	5.4407
44.6272	13.9954	56.9965	5.6000

Table 11. Stress Intensity Factor (K_I) Vs. Depth Tables (due to Sz Hoop Stress) for the Outer and Middle Closure-Lids of Waste Package Outer Barrier (Continued)

Outer Closure Lid		Middle Closure Lid	
K_I (MPa•m^{½})[a]	Depth (mm)[b]	K_I (MPa•m^{½})[c]	Depth (mm)[d]
44.8409	14.3967	57.3567	5.7593
44.9743	14.7955	57.6444	5.9203
45.0329	15.1968	57.7587	6.0797
45.0208	15.5956	57.6946	6.2407
44.9464	15.9969	57.5522	6.4000
44.8182	16.3957	57.3322	6.5593
44.6449	16.7945	57.0353	6.7203
44.4361	17.1958	56.6626	6.8797
44.2112	17.5946	56.1419	7.0407
43.9968	17.9959	55.3276	7.2000
43.7750	18.3947	54.4422	7.3593
43.5578	18.7960	53.4878	7.5203
43.3569	19.1948	54.6294	7.6797
43.1853	19.5961	56.2191	7.8407
43.0560	19.9949	57.7865	8.0000

Source: [a] BSC 2004 [DIRS 169985], Table 8-3, Column 5 labeled SIF due to Sz MPa-m$^{0.5}$; DTN: LL030607012251.065 [DIRS 163968].
[b] BSC 2004 [DIRS 169985], Table 8-3, Column 1; DTN: LL030607012251.065 [DIRS 163968].
[c] BSC 2004 [DIRS 169985], Table 8-2, Column 5 labeled SIF due to Sz MPa-m$^{0.5}$.
[d] BSC 2004 [DIRS 169985], Table 8-2, Column 1; DTN: LL030607012251.065 [DIRS 163968].

The variation in the stress profile with depth is due to variability. The provided hoop stress state was determined to vary with angle (θ) around the circumference of the Alloy 22 waste package outer and middle closure-lid welds ($\theta = 0$ point arbitrarily chosen) according to the following functional form (BSC 2004 [DIRS 169985], Table 8-1; DTN: LL030607012251.065 [DIRS 163968]):

$$\sigma(x,\theta) = \sigma(x,0) - (17.236893) \times (1 - \cos(\theta)) \quad \text{(Eq. 4)}$$

Note that $\sigma(x, 0)$ (defined in Equation 3) uses the stress coefficients (A_i) defined in Table 10 with x (in mm). Based on the angular stress variation in Equation 4, the stress intensity factor variation with angle is given by (BSC 2004 [DIRS 169985], Table 8-1; DTN: LL030607012251.065 [DIRS 163968]):

$$K_I(x,\theta) = K_I(x) \times \left(\frac{\sigma(Thck,\theta)}{\sigma(Thck,0)} \right) \quad \text{(Eq. 5)}$$

where $Thck$ is the lid thickness and $K_I(x)$ is given by the values in Table 11. The variation of the stress and stress intensity factor profiles with angle is due to variability (BSC 2004 [DIRS 169985], Section 6.4.5).

The uncertainty in the stress and stress intensity factor profiles is introduced through a scaling factor, z. The scaling factor, z, which is sampled from a normal distribution with a mean of zero and a standard deviation of 5 percent of the yield strength, YS, with an upper-bound of 15 percent of the YS and a lower-bound of –15 percent of the YS (BSC 2004 [DIRS 169985], Table 8-1).

The stress relation, accounting for uncertainty, is given by:

$$\sigma_u(x,\theta,z) = \sigma(x,\theta) \times \left(\frac{\sigma(Thck,\theta) + z}{\sigma(Thck,\theta)} \right) \quad \text{(Eq. 6)}$$

and the stress intensity factor relation is given by:

$$K_{Iu}(x,\theta,z) = K_I(x,\theta) \times \left(\frac{\sigma(Thck,\theta) + z}{\sigma(Thck,\theta)} \right) = K_I(x,0) \times \left(\frac{\sigma(Thck,\theta) + z}{\sigma(Thck,0)} \right) \quad \text{(Eq. 7)}$$

The inputs discussed in this section is appropriate for their intended use because they were developed for this purpose and provide a reasonable estimate of the stress and stress intensity factor profiles for the outer and middle closure lids of waste package outer barrier.

The uncertainty treatment of these inputs is encompassed in the parameter, z, sampled once per realization of the integrated waste package degradation analysis for each closure lid (i.e., a different value of z is sampled for each lid in a given realization).

The stress and stress intensity factor profiles for the waste package outer barrier closure lids are technical product output obtained from controlled and confirmed sources.

4.1.6 Slip Dissolution Inputs

The slip dissolution model for stress corrosion cracking uses a threshold stress, a threshold stress intensity factor, an incipient crack size, and crack growth rate parameters (functions of n, the repassivation slope). These inputs and their sources are listed in Table 12.

Table 12. Slip Dissolution Inputs Used in the IWPD Analysis and Their Sources

Input Name	Input Value	Units
Threshold stress	0.9 × YS at 473 K [a]	MPa
Incipient crack size	0.05 [a]	mm
Fraction of embedded weld flaws to propagate	0.25 [a]	N/A
Threshold stress intensity factor, K_{ISCC}	Equation 8 [a]	MPa $m^{1/2}$
Repassivation slope, *n*	Truncated normal (at ±2 sd) with a mean of 1.304 and sd of 0.16 [a]	N/A
Distance between through-wall cracks	"the plate thickness"[b]	mm

Source: [a] BSC 2004 [DIRS 169985], Table 8-1 DTN: LL030607012251.065 [DIRS 163968].
[b] BSC 2004 [DIRS 169985], Section 6.5.1.

The threshold stress is defined as the minimum stress at which cracks initiate on a "smooth" surface. This report refers to these as incipient cracks (to distinguish them from weld flaws), which typically form at local surface defects, such as grain boundary junctions and surface roughness. Incipient cracks are 0.05 mm long (BSC 2004 [DIRS 169985], Table 8-1).

Weld flaws are already nucleated and, thus, do not require a stress threshold to nucleate. However, most weld flaws are embedded within the material and, therefore, not exposed to the environment. As general corrosion proceeds, some initially embedded weld flaws will be exposed to the environment (BSC 2004 [DIRS 169985], Section 6.2.2) while others are "corroded away." This evolution of the number of defects is not considered in detail. A conservative approach is used (BSC 2004 [DIRS 169985], Section 6.2.2), in which the fraction of weld flaws embedded within the outer one fourth of the weld thickness are sites for crack propagation by the slip-dissolution mechanism.

If the stress intensity factor at the crack tip is below the threshold stress intensity factor, no crack growth will occur. The threshold stress intensity factor, K_{ISCC}, is given as a function of the repassivation slope, *n* and V_{gc} (which equals 7.23 nm/yr and is expressed in units of mm/sec for use in Equation 8) (BSC 2004 [DIRS 169985], Table 8-1):

$$K_{ISCC} = \left(\frac{V_{gc}}{\bar{A}} \right)^{1/\bar{n}} \quad \text{(Eq. 8)}$$

$\bar{A}$ and $\bar{n}$ are functions of *n*, as discussed below. The threshold stress intensity factor is applied to both incipient cracks and weld flaws. The variations in the threshold stress and stress intensity factor distributions are entirely due to uncertainty. The thresholds are sampled once per realization of the IWPD analysis (i.e., the same value of these thresholds is used for each lid in a given realization).

Once crack growth initiates, the crack(s) grow at a velocity given by (BSC 2004 [DIRS 169985], Table 8-1) (DTN: LL030607012251.065 [DIRS 163968]):

$$V_t = \overline{A}\left(K_I\right)^{\overline{n}} \quad \text{(Eq. 9)}$$

where V_t is the crack growth rate in mm/sec, and K_I is the stress intensity factor in MPa(m)$^{1/2}$. Parameters, $\overline{A}$ and $\overline{n}$, in the above equation are expressed in terms of the repassivation slope, *n*, as follows:

$$\overline{A} = 7.8 \times 10^{-2} n^{3.6} \left(4.1 \times 10^{-14}\right)^{n} \quad \text{(Eq. 10)}$$

$$\overline{n} = 4n \quad \text{(Eq. 11)}$$

In the IWPD analysis, the parameter *n* is represented by a truncated normal distribution (at ±2 sd) with a mean of 1.304, and an sd of 0.16. The variation in the repassivation slope, *n*, is entirely due to uncertainty. The repassivation slope is sampled once per realization of the IWPD analysis (i.e., the same value of *n* is used for each lid in a given realization).

Analyses presented in *Stress Corrosion Cracking of the Drip Shield, the Waste Package Outer Barrier, and the Stainless Steel Structural Material* (BSC 2004 [DIRS 169985], Section 6.5.1), indicate that the distance between two neighboring cracks must be greater than the plate thickness for the stress (and stress intensity factor) profile to be of sufficient magnitude to propagate a crack through-wall. This information is used in Section 6.3.2.1 to determine the crack density used in the IWPD analysis.

The inputs discussed in this section are appropriate for their intended use because they were developed for this purpose and provide reasonable estimates of the stress corrosion crack growth characteristics for the outer and middle closure lids of the Alloy 22 waste package outer barrier. The slip dissolution parameters for the waste package outer barrier closure lids are technical product output information obtained from controlled and confirmed sources.

4.1.7 Waste Package Outer Barrier Microbially Influenced Corrosion Inputs

The treatment of microbially influenced corrosion (MIC) of the Alloy 22 waste package outer barrier requires a threshold relative humidity (RH) for microbial activity and a general corrosion rate multiplier representing the effect of microbial activity. These inputs and their sources are listed in Table 13.

Table 13. Waste Package Outer Barrier Microbially Influenced Corrosion Inputs and Their Sources

Input Name	Input Source	Input Value	Units
MIC Threshold RH	BSC 2004 [DIRS 169984], Section 6.4.5 DTN: MO0409MWDUGCMW.000 [DIRS 171714]	0.9	fraction
General Corrosion Rate MIC Enhancement Factor	BSC 2004 [DIRS 169984], Section 6.4.5 DTN: MO0409MWDUGCMW.000 [DIRS 171714]	Uniform over the range (1, 2)	N/A

According to *General Corrosion and Localized Corrosion of Waste Package Outer Barrier* (BSC 2004 [DIRS 169984], Section 6.4.5; DTN: MO0409MWDUGCMW.000 [DIRS 171714]), general corrosion rates should be enhanced due to the effect of MIC when the relative humidity exceeds 90 percent. The value for the threshold RH above which MIC takes place is fixed (i.e., no uncertainty or variability).

The general corrosion rate of the waste package outer barrier is enhanced due to MIC by a factor between 1 and 2 (i.e., no enhancement up to the general corrosion rate being doubled) (BSC 2004 [DIRS 169984], Section 6.4.5; DTN: MO0409MWDUGCMW.000 [DIRS 171714]). Thus, the general corrosion rate enhancement factor is sampled from a uniform distribution with an upper-bound of 2 and a lower-bound of 1. The general corrosion rate enhancement factor is applied to the entire waste package surface (BSC 2004 [DIRS 169984], Section 6.4.5; DTN: MO0409MWDUGCMW.000 [DIRS 171714]). The variation in the general corrosion rate MIC enhancement factor is entirely due to uncertainty (BSC 2004 [DIRS 169984], Section 6.4.5).

The parameters discussed in this section are appropriate for their intended use because they were developed for this purpose and provide a reasonable estimate of the affects of microbial action on the waste package outer barrier. The parameters are technical product output obtained from controlled and confirmed sources.

4.1.8 Waste Package Early Failure Analysis Inputs

Several mechanisms that could result in early failure of the waste package were considered in *Analysis of Mechanisms for Early Waste Package/Drip Shield Failure* (BSC 2004 [DIRS 170024]). It was determined that improper heat treatment, improper stress mitigation, and mishandling of the waste package could have adverse consequences on waste package performance (BSC 2004 [DIRS 170024], Section 6.4.8). The probabilities of occurrence for these three mechanisms were combined to yield an overall probability of waste package early failure. The number of waste packages affected per realization is given by a Poisson distribution with an uncertain intensity. These values and their sources are summarized in Table 14.

Table 14. Waste Package Early Failure Inputs and Their Sources

Input Name	Input Source	Input Value	Units
Evaluation Probability per WP (Uncertain Poisson Intensity)	BSC 2004 [DIRS 170024], Section 7, Table 22	Log normal distribution with a median of 7.2×10^{-6} and an error factor of 15, truncated at an upper value of 7.44213×10^{-3}	per waste package
Number of Early Failed WP per Realization	BSC 2004 [DIRS 170024], Section 7, Table 22	Poisson Distribution with intensity given above multiplied by number of waste packages considered.	number of waste packages per realization

The “Evaluation Probability per WP” distribution is sampled once per realization (i.e., it is an uncertainty distribution). The sampled value is then multiplied by the number of waste packages per realization to give the intensity for the Poisson distribution for the number of early failed waste packages per realization. The Poisson distribution is sampled once per realization to give the number of affected waste packages in the realization. In this representation, variation in the number of early failed waste packages is expressed as variability deriving from a discrete Poisson distribution with an uncertain intensity parameter. The uncertain intensity parameter is the product of the uncertain rate of waste package failures (log normally distributed) and the number of waste packages in a realization. Also, see Section 6.3.8 for further discussion of early failure and Section 6.4.12 for discussion of implementation (including a discussion of a marginal distribution that incorporates uncertainty).

The following recommendations are made in *Analysis of Mechanisms for Early Waste Package/Drip Shield Failure* (BSC 2004 [DIRS 170024], Section 6.4.8) for evaluating the consequences of early failure of the Alloy 22 waste package outer barrier:

- A failure of the waste package outer barrier shell and outer and middle closure lids should be assumed
- The affected waste packages should be assumed to fail immediately upon initiation of degradation processes
- The entire waste package surface area should be considered affected by improper heat treatment
- The materials of the entire affected area should be assumed lost upon failure of the waste packages because the affected area will be subjected to stress corrosion cracking and highly enhanced localized and general corrosion.

The inputs are technical product output information obtained from controlled and confirmed sources.

4.2 CRITERIA

The technical work plan for this activity (BSC 2004 [DIRS 171583], Table 3-1) has identified the following acceptance criteria (AC) based on the requirements mentioned in *Project Requirements Document* (PRD) (Canori and Leitner 2003 [DIRS 166275]) and *Yucca Mountain Review Plan, Final Report* (NRC 2003 [DIRS 163274]):

1. System Description and Demonstration of Multiple Barriers (NRC 2003 [DIRS 163274], Section 2.2.1.1.3; Canori and Leitner 2003 [DIRS 166275], PRD-002/T-014, PRD-002/T-016)

   Specific requirements involve identification of multiple barriers (natural and engineered), describing the capabilities of these barriers to isolate waste, and providing technical bases for capabilities descriptions consistent with the postclosure performance objectives. To comply with these requirements, the following acceptance criteria are identified in the technical work plan (BSC 2004 [DIRS 171583], Table 3-1):

   - AC1: Identification of Barriers is Adequate
   - AC2: Description of Barrier Capability to Isolate Waste is Acceptable

- AC3: Technical Basis for Barrier Capability is Adequately Presented.

2. Degradation of Engineered Barriers (NRC 2003 [DIRS 163274], Section 2.2.1.3.1.3; Canori and Leitner 2003 [DIRS 166275], PRD-002/T-015)

   Specific requirements include describing deterioration or degradation of engineered barriers and modeling degradation processes using data for performance assessment, including total system performance assessment (TSPA). Consideration of uncertainties and variabilities in model parameters and alternative conceptual models are also required. To fulfill these requirements, the following acceptance criteria are identified in the technical work plan (BSC 2004 [DIRS 171583], Table 3-1):

   - AC1: System Description and Model Integration are Adequate
   - AC2: Data are Sufficient for Model Justification
   - AC3: Data Uncertainty is Characterized and Propagated Through the Model Abstraction
   - AC4: Model Uncertainty is Characterized and Propagated Through the Model Abstraction
   - AC5: Model Abstraction Output is Supported by Objective Comparisons.

The Yucca Mountain Review Plan Criteria are addressed in Section 7.3.

4.3 CODES AND STANDARDS

The process of implementing these models is consistent with the methodology described in the ASTM Standard Practice C-1174 for prediction of the long-term behavior of EBS components in a geologic repository (ASTM C 1174-97 [DIRS 105725]).

5. ASSUMPTIONS

None of the following assumptions requires any further confirmation in addition to the rationale provided below prior to the use of the parameters developed in this document.

5.1 RELATIVE HUMIDITY THRESHOLD

Assumption: It is conservatively assumed that no relative humidity threshold for the initiation of corrosion processes exists (e.g., corrosion is allowed to occur at any exposure relative humidity).

Rationale: The relative humidity threshold is the relative humidity below which water will not form on a clean metal surface and electrochemical processes will not occur (ASM International 1987 [DIRS 133378], p. 82). For clean metal surfaces, the relative humidity must exceed about 60 percent before a thin film of moisture will form on the metal surface, providing an electrolyte for ionic current transfer (ASM International 1987 [DIRS 133378], p. 82). Cleanliness, corrosion product build-up, and hygroscopic salts or contaminants can cause water absorption at lower relative humidities (ASM International 1987 [DIRS 133378], p. 80). *General Corrosion and Localized Corrosion of Waste Package Outer Barrier* (BSC 2004 [DIRS 169984], Assumption 5.1) and *General Corrosion and Localized Corrosion of the Drip Shield* (BSC 2004 [DIRS 169845], Section 5.2) assume the existence of a relative humidity threshold for the initiation of corrosion processes. The assumption that no relative humidity threshold for the initiation of corrosion processes exists is conservative because use of a relative humidity threshold would delay the corrosion initiation start time.

Confirmation Status: This assumption is appropriate for its intended use and is conservative. On this basis, this assumption requires no further confirmation.

Use in Analysis: This assumption is used throughout this report.

5.2 CORROSION BEHAVIOR OF THE WELD REGIONS

Assumption: The general corrosion and localized corrosion behavior of the weld metal does not significantly differ from the general corrosion and localized corrosion behavior of the Alloy 22 base material.

Rationale: This assumption is consistent with *Waste Package Operations Fabrication Process Report* (Plinski 2001 [DIRS 156800], Section 6.3), which states, “Filler metal material shall be selected to be compatible with the base material.” This assumption is also consistent with analyses in *General Corrosion and Localized Corrosion of Waste Package Outer Barrier* (BSC 2004 [DIRS 169984], Sections 6.4.3 and 6.4.4) in which it was found that welded regions had similar general and localized corrosion behavior as the base metal.

Confirmation Status: This assumption is consistent with the current state of knowledge and is appropriate for its intended use; therefore, no further confirmation is required.

Use in Analysis: This assumption is used throughout this document in the integrated waste package degradation analysis using parameters appropriate for Alloy 22 in the weld regions.

5.3 CORROSION BEHAVIOR OF THE OUTER LID CLOSURE WELD REGION

Assumption: The corrosion behavior of the stress-mitigated (laser-peened) outer lid closure weld region does not significantly differ from the corrosion behavior of a closure lid weld region that has not undergone stress mitigation.

Rationale: Laser peening involves the use of a laser pulse that induces a shock wave within the material being peened resulting in the formation of a compressive surface layer. Laser peening causes less surface damage than conventional shot peening (Chen et al. 2002 [DIRS 165441]) particularly because in laser peening no physical contact is made with the part to be peened. Comparisons of the corrosion rates (measured by the polarization resistance technique in simulated acidified water at 90°C and potentiodynamic polarization curves) of unmitigated and laser-peened Alloy 22 samples have shown that laser peened samples exhibited lower corrosion rates than unmitigated samples (Chen et al. 2002 [DIRS 165441], Figure 9). In addition, laser-peened samples exhibited lower passive current densities (in potentiodynamic polarization tests) than unmitigated samples (Chen et al. 2002 [DIRS 165441], Figure 10). The potentiodynamic polarization curves did not show the initiation of localized corrosion before the transpassive potential was reached. Conservatively, no credit is taken in this report for the increased resistance to corrosion processes imparted by the laser peening process. This assumption is consistent with assumptions made in *General Corrosion and Localized Corrosion of Waste Package Outer Barrier* (BSC 2004 [DIRS 169984], Assumption 5.6).

Confirmation Status: This is a conservative assumption and does not require further confirmation.

Use in Analysis: This assumption is used throughout this report.

6. SCIENTIFIC ANALYSIS DISCUSSION

This section provides analysis objectives for the waste package and drip shield degradation in the integrated waste package degradation (IWPD) analysis. The implementation of the models and analyses for the degradation processes considered are described. The IWPD analysis results are discussed in terms of a set of profiles for waste package and drip shield failure and average number of penetrations as a function of time. The results of all analyses documented in this report are tracked by output DTN: MO0310MWDWAPAN.002.

The IWPD analysis itself (Section 6.4), not the resultant curves from the IWPD analysis presented in Section 6.5 (which are for illustrative purposes), is used directly in total system performance assessment (TSPA). The IWPD analysis simulates general corrosion and stress corrosion cracking of the waste package outer barrier and general corrosion of the drip shield. Analysis of localized corrosion is not included in the IWPD analysis. The outputs of this report are inputs and methodologies used by TSPA to evaluate waste package and drip shield degradation as a function of exposure time under exposure conditions anticipated in the repository.

6.1 ANALYSIS OBJECTIVES

The License Application (LA) waste package design consists of two layers: an Alloy 22 outer barrier and a Stainless Steel Type 316 inner vessel (BSC 2003 [DIRS 165406]). A drip shield with Titanium Grade 7 water diversion plates will be placed over the waste package (BSC 2004 [DIRS 168489]). The space between the drip shield and the emplacement drift is open for air circulation and there is no backfill material used. Although the stainless steel inner vessel provides structural stability to the Alloy 22 outer barrier, no other performance credit is taken for the waste package inner vessel. The waste package outer barrier has two Alloy 22 closure lids (referred to as the waste package outer barrier outer and middle closure lids). The Stainless Steel Type 316 waste package inner vessel has one Stainless Steel Type 316 closure lid (referred to as the waste package inner vessel closure lid). The waste package outer barrier closure lids are welded to the waste package outer barrier and the waste package inner vessel closure lid is welded to the waste package inner vessel after the waste form (spent nuclear fuel or high-level waste glass, or both) is loaded.

The drip shield and waste package are subject to various degradation processes including general corrosion and stress corrosion cracking. The Integrated Waste Package Degradation (IWPD) analysis developed in this technical product is used directly in total system performance assessment (TSPA) analysis to evaluate degradation of the drip shields and waste packages with time. In addition to the drip shield and waste package design inputs discussed above, the primary inputs to the IWPD analysis are documented in the reports summarized below:

- *General Corrosion and Localized Corrosion of the Drip Shield* (BSC 2004 [DIRS 169845])
  - General corrosion inputs for the Titanium Grade 7 drip shield (Section 4.1.2). The general corrosion treatment for the Titanium Grade 7 drip shield includes an uncertain distribution of general corrosion rates.

- *General Corrosion and Localized Corrosion of Waste Package Outer Barrier* (BSC 2004 [DIRS 169984])
  - General corrosion inputs for the Alloy 22 waste package outer barrier (Section 4.1.3). The general corrosion treatment for the Alloy 22 waste package outer barrier includes a variability distribution of general corrosion rates applicable at 60°C and an uncertain distribution for an Arrhenius-type temperature dependence.
  - An uncertain distribution for a general corrosion rate multiplier to represent the effect of MIC on general corrosion (Section 4.1.7).
- *Stress Corrosion Cracking of the Drip Shield, the Waste Package Outer Barrier, and the Stainless Steel Structural Material* (BSC 2004 [DIRS 169985])
  - Stress and stress intensity factor profiles for the closure weld regions of the Alloy 22 waste package outer barrier (Section 4.1.5). These inputs include an angular variability treatment and an uncertainty treatment.
  - Slip dissolution inputs such as stress and stress intensity factor thresholds for the closure weld regions of the Alloy 22 waste package outer barrier and stress corrosion crack growth velocity inputs (Section 4.1.6). These inputs are 100 percent uncertain.
  - An assessment of the area of the Alloy 22 waste package outer barrier subject to stress corrosion cracking. This input is neither uncertain nor variable.
- *Analysis of Mechanisms for Early Waste Package/Drip Shield Failure* (BSC 2004 [DIRS 170024])
  - Inputs for the number and size of weld flaws (Section 4.1.4)
  - Inputs for the mechanisms of early failure and their consequences (Section 4.1.8).

The IWPD analysis uses a stochastic simulation approach and provides a description of the variation of waste package and drip shield degradation as a function of time for specific design and thermal-hydrologic exposure conditions. The objectives of the IWPD analysis are:

- To provide a representation of waste package degradation processes in the repository;
- To capture the effects of uncertainty and variability both in exposure conditions and degradation processes over a geologic time scale.

The TSPA-LA waste package degradation analysis simulates the behavior of a few hundred waste packages (Section 6.4). Effects of spatial and temporal variations in the exposure conditions over the repository are simulated by explicitly incorporating exposure condition histories into the analysis (representative thermal hydrologic histories are used in the present analysis (Section 6.4.5), but repository-relevant thermal hydrologic histories are used in TSPA). In addition, potentially variable corrosion processes within a single waste package are represented by dividing the waste package surface into subareas called "patches" and stochastically sampling the degradation parameter values for each patch. The use of patches explicitly represents the variability in degradation processes within a single waste package at a given time.

In the TSPA-LA, uncertainty in waste package degradation is analyzed with multiple realizations of the IWPD analysis. For each realization, values are sampled for the uncertain degradation parameters and passed to the IWPD analysis. Each realization is a complete IWPD analysis simulation of a given number of waste packages explicitly considering variability in the degradation processes. Accordingly, each of the IWPD analysis outputs (i.e., the fraction of the total number of waste packages and drip shields failed versus time and of the average number of patch and crack penetrations per failed waste package (or drip shield)) are reported as a group of "degradation profile curves" (resulting from the multiple realizations) representing the potential range of the output parameters. For example, the waste package failure time profiles are reported with a group of curves representing the cumulative probability of waste package failures as a function of time. The outputs of this report are inputs and methodologies, which are used by TSPA to evaluate waste package and drip shield degradation as a function of exposure time under exposure conditions anticipated in the repository.

6.1.1 Alternative Scientific Approaches and Computational Methods Considered

The integrated waste package degradation (IWPD) analysis documented in this report uses the WAPDEG software (BSC 2002 [DIRS 161240]). The WAPDEG software (BSC 2002 [DIRS 161240]) was developed specifically for the purpose of implementing the scientific approaches and computational methods specified in documents supporting this analysis (BSC 2004 [DIRS 169845]; BSC 2004 [DIRS 169984]; BSC 2004 [DIRS 169985]; BSC 2004 [DIRS 170024]). This scientific approaches or technical methods, or both, as well as computational methods to be used are specified in documents supporting this analysis (BSC 2004 [DIRS 169845]; BSC 2004 [DIRS 169984]; BSC 2004 [DIRS 169985]; BSC 2004 [DIRS 170024]) and justification would be required in order to deviate from these specifications. Alternative conceptual models (i.e., alternative scientific approaches or technical methods, or both) and computational methods were considered, as appropriate, during the development of the documents supporting this analysis. The reader is referred to those documents for further details on the alternative scientific approaches or technical methods considered that were not used and the rationale for not selecting them (BSC 2004 [DIRS 169845]; BSC 2004 [DIRS 169984]; BSC 2004 [DIRS 169985]; BSC 2004 [DIRS 170024]).

Other software or computational methods similar to those used exist. For example, the Electric Power Research Institute (EPRI) has used its Integrated Multiple Assumptions and Release Code (IMARC) model to evaluate repository performance (EPRI 2002 [DIRS 158069]). Also, the Nuclear Regulatory Commission (NRC) has used its Total-system Performance Assessment (TPA) code to evaluate repository performance (Codell et al. 2001 [DIRS 164795]). The EPRI IMARC uses a logic tree methodology and should be used as a high-level analysis tool rather than a performance assessment code that can be used to incorporate uncertainties in all phases of the analysis (EPRI 2002 [DIRS 158069], Section 9.1). For this reason, the EPRI IMARC was not selected for use in this analysis. The NRC TPA code evaluates the performance of a prototypical waste package for each repository subarea (Codell et al. 2001 [DIRS 164795], Section 2.2.3). The NRC TPA code assumes that when this prototypical waste package fails, all waste packages in the repository subarea are failed (Codell et al. 2001 [DIRS 164795], Section 2.2.3). In this respect, the NRC TPA code is not as sophisticated as the WAPDEG code which can simulate several waste packages, to represent variability, in each repository subarea (Section 6.1). For this reason, the NRC TPA code was not selected for use in this analysis. Also, neither the EPRI IMARC nor the NRC TPA code is readily available for use on the project. Furthermore, the WAPDEG software (BSC 2002 [DIRS 161240]) was developed specifically to implement the scientific approaches and computational methods used in evaluating drip shield and waste package performance for the project. On this basis, the WAPDEG software (BSC 2002 [DIRS 161240]) was selected for use in this analysis.

6.2 FEATURES, EVENTS, AND PROCESSES INCLUDED IN ANALYSIS

The development of a comprehensive list of features, events, and processes (FEPs) potentially relevant to postclosure performance of the Yucca Mountain repository is an ongoing, iterative process based on site-specific information, design, and regulations. To support TSPA-LA, the FEP list was re-evaluated in accordance with *The Enhanced Plan for Features, Events, and Processes (FEPs) at Yucca Mountain* (BSC 2002 [DIRS 158966], Section 3.2). Table 15 provides a list of FEPs included in this report and provides specific references to sections within this report where the FEPs are discussed. No FEPs are excluded by the analyses in this report. See also DTN: MO0407SEPFEPLA.000 [DIRS 170760] for a description of these FEPs and *FEPs Screening of Processes and Issues in Drip Shield and Waste Package Degradation* (BSC 2004 [DIRS 169997]) for a complete list of all FEPs related to waste package and drip shield degradation.

Table 15. Included FEPs

FEP No.	FEP Name	Section Where Disposition is Described
2.1.03.01.0A	General corrosion of waste packages	6.3.4 and 6.4.7; BSC 2004 [DIRS 169984]
2.1.03.01.0B	General corrosion of drip shields	6.3.3 and 6.4.6; BSC 2004 [DIRS 169845]
2.1.03.02.0A	Stress corrosion cracking (SCC) of waste packages	6.3.5 and 6.4.10; BSC 2004 [DIRS 169985]
2.1.03.05.0A	Microbially influenced corrosion (MIC) of waste packages	6.3.6 and 6.4.11; BSC 2004 [DIRS 169984]
2.1.03.08.0A	Early failure of waste packages	6.3.8 and 6.4.12; BSC 2004 [DIRS 170024]
2.1.03.11.0A	Physical form of waste package and drip shield	6.3.2

6.3 DESCRIPTION OF INTEGRATED WASTE PACKAGE DEGRADATION ANALYSIS

The License Application (LA) waste package design consists of two layers: an Alloy 22 waste package outer barrier and a Stainless Steel Type 316 waste package inner vessel (BSC 2003 [DIRS 165406]). The highly corrosion-resistant Alloy 22 waste package outer barrier is responsible for the long waste package lifetime. In this report, the only performance credit taken for the Stainless Steel Type 316 inner vessel is for the structural support it provides to the waste package outer barrier before waste package breach. Although the waste package inner vessel would also provide some performance for waste containment and potentially act as a barrier to radionuclide transport after waste package outer barrier breach, the potential performance of this barrier is far less than that of the more corrosion resistant Alloy 22 waste package outer barrier. For this reason, the corrosion performance of the waste package inner vessel is conservatively ignored in this report. The waste package outer barrier has two Alloy 22 closure lids. The waste package closure lids are welded to the waste package outer barrier after the waste form (spent nuclear fuel or high-level waste glass, or both) is loaded. A drip shield with Titanium Grade 7 water diversion plates will be placed over the waste package (BSC 2004 [DIRS 168489]). The space between the drip shield and the emplacement drift is open for air circulation and there is no backfill material used.

Over the emplacement period, the drip shield and waste package are potentially subject to various degradation processes including general corrosion and stress corrosion cracking. The IWPD analysis itself (Section 6.4), not the resultant curves from the IWPD analysis presented in Section 6.5 (which are for illustrative purposes), is used directly in total system performance assessment (TSPA). The outputs of this report are inputs and methodologies used by TSPA to evaluate waste package and drip shield degradation as a function of exposure time under exposure conditions anticipated in the repository.

The IWPD analysis makes use of the WAPDEG software. In WAPDEG, corrosion functional forms and events are specified to apply to specific “water conditions” (BSC 2002 [DIRS 162606], Section 3.2.3). For example, in WAPDEG, a general or localized corrosion functional form is specified to apply to a specific barrier and water condition. Events, such as stress corrosion cracking or microbially influenced corrosion, apply to a specific barrier; however, they may apply to multiple water conditions. Using this input design, the effects of an event can be identical under different water conditions. In the implementation discussed in this report, the water condition on the outside of the drip shield differs from that on the underside of the drip shield and the waste package surface before drip shield failure. Upon drip shield failure, the waste package is exposed to the water condition previously on the outside surface of the drip shield and the waste package general corrosion functional form appropriate for the new water condition is applied.

6.3.1 Drip Shield Design

The only drip shield degradation process in the Integrated Waste Package Degradation (IWPD) analysis is general corrosion (Section 6.3.3). General corrosion is analyzed separately for the drip shield outer and inner surfaces. The drip shield outer surface uses a different general corrosion rate (Section 6.3.3) than the drip shield inner surface. As will be discussed in Section 6.3.3, the variation in the general corrosion rate of the drip shield is considered to be only due to uncertainty (i.e., there is no variability in the general corrosion rate on the inner and outer surfaces of the drip shield). For these reasons, unlike the waste packages, each drip shield is analyzed as a single entity. The waste package surface is analyzed as being composed of several subareas referred to as patches (Section 6.3.2) in order to represent spatial variation in degradation processes on the waste package surfaces.

The drip shield plate thickness (Table 3) is used directly in the input to WAPDEG (Section 6.4.6). WAPDEG does not require the drip shield surface area; it is only necessary that the number of drip shield patches (i.e., one) be specified.

6.3.2 Waste Package Design

In the Integrated Waste Package Degradation (IWPD) analysis, the waste package surface is divided into subareas referred to as patches (Figure 1), which are used to simulate variability across the barrier surfaces. It is at the patch-level that the degradation modes are applied (e.g., each patch might have a different general corrosion rate, crack growth threshold, etc.). The IWPD analysis outputs the fraction of drip shield and waste package failures versus time and the average (per failed drip shield or waste package) number of pit, crack, and patch penetrations for each drip shield or waste package, or both versus time.

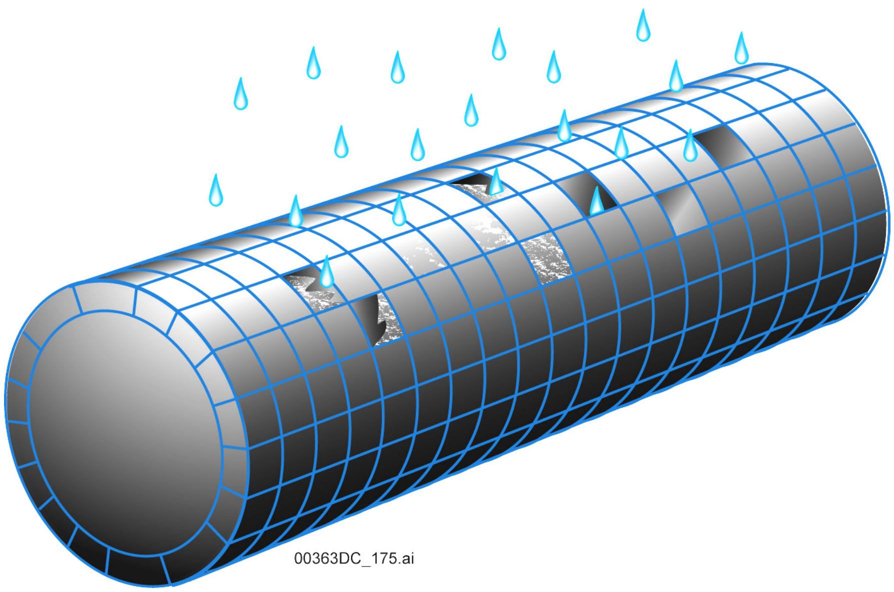


Figure 1. Schematic Representation of Waste Package Patches

As discussed in Section 4.1.1, two nominal waste package configurations are analyzed in this report. This treatment is consistent with the approach used in the TSPA-SR Model (CRWMS M&O 2000 [DIRS 153246], Table 4.1-1). The first waste package configuration is referred to as the commercial spent nuclear fuel (CSNF) waste package configuration (CRWMS M&O 2000 [DIRS 153246], Table 4.1-1) for which the 21-PWR waste package configuration parameters are used (BSC 2001 [DIRS 157812]). The 21-PWR waste package configuration is an appropriate representation of the CSNF waste package configuration since the 21-PWR waste package configuration is the most common waste package configuration in the repository (BSC 2003 [DIRS 163855], Table 11). Using the waste package configuration parameters listed in Table 3, the CSNF waste package configuration surface area is

$$\text{CSNF WP Surface Area} = \pi \cdot (1{,}564\,\text{mm}) \times (4{,}775\,\text{mm}) = 2.346 \times 10^{7}\ \text{mm}^2 \qquad \text{(Eq. 12)}$$

Note that the surface area of the closure lids was not considered. Because the CSNF waste package surface area is primarily used to determine the fraction of waste package surface area subjected to stress corrosion cracking (later in this section), it is conservative and appropriate to ignore the closure lid surface area in determining the total waste package surface area.

The second waste package configuration analyzed is the codisposal (CDSP) waste package configuration (CRWMS M&O 2000 [DIRS 153246], Table 4.1-1) whose length is considered to be the average length of the 5 HLW/1 DOE SNF long (BSC 2001 [DIRS 157818]) and short (BSC 2001 [DIRS 157817]) waste package configurations (which have roughly equal populations in the inventory). The 5 HLW/1 DOE SNF (codisposal) long and short waste package configurations are appropriate representations of the CDSP waste package configuration since these are the most common high-level waste (HLW) waste package configurations in the repository (BSC 2003 [DIRS 163855], Table 11). Again using the waste package configuration parameters listed in Table 3, the CDSP waste package surface area is:

$$\text{CDSP WP Surface Area} = \pi \cdot (2{,}030\,\text{mm}) \times \left(\frac{(3{,}200 + 4{,}827)}{2}\,\text{mm} \right) = 2.560 \times 10^{7}\ \text{mm}^{2} \quad \text{(Eq. 13)}$$

The 5 HLW/1 DOE SNF long (BSC 2001 [DIRS 157818]) and short (BSC 2001 [DIRS 157817]) waste package configurations both have the same waste package outer barrier outer diameter (2,030 mm) as shown in Table 3.

The general corrosion model used for the waste package is based on weight-loss measurements for samples exposed in the LTCTF (BSC 2004 [DIRS 169984], Section 6.4.3). For the waste package outer barrier, samples with the crevice geometry were used to generate the general corrosion rate distribution (applied at 60°C). The crevice geometry samples have nominal dimensions of 2 in. × 2 in. × 1/8 in. and a 0.312-in. diameter hole in the center for sample mounting (BSC 2004 [DIRS 169984], Section 6.4.3). Therefore, the exposed surface area, A, for a crevice geometry sample is calculated as follows:

$$A = 2ab + 2bc + 2ac - \left(\frac{\pi d^{2}}{2} \right) + \pi dc \quad \text{(Eq. 14)}$$

where a is the length of the specimen, b is the width of the specimen, c is the thickness of the specimen, and d is diameter of hole. Using the above-mentioned dimensions, the exposed surface area for a crevice sample (converted to mm^2) is 5,787 mm^2. The IWPD analysis uses a patch size of about four (4) times this area (23,150 mm^2). Therefore, the CSNF waste packages are composed of 1,014 patches and the CDSP waste packages composed of 1,106 patches. In Section 6.3.4, the general corrosion rate distribution applied to the waste package outer barrier is modified to reflect this change in scale between the smaller crevice geometry sample size and the patch size.

Effectively, the waste package outer barrier is composed of two different regions; the closure lid region and the shell region. The waste package outer barrier shell region thickness, 20 mm for the CSNF waste package configuration and 25 mm for the CDSP waste package configuration (Table 3), is used indirectly in the formulation of inputs to the WAPDEG software. CSNF and CDSP waste package configurations have similar closure-lid configurations. The waste package outer barrier outer closure lid thickness (and weld thickness) is 25 mm for CSNF and CDSP waste package configurations (Table 8). The waste package outer barrier middle closure lid thickness (and weld thickness) is 10 mm (Table 8). These thicknesses are used as direct inputs to WAPDEG. WAPDEG does not analyze the waste package outer barrier closure lid and the shell regions independently. Both waste package outer barrier regions are analyzed as being composed of two layers (Figure 2); the outer analyzed layer is 25 mm thick and the inner analyzed layer is 10 mm thick. Use of two layers is straightforward for analysis of the closure lid region of the waste package outer barrier. For the waste package outer barrier shell region, the general corrosion rate used for the analyzed outer layer is very large (~10^{10} mm/yr) effectively leading to instantaneous penetration. Therefore, the waste package outer barrier shell region of the analyzed outer layer does not contribute to waste package performance. The general corrosion rate used for the waste package outer barrier shell region of the analyzed inner layer of the CSNF waste package configuration is decreased by a factor of 20 mm/10 mm = 2 (i.e., multiplied by a factor of 0.5). In this way, the analyzed 10-mm inner layer for the waste package outer barrier shell region "behaves" (in the analysis) like a 20-mm layer. Similarly, the general corrosion rate used for the waste package outer barrier shell region of the analyzed inner layer of the CDSP waste package configuration is decreased by a factor of 25 mm/10 mm = 2.5 (i.e., multiplied by a factor of 0.4). In this way, the analyzed 10-mm inner layer behaves (in the analysis) like a 25-mm layer.

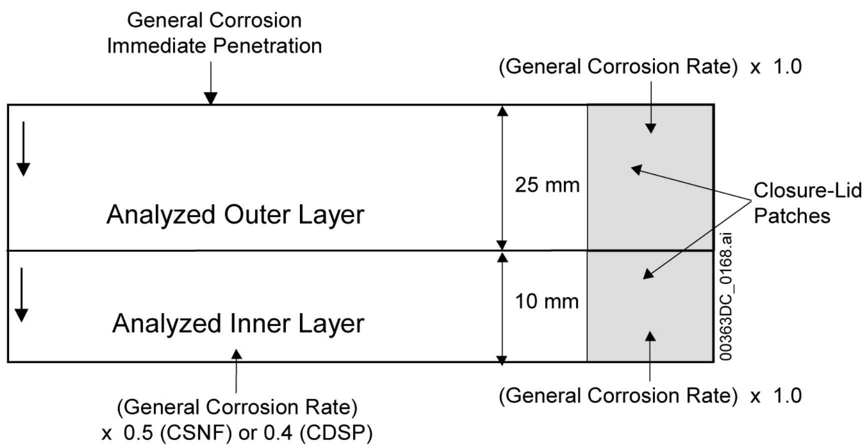


Figure 2. Schematic of Waste Package Configuration in IWPD Analysis to Implement Stress Corrosion Cracking of Dual Closure Lids of Waste Package Outer Barrier

6.3.2.1 Stress Corrosion Cracking Patches

The Integrated Waste Package Degradation (IWPD) analysis subjects a fraction of the waste package surface to stress corrosion cracking. This area fraction is the same as the fraction of the total surface area represented by the closure-lid patches identified in Figure 2 (the bulk of the closure lid is not analyzed, only the closure lid weld region). As mentioned above, the area of a waste package patch is 23,150 mm^2. Making the reasonable analysis assumption that the patches are square, the length of one side of a patch is about 152 mm.

The closure-lid weld region is represented as a cylinder, one-patch side wide and with the same radius as the waste package. This results in the fraction of area represented by the closure weld region for CSNF waste packages being:

$$\frac{\text{Closure–Lid Weld Region Area}}{\text{WP Surface Area}} = \frac{\pi\,(1{,}564\,\text{mm})(152\,\text{mm})}{2.346\times10^{7}\,\text{mm}^2} \approx 0.032 \qquad \text{(Eq. 15)}$$

or about 32 patches. For CDSP waste packages the fraction of area represented by the closure weld region is:

$$\frac{\text{Closure–Lid Weld Region Area}}{\text{WP Surface Area}} = \frac{\pi\,(2{,}030\ \text{mm})(152\ \text{mm})}{2.560 \times 10^{7}\ \text{mm}^{2}} \approx 0.038 \qquad \text{(Eq. 16)}$$

or about 42 patches.

Analyses presented in *Stress Corrosion Cracking of the Drip Shield, the Waste Package Outer Barrier, and the Stainless Steel Structural Material* (BSC 2004 [DIRS 169985], Section 6.5.1), indicate the distance between two neighboring cracks must be greater than the plate thickness for the stress (and stress intensity factor) profile to be of sufficient magnitude to propagate a crack through-wall. Therefore, for the waste package outer barrier outer closure-lid (25-mm thick (Table 8)), and again making the analysis assumption that the patches are square (side length about 150 mm), about six cracks per patch are able to propagate through-wall. For the waste package outer barrier middle closure-lid (10-mm thick (Table 8)), about 15 cracks per patch are able to propagate through-wall. WAPDEG propagates cracks on a patch until the first crack penetrates, then ceases crack propagation for any remaining cracks. If, for example, 32 patches are subject to crack growth and all fail by cracking, only 32 crack penetrations (the first crack to penetrate on each patch) will be reported, regardless of how many cracks per patch were considered. Therefore, it is appropriate (and conservative) to multiply the number of crack penetrations reported by WAPDEG by the number of cracks per patch to get a measure of the total number of cracks (Section 6.4.10).

6.3.3 Drip Shield General Corrosion Model Discussion

Details of the general corrosion rate distributions used for the drip shield are given in *General Corrosion and Localized Corrosion of the Drip Shield* (BSC 2004 [DIRS 169845], Section 6.5.5) and are tracked with DTN: MO0408MWDGLCDS.002 [DIRS 171486]. Also, see Section 4.1.2 for a discussion of the drip shield general corrosion inputs and Section 6.4.6 for discussion of implementation.

The drip shield outer surface is exposed to a more complicated chemistry and geometry than the drip shield inner surface because dust and/or mineral films (from evaporation of dripping water) form crevices on the drip shield outer surfaces. In contrast, the drip shield inner surfaces will not be exposed to dripping water or significant dust film formation (BSC 2004 [DIRS 169845], Section 6.5.5). Therefore, the general corrosion of the inner surface and the outer surface of the drip shield are analyzed by using different sets of corrosion data (BSC 2004 [DIRS 169845], Section 6.5.5). The general corrosion rate cumulative distribution function applicable to the under side of the drip shield is shown in Table 4. The general corrosion rate cumulative distribution function applicable to the top side of the drip shield is shown in Table 5.

For each realization of the Integrated Waste Package Degradation analysis, a single general corrosion rate is sampled from each general corrosion rate distribution and applied to all drip shields. The variation in these inputs is entirely due to uncertainty (BSC 2004 [DIRS 169845], Section 6.5.5). Using this approach, all drip shields in the repository fail by general corrosion at the same time for a given realization.

The maximum general corrosion rate for the cumulative distribution function applied to the under side of the drip shield (Table 4) is approximately 1.13×10^{-4} mm/yr and the maximum general corrosion rate for the cumulative distribution function applied to the top side of the drip shield (Table 5) is approximately 3.20×10^{-4} mm/yr. Therefore, the earliest possible drip shield failure by general corrosion is about 35,000 years.

6.3.4 Waste Package Outer Barrier General Corrosion Model Discussion

Details of the general corrosion rate distributions used for the Alloy 22 waste package outer barrier are given in *General Corrosion and Localized Corrosion of Waste Package Outer Barrier* (BSC 2004 [DIRS 169984], Section 6.4.3). Also, see Section 4.1.3 for a discussion of the waste package outer barrier general corrosion inputs and Section 6.4.7 for discussion of implementation. The Alloy 22 general corrosion rate is a function of exposure temperature. The temperature dependence follows an Arrhenius relationship:

$$R = \exp\left[C_o - \frac{C_1}{T}\right] \quad \text{(Eq. 17)}$$

where

R = general-corrosion rate
T = temperature (Kelvin)
C_o = intercept term
C_1 = slope term (Kelvin)

as discussed in *General Corrosion and Localized Corrosion of Waste Package Outer Barrier* (BSC 2004 [DIRS 169984], Section 6.4.3). The sign of the slope term in this report is negative with respect to the slope term in *General Corrosion and Localized Corrosion of Waste Package Outer Barrier* (BSC 2004 [DIRS 169984], Section 6.4.3) to be consistent with the input requirements of WAPDEG. The slope term, C_1, is normally distributed with a mean of 3,116.47 K and a standard deviation of 296.47 K (BSC 2004 [DIRS 169984], Section 6.4.3; DTN: MO0409MWDUGCMW.000 [DIRS 171714]).

The intercept term, C_o, is determined from the general corrosion rate distribution derived from the weight loss of the 5-year crevice geometry samples exposed in the LTCTF (BSC 2004 [DIRS 169984], Section 6.4.3) and the value of the slope term, C_1. The general corrosion rate distribution derived from the weight loss of the 5-year crevice geometry samples exposed in the LTCTF represents the distribution of long-term general corrosion rates of the waste package outer barrier at 60°C (333.15 K). Therefore:

$$\ln(R_o) = C_o - \frac{C_1}{333.15\ \text{K}} \quad \text{(Eq. 18)}$$

or

$$C_o = \ln(R_o) + \frac{C_1}{333.15\ \text{K}} \quad \text{(Eq. 19)}$$

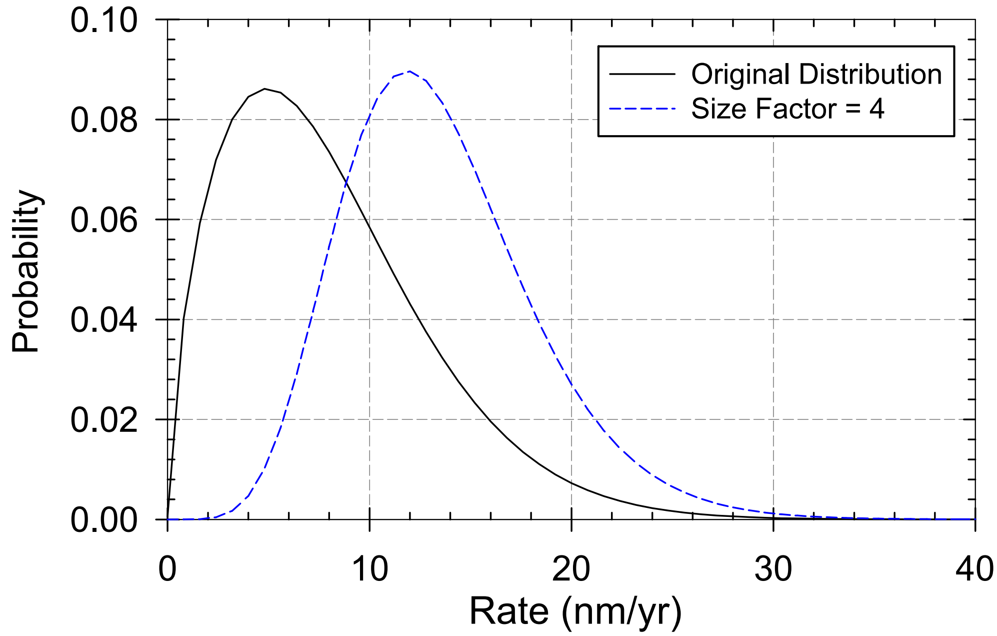
where R_o is the general corrosion rate distribution from the 5-year exposed crevice geometry samples. Substituting for C_o in Equation 17,

$$R = \exp\left[\ln(R_o) + C_1\left(\frac{1}{333.15\text{K}} - \frac{1}{T}\right)\right] \qquad \text{(Eq. 20)}$$

General Corrosion and Localized Corrosion of Waste Package Outer Barrier (BSC 2004 [DIRS 169984], Section 6.4.3) states that R_o is given by a Weibull distribution (Equation 1) ($\alpha = 8.88$ nm/yr, $\beta = 1.62$, and $\theta = 0$) (Table 6). This is a two-parameter Weibull distribution (since the location parameter, θ, is zero) with α being the scale parameter and β the shape parameter. As discussed in Section 6.3.2, the patch area used to analyze the waste packages is four times the area of the crevice geometry sample size used to determine the R_o distribution. Therefore, the general corrosion rates used in the IWPD analysis are adjusted to account for the effects of this change of scale (Aziz 1956 [DIRS 159379]; Shibata 1996 [DIRS 119589]). The method employed to accomplish this change in scale corresponds to using the highest of four sampled corrosion rates (from the two-parameter Weibull distribution) to analyze general corrosion of the waste package patch. This approach is conservative and appropriate for this application. The approach is conservative because it is probable that not all four samples from the Weibull distribution will have the highest rate, therefore, a more realistic representation of the overall general corrosion rate would be the average of the four sampled corrosion rates. However, this approach would not account for the fact that one fourth of the patch has the maximum of the four sampled corrosion rates. On this basis, the proposed approach is conservative and appropriate for this application.

Mathematically stated, if *CDF(x)* is the cumulative probability distribution, then the probability that x will be the largest amongst n observations is $[CDF(x)]^n$ (Aziz 1956 [DIRS 159379]; Shibata 1996 [DIRS 119589]). In this context, n can be called the size factor. The effect of this method is to shift the median general corrosion rate to higher values and to decrease the probability of sampling lower general corrosion rates. This can be seen in Figure 3 where the original distribution for R_o is plotted along with the distribution resulting from a size factor of 4.

The variation in R_o is entirely due to variability (i.e., a cumulative distribution function for $\ln(R_o)$ is used in the Integrated Waste Package Degradation (IWPD) analysis). *General Corrosion and Localized Corrosion of Waste Package Outer Barrier* (BSC 2004 [DIRS 169984], Section 6.4.3) states that C_1 is given by a truncated (at ±3 sds) normal distribution with a mean of 3,116.47 K and a standard deviation of 296.47 K (Table 7). The variation in the general corrosion rate slope term, C_1, is entirely due to uncertainty. For each realization of the IWPD analysis, a single general corrosion rate slope term is sampled and applied to the Alloy 22 waste package outer barrier surfaces. Spatial and temporal variability in the waste package surface temperatures in the repository lead to spatial and temporal variability in the general corrosion rate of the Alloy 22 waste package outer barrier.



Source DTN: MO0409MWDUGCMW.000 [DIRS 171714].

Output DTN: MO0310MWDWAPAN.002.

Figure 3. Effect of Scaling General Corrosion Distribution by a Size Factor of Four

6.3.5 Waste Package Stress Corrosion Cracking Model Discussion

Weld residual stresses are a potential driving force for stress corrosion cracking. All regions of the waste package (including fabrication welds), except the waste package outer barrier closure-lid weld regions, are stress relief annealed before the waste packages are loaded with waste (Plinski 2001 [DIRS 156800], Section 8.1.7), and, thus, do not develop residual stress/stress intensity factors high enough for stress corrosion cracking to occur (BSC 2004 [DIRS 169985], Section 6.4.2). Stress corrosion cracking of the waste package outer barrier closure lid weld regions is analyzed in this report. Analyses of the potential for stress corrosion cracking due to seismic-induced loading and rockfalls are not discussed in this report.

A dual closure-lid design (Figure 4) for the Alloy 22 waste package outer barrier (or outer shell) is used for license application (Bokhari 2003 [DIRS 162429]). The outer closure lid is 25-mm thick and the middle closure lid is 10-mm thick (Bokhari 2003 [DIRS 162429]). The primary differences in closure lid design to be used for license application with respect to the closure lid design used in site recommendation are (a) the full penetration stainless steel lid weld will be replaced with a spread ring and seal weld; (b) the outer closure lid extension is eliminated; (c) the outer closure lid mitigation method will be laser peening instead of induction annealing; and (d) no laser peening will be applied to the middle closure lid (Bokhari 2003 [DIRS 162429]). The effects of the peening method applied to the outer closure lid are accounted for in the stress and stress intensity factor profiles discussed in the next section.

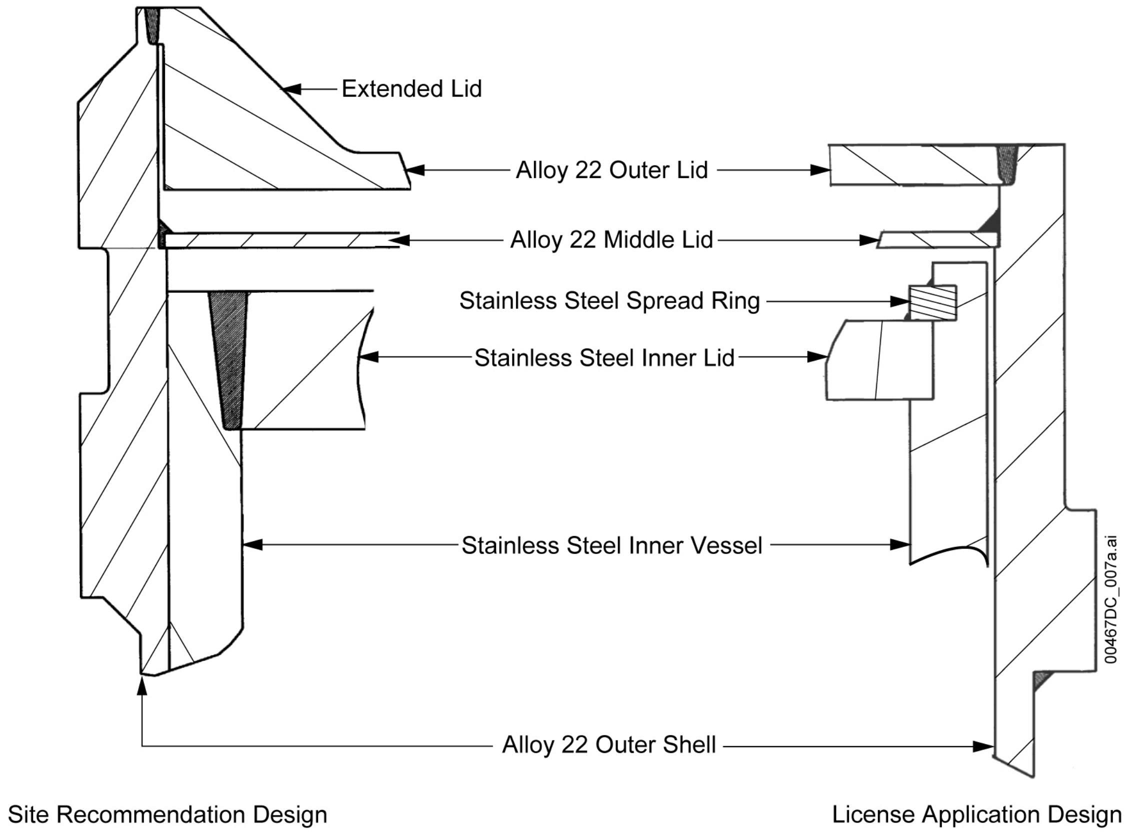


Figure 4. Schematic of the Dual Closure Lids of Waste Package Outer Barrier

One can see in Figure 4 that there is a physical separation between the two lids. Thus, any stress corrosion cracks initiated in the outer closure lid stop after penetrating it, and then the middle closure-lid welds are subject to the external environment and the potential for stress corrosion crack initiation and growth.

6.3.5.1 Stress and Stress Intensity Factor Profiles

Inputs to this analysis include stress and stress intensity factor profiles (stress or stress intensity factor versus depth) appropriate for both the outer closure and middle closure lids of the waste package outer barrier. Table 9 summarizes these inputs and their sources. These inputs can be found in *Stress Corrosion Cracking of the Drip Shield, the Waste Package Outer Barrier, and the Stainless Steel Structural Material* (BSC 2004 [DIRS 169985]).

In *Stress Corrosion Cracking of the Drip Shield, the Waste Package Outer Barrier, and the Stainless Steel Structural Material* (BSC 2004 [DIRS 169985], Section 6.2.2), it is concluded that the hoop stress, which promotes radially oriented crack growth, is the dominant component of stress in the waste package outer barrier closure lid weld regions. On this basis, only the hoop stress profiles are considered further in this report.

The hoop stress (σ in MPa) as a function of depth (x in mm) in the closure weld regions of the Alloy 22 waste package outer barrier is given by a third order polynomial equation of the form (BSC 2004 [DIRS 169985], Table 8-1; DTN: LL030607012251.065 [DIRS 163968]):

$$\sigma(x,0) = A_0 + A_1 \times x + A_2 \times x^2 + A_3 \times x^3 \qquad \text{(Eq. 21)}$$

where the values of the coefficients (A_i's) used in the Integrated Waste Package Degradation (IWPD) analysis are given in Table 10. The second argument in the stress function is used to represent angular variation (θ = 0 arbitrarily chosen) around the circumference of the Alloy 22 waste package outer and middle closure-lid weld regions. The angular variation is included using the following functional form (BSC 2004 [DIRS 169985], Section 6.4.5, Table 8-1; DTN: LL030607012251.065 [DIRS 163968]):

$$\sigma(x,\theta) = \sigma(x,0) - (17.236893) \times (1 - \cos(\theta)) \qquad \text{(Eq. 22)}$$

Note that $\sigma(x, 0)$ (defined in Equation 21) uses the stress coefficients (A_i) defined in Table 10 with x in units of mm. Based on the angular stress variation in Equation 22, the stress intensity factor variation with angle is given by (BSC 2004 [DIRS 169985], Section 6.4.5, Table 8-1; DTN: LL030607012251.065 [DIRS 163968]):

$$K_I(x,\theta) = K_I(x) \times \left(\frac{\sigma(Thck,\theta)}{\sigma(Thck,0)} \right) \qquad \text{(Eq. 23)}$$

where *Thck* is taken to be the maximum depth value given in Table 11 and $K_I(x)$ is given by the values in Table 11. The variation of the stress and stress intensity factor profiles with angle is due to variability (BSC 2004 [DIRS 169985], Section 6.4.5).

The uncertainty in the stress and stress intensity factor profiles is introduced through a scaling factor, z. The scaling factor, z, which is sampled from a normal distribution with a mean of zero and a standard deviation of 5 percent of the yield strength, YS, has an upper-bound of 15 percent of the YS and a lower-bound of –15 percent of the YS (BSC 2004 [DIRS 169985], Section 6.4.5). The numerical value of the yield strength, YS, used in these calculations is the yield strength at 473 K (Table 12). The value of YS (285 MPa) is obtained by linear interpolation between the values of the yield strength at 366 K (338 MPa) and 477 K (283 MPa) (Table 9), i.e.:

$$\text{YS} = 338\,\text{MPa} + \left(\frac{473\ \text{K} - 366\ \text{K}}{477\ \text{K} - 366\ \text{K}} \right) \times (283\ \text{MPa} - 338\ \text{MPa}) = 285\,\text{MPa} \qquad \text{(Eq. 24)}$$

The stress relation, accounting for uncertainty, is given by:

$$\sigma_u(x,\theta,z) = \sigma(x,\theta) \times \left(\frac{\sigma(Thck,\theta) + z}{\sigma(Thck,\theta)} \right) \quad \text{(Eq. 25)}$$

and the stress intensity factor relation is given by:

$$K_{Iu}(x,\theta,z) = K_I(x,\theta) \times \left(\frac{\sigma(Thck,\theta) + z}{\sigma(Thck,\theta)} \right) = K_I(x,0) \times \left(\frac{\sigma(Thck,\theta) + z}{\sigma(Thck,0)} \right) \quad \text{(Eq. 26)}$$

The uncertainty treatment of these inputs is encompassed in the parameter z, which is sampled once per realization of the Integrated Waste Package Degradation analysis for each closure lid (i.e., a different value of z is sampled for each lid in a given realization).

6.3.5.2 Weld Flaws

Flaws in the closure-lid welds are likely sites for stress corrosion cracking initiation. Weld flaws are generally larger than other surface defects and are conservatively considered to maintain their depth relative to the advancing general corrosion front (i.e., they are not removed by general corrosion processes). Therefore, the characteristics of weld flaws in the closure welds are important inputs to the waste package stress corrosion cracking analysis. As discussed earlier, residual stress analyses showed that the hoop stress is the dominant stress driving crack growth; thus, only radially oriented weld flaws are potential sites for stress corrosion cracking initiation.

This section lists the design information inputs to the integrated waste package degradation (IWPD) analysis of weld flaws for the Alloy 22 waste package outer barrier (or outer shell) closure-lid welds.

The probability of nondetection, P_{ND}, of weld flaws of length x using a nondestructive evaluation (NDE) technique is (BSC 2004 [DIRS 170024], Section 6.2.1.2.1, Equation 21):

$$P_{ND}(x) = \varepsilon + \frac{1}{2}(1-\varepsilon) erfc\left(v \times \ln\left(\frac{x}{b} \right) \right) = \frac{\varepsilon + 1}{2} + \frac{\varepsilon - 1}{2} erf\left(v \times \ln\left(\frac{x}{b} \right) \right) \quad \text{(Eq. 27)}$$

The parameters in Equation 27 are identified in Table 16 and correspond to inputs in Table 8.

Table 16. Probability of Nondetection Inputs Used in the IWPD Analysis and Their Sources

Input Name	Input Value	Units
Lower limit of probability of nondetection, ε	0.005	N/A
Characteristic flaw size, b	2.5	mm
Shape factor, v	3	N/A

Source: BSC 2004 [DIRS 170024], Table 11.

Table 17 lists the inputs to the IWPD analysis of weld flaws for the Alloy 22 waste package outer barrier closure-lid welds.

Table 17. Weld Flaw Analysis Inputs Used in the IWPD Analysis and Their Sources

Input Name	Input Source	Input Value	Units
CSNF WP outer closure lid weld volume (V)	BSC 2003 [DIRS 164610], Table 19	1350189	mm^3
CSNF WP middle closure lid weld volume (V)	BSC 2003 [DIRS 164610], Table 18	490478	mm^3
CDSP WP outer closure lid weld volume (V)	BSC 2003 [DIRS 164610], Table 19	1753091	mm^3
CDSP WP middle closure lid weld volume (V)	BSC 2003 [DIRS 164610], Table 18	639901	mm^3
Weld Thickness (th)	BSC 2001 [DIRS 157812], BSC 2001 [DIRS 157817], and BSC 2001 [DIRS 157818], Sheet 3 of 3	25 for outer closure lid 10 for middle closure lid	mm
Number of sample welds	BSC 2004 [DIRS 170024], Section 6.2.1.1.2	16	N/A
Number of weld flaws (n_f)	BSC 2004 [DIRS 170024], Table 11	7	N/A
Cumulative size of weld flaws (S_f)	BSC 2004 [DIRS 170024], Appendix I, p. I-3	31.75	mm
Cumulative volume of sample welds, V_f	BSC 2004 [DIRS 170024], Appendix I, p. I-26 Identified as “total volume of weld in the 16 specimen rings”	18610540.3277924	mm^3
Flaw size distribution parameter(λ_s)	BSC 2004 [DIRS 170024], Equation 2	Gamma distribution with a mean of n_f /S_f and a standard deviation of sqrt(n_f)/S_f	mm^{-1}
Flaw count distribution parameter (λ_c)	BSC 2004 [DIRS 170024], Equation 12	Gamma distribution with a mean of (n_f + ½)/ V_f and a standard deviation of sqrt(n_f + ½)/ V_f	mm^{-3}
Fraction of radial-oriented flaws (F_r)	BSC 2004 [DIRS 170024], Table 12	0.008	N/A
Fraction of plate to be included for propagating embedded flaws ($F\psi$)	BSC 2004 [DIRS 169985], Table 8-1	0.25	N/A

Weld flaw sizes follow an exponential distribution of parameter λ_s normalized to the weld thickness (BSC 2004 [DIRS 170024], Attachment I). The flaw size probability density function is shown below:

$$f_s(x) = \frac{\lambda_s \exp(-\lambda_s \cdot x)}{1 - \exp(-\lambda_s th)} \quad \text{(Eq. 28)}$$

The flaw size distribution parameter (representing uncertainty), λ_s, is gamma distributed with shape parameter n_f, and scale parameter, $1/S_f$.

The fraction of nondetected defects remaining in the weld after inspection is given by the integration of the two functions above (Equations 27 and 28):

$$F_{nr}(th) = \int_0^{th} P_{ND}(u) f_s(u) du \qquad \text{(Eq. 29)}$$

While the postinspection weld flaw sizes is given by the cumulative distribution function:

$$G(x) = \frac{\int_0^{x} P_{ND}(u) f_s(u) du}{F_{nr}(th)} \qquad \text{(Eq. 30)}$$

The distribution for the number of defects before any inspection or repair follows a Poisson distribution with parameter λ_c. The flaw count distribution parameter (representing epistemic uncertainty), λ_c, is gamma distributed with shape parameter, (n_f + ½), and scale parameter, 1/V_f.

The distribution for the number of defects that remain after inspection is Poisson distributed with parameter λ (count per closure weld given volume, V, and thickness, th), given by the product below (Equation 31). This expression contains the fraction of weld flaws that are radially oriented, F_r, the fraction of embedded weld flaws able to propagate, F_ψ, and the fraction of nondetected defects, $F_{nr}(th)$:

$$\lambda = F_r \times F_\psi \times F_{nr}(th) \times (V \times \lambda_c) \qquad \text{(Eq. 31)}$$

The various weld volumes, V, and thicknesses, th, are as given for each of the four closure lid types (Table 17).

In summary, variation for weld flaw sizes is expressed as variability at the waste package level given by the truncated exponential probability density function in Equation 28, with an uncertain parameter, λ_s, sampled for each realization. The variation in the number of weld flaws is expressed as variability at the waste package level given by a Poisson distribution, with an uncertain parameter λ (count per closure weld) given by Equation 31. This parameter in turn is a function of parameters, λ_s (from the fraction of nondetected flaws, $F_{nr}(th)$ term), and λ_c, which are sampled as uncertain for each realization.

6.3.5.3 Slip Dissolution Mechanism

The Slip Dissolution Mechanism for stress corrosion cracking (BSC 2004 [DIRS 169985], Section 6.3) requires a threshold stress, a stress intensity factor threshold, an incipient crack size, and crack growth rate parameters (which are functions of n, the repassivation slope). These inputs and their sources are listed in Table 12.

The threshold stress is defined as the minimum stress at which cracks initiate on a "smooth" surface. This analysis refers to these as incipient cracks (to distinguish them from weld flaws) and typically form at local surface defects such as grain boundary junctions and surface roughness. Incipient cracks are considered to be 0.05 mm in length at the time of their nucleation (BSC 2004 [DIRS 169985], Table 8-1). The threshold stress is 90 percent of the yield strength (Table 12). Incipient cracks nucleate when general corrosion has penetrated to the depth at which the stress profile (Section 6.3.5.1) exceeds the threshold stress.

Weld flaws are already nucleated and, thus, do not require a stress threshold to nucleate. However, most weld flaws are embedded within the material and, therefore, not exposed to the environment. As general corrosion proceeds, some initially embedded weld flaws will be exposed to the environment (BSC 2004 [DIRS 169985], Section 6.2.2) while others are "corroded away." This evolution of the number of defects is not considered in detail. It has been recommended that a conservative approach is to consider the fraction of weld flaws embedded within the outer one-fourth of the weld thickness (BSC 2004 [DIRS 169985], Section 6.2.2) to be capable of propagation by the slip-dissolution mechanism. As discussed in Section 6.3.5.2, only 0.8 percent of weld flaws are capable of propagation based on their orientation with respect to the dominant stress components.

Stress corrosion crack growth can occur when the stress intensity factor at the tip of the incipient crack or weld flaw exceeds or is equal to a threshold stress intensity factor. The depth of the tip is the sum of the general corrosion depth and the crack or weld flaw depth. The stress intensity factor at this depth is determined from the stress intensity factor profile (Section 6.3.5.1). The threshold stress intensity factor, K_{ISCC}, is given as a function of the repassivation slope, n and V_{gc} (which equals 7.23 nm/yr or 7.23×10^{-6} mm/yr) (BSC 2004 [DIRS 169985], Section 6.3.5):

$$K_{ISCC} = \left(\frac{7.23 \times 10^{-6} \, \frac{\text{mm}}{\text{yr}}}{\overline{A}} \right)^{1/\overline{n}} \qquad \text{(Eq. 32)}$$

$\overline{A}$ and $\overline{n}$ are functions of n, as discussed below. The threshold stress intensity factor is applied to both incipient cracks and weld flaws. It should be noted that parameter $\overline{A}$, and the equations using $\overline{A}$ are converted from units of mm/s (as expressed in Section 4.1.6) to mm/yr in this Section in order to be consistent with their use in the IWPD analysis.

Once crack growth initiates the crack(s) grow at a velocity given by (BSC 2004 [DIRS 169985], Table 8-1; DTN: LL030607012251.065 [DIRS 163968]):

$$V_t = \overline{A}(K_I)^{\overline{n}} \qquad \text{(Eq. 33)}$$

where V_t is the crack growth rate in mm/yr, and K_I is the stress intensity factor in $\text{MPa(m)}^{1/2}$. Parameters, $\overline{A}$ and $\overline{n}$, in the above equation are expressed in terms of the repassivation slope, n, as follows.

$$\overline{A} = 7.8 \times 10^{-2} n^{3.6} \left(4.1 \times 10^{-14}\right)^{n} \times \left[\left(60 \frac{\text{s}}{\text{min}}\right) \left(60 \frac{\text{min}}{\text{hr}}\right) \left(24 \frac{\text{hr}}{\text{day}}\right) \left(365.25 \frac{\text{day}}{\text{yr}}\right) \right] \qquad \text{(Eq. 34)}$$

$$\overline{n} = 4n \qquad \text{(Eq. 35)}$$

In the IWPD analysis, the parameter n is represented by a truncated normal distribution (at ±2 standard deviations (sds)) with a mean of 1.304, a sd of 0.16 (Table 12). The variation in the repassivation slope, n, is entirely due to uncertainty. The repassivation slope is sampled once per realization of the IWPD analysis (i.e., the same value of n is used for each lid in a given realization).

The variations in the threshold stress and threshold stress intensity factor (through its dependence on n) distributions are entirely due to uncertainty. The thresholds are sampled once per realization of the IWPD analysis (i.e., the same value of these thresholds are used for each lid in a given realization).

6.3.6 Waste Package Microbially Influenced Corrosion

Analyses conducted in *General Corrosion and Localized Corrosion of Waste Package Outer Barrier* (BSC 2004 [DIRS 169984], Section 6.4.5) evaluate the effects of microbially influenced corrosion (MIC) on corrosion of the waste package outer barrier. It is concluded in that report that the effect of MIC is adequately represented by a multiplier applied to the general corrosion rate of the waste package outer barrier (BSC 2004 [DIRS 169984], Section 6.4.5), i.e.:

$$CR_{MIC} = CR_{st} \times f_{MIC} \qquad \text{(Eq. 36)}$$

where CR_{MIC} is the general corrosion rate in presence of microorganisms, CR_{st} is the general corrosion rate of the alloy in absence of MIC, and f_{MIC} is the MIC factor. The MIC factor, f_{MIC}, is uniformly distributed between 1 and 2. The variation in f_{MIC}, is entirely due to uncertainty (BSC 2004 [DIRS 169984], Section 6.4.5; DTN: MO0409MWDUGCMW.000 [DIRS 171714]). The MIC factor is applied to the waste package outer barrier general corrosion rate when the relative humidity (a measure of water activity) at the waste package outer barrier surface is above 90 percent. See Section 6.4.11 for implementation of MIC in the IWPD analysis.

6.3.7 Inside-Out Degradation

When a waste package fails, the IWPD analysis initiates corrosion degradation of the waste package inner surface (inside-out corrosion). The inside-out corrosion analysis includes general corrosion of the Alloy 22 waste-package outer barrier. The inside-out corrosion could cause penetrations by general corrosion in addition to those by outside-in corrosion. WAPDEG (BSC 2002 [DIRS 162606], Section 3.1) inside-out general corrosion initiates on the next time step after the time of the waste package failure. The in-package water condition is considered to be the same as the water condition initially on the outside of the drip shield. Since the drip shields life span is shorter than the waste packages (Section 6.5), the water condition initially on the outside of the drip shield is employed for the water condition contacting the waste package inner and outer surfaces at the time of waste package failure. Similar to the outside-in general corrosion rates, the inside-out corrosion rates are modified for the analyzed waste package configuration (Figure 2) and for patch scaling effects (Section 6.3.4). Inside-out stress corrosion cracking is not simulated since it would be of negligible consequence to waste package performance either because the waste package has already been breached by the much larger patch penetrations (due to general corrosion) or because the patches susceptible to stress corrosion cracking have already breached.

6.3.8 Waste Package Early Failure Analysis

Analysis of Mechanisms for Early Waste Package/Drip Shield Failure (BSC 2004 [DIRS 170024], Section 6.1.6) identified several general types of manufacturing defects including weld flaws, base metal flaws, improper weld material, improper base metal, improper heat treatment, improper weld-flux material, poor weld-joint design, contamination, mislocated welds, missing welds, handling damage, and administrative or operational error. Weld flaws in waste package welds have been discussed in Sections 4.1.4 and 6.3.5 in relation to their effect on stress corrosion cracking.

Of the types of manufacturing defects identified, only improper heat treatment and handling damage (including improper laser peening) were carried forward for analysis and were considered together, because they share the same consequence of increasing the susceptibility of the waste package to stress corrosion cracking (BSC 2004 [DIRS 170024], Section 7). Improper heat treatment is, by far, the dominant process in terms of probability (BSC 2004 [DIRS 170024], Section 7). Improper heat treatment and handling damage (including improper laser peening) shall be collectively referred to as "waste package early failure" for the remainder of this report.

Variation in the number of early failed waste packages is expressed as variability deriving from a discrete Poisson distribution with an uncertain intensity parameter. The uncertain intensity parameter is the product of the uncertain rate of waste package failures (log normally distributed) and the number of waste packages in a realization. As summarized in Table 14 in Section 4.1.8, the Poisson intensity is sampled from a log normal distribution with a median of 7.2×10^{-6} and an error factor of 15 (BSC 2004 [DIRS 170024], Section 7, Table 22).

These inputs need to be adjusted to conform to the input requirements of GoldSim (GoldSim Technology Group 2002 [DIRS 160643], Appendix B) for log normal distributions. First, note that the median is equal to the geometric mean for log normal distributions (Evans et al. 1993 [DIRS 112115], Chapter 25). Second, according to *Analysis of Mechanisms for Early Waste Package/Drip Shield Failure* (BSC 2004 [DIRS 170024], Section 6.2.2), the shape parameter, σ_k, is related to the error factor by:

$$\sigma_k = \frac{\ln(EF)}{1.645} = \ln\left(EF^{1/1.645}\right) \qquad \text{(Eq. 37)}$$

The shape parameter is the standard deviation in log space (Evans et al. 1993 [DIRS 112115], Chapter 25). Therefore, the geometric standard deviation of the log normal distribution is given by (GoldSim Technology Group 2002 [DIRS 160643], Appendix B):

$$e^{\sigma_k} = EF^{1/1.645} \qquad \text{(Eq. 38)}$$

The input parameters for GoldSim are as summarized in Table 18.

Table 18. Waste Package Early Failure Inputs to the GoldSim Software

Input Name	Input Source	Input Value	Units
Evaluation probability per Waste Package (Uncertain Poisson intensity)	Section 6.3.8	Log normal distribution with a geometric mean of 7.2×10^{-6} and a geometric sd of $15^{(1/1.645)}$ truncated at an upper-bound of 7.44213×10^{-3}	per Waste Package
Number of Early Failed Waste Package per realization	BSC 2004 [DIRS 170024], Section 7, Table 22	Poisson Distribution with intensity given above multiplied by number of waste packages considered.	# Waste Package/Realization

While the failure mechanisms are expected to result in enhanced probability of stress corrosion cracking, the waste packages are treated as failed upon initiation of corrosion processes. The following recommendations are made in *Analysis of Mechanisms for Early Waste Package/Drip Shield Failure* (BSC 2004 [DIRS 170024], Section 6.4.8) for evaluating the effects of waste package early failure:

- A failure of the waste package outer barrier shell and outer and middle closure lids should be assumed
- The affected waste packages should fail immediately upon initiation of degradation processes
- The entire waste package surface area should be considered affected by improper heat treatment
- The materials of the entire affected area should be assumed lost upon failure of the waste packages because the affected area could be subjected to stress corrosion cracking and enhanced localized and general corrosion.

6.4 INTEGRATED WASTE PACKAGE DEGRADATION ANALYSIS FORMULATION

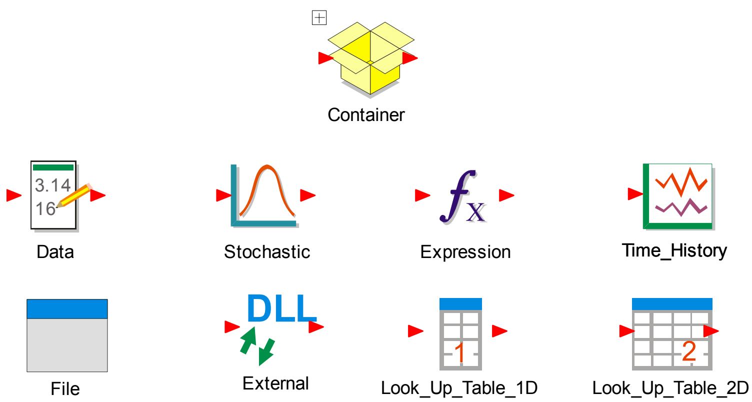
The IWPD analysis makes use of several software packages. These are listed in Section 3. WAPDEG is a dynamic-link library (DLL), which is used to analyze the variability in waste package degradation. GoldSim is used to pass input to WAPDEG and is responsible for treating the uncertainty in WAPDEG inputs. GoldSim also calls several other DLLs that are used to implement uncertainty in various inputs to WAPDEG. These include the SCCD DLL, for the treatment of uncertainty in stress and stress intensity factor profiles, and the CWD DLL, for the treatment of uncertainty in the number and size of closure lid weld (manufacturing) defects. Throughout this section, reference will be made to various parts of the GoldSim input file as well as to the various input files, parameters, and parameter distributions used in waste package degradation analysis.

6.4.1 GoldSim Implementation Overview

In this section, a brief overview of a GoldSim input file that calls the WAPDEG software is presented. A more detailed description of the GoldSim software can be found in *GoldSim*

Graphical Simulation Environment: User's Guide (GoldSim Technology Group 2002 [DIRS 160643]). GoldSim is a graphical simulation environment, used in this report to prepare an input file for the WAPDEG software. A typical GoldSim simulation contains multiple realizations. Each realization is equally likely, and represents one particular sampling of the uncertain parameters.

The GoldSim graphical elements used to develop an input data set for WAPDEG are illustrated in Figure 5.

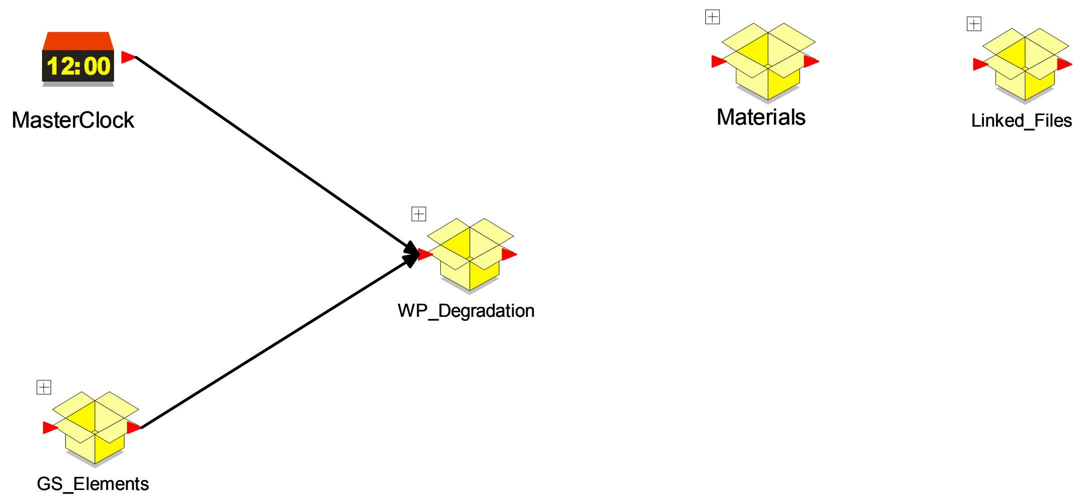


Output DTN: MO0310MWDWAPAN.002.

Figure 5. Graphical Elements Used in the GoldSim

Container elements are similar to subdirectories on a hard disk in that other graphical elements reside within them. Data elements are fixed values (or vectors of values). Stochastic elements define distributions, which are typically sampled once per realization. Expression elements are used to evaluate expressions (e.g., to multiply a data element by a stochastic value). Time_History elements are used to graph results (e.g., the contents of a Look_Up_Table_1D element). File elements contain the file names that will be passed to the simulation runs. The corresponding files must be present in the master directory. External elements are used to call external dynamic link libraries (DLLs), such as WAPDEG. Look_Up_Table_1D and Look_Up_Table_2D elements are typically used to store tables of input values or output values associated with external elements.

A schematic of a portion of the GoldSim input file, which calls WAPDEG, is shown in Figure 6.

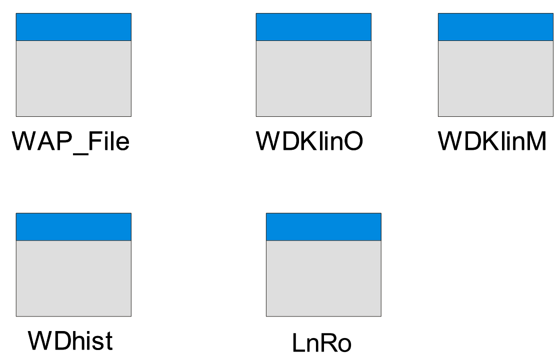


Output DTN: MO0310MWDWAPAN.002.

Figure 6. GoldSim File Calling the WAPDEG

Figure 6 is a screen capture of the top-level view of the GoldSim input file used in this analysis. The MasterClock is a built-in GoldSim element, which contains GoldSim-specific input parameters. The only GoldSim-specific parameters that impact the analysis results are the random seed used and the number of realizations.

The materials container element is a built-in GoldSim element, which is not used in this analysis. The contents of the Linked_Files container element are shown in Figure 7.

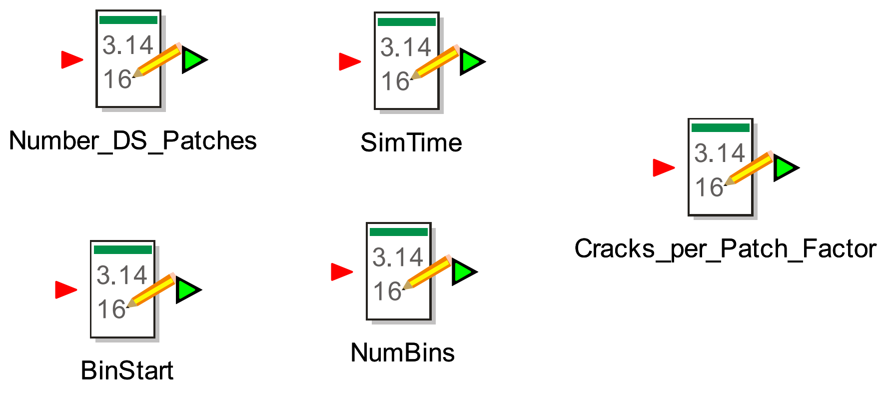


Output DTN: MO0310MWDWAPAN.002.

Figure 7. Contents of the Linked_Files Container Element

The file elements within the Linked_Files container element are linked to file names. For instance the WAP_File element is linked to the file "WD4DLL.WAP," a required file for the execution of WAPDEG.

The contents of the GS_Elements container element are shown in Figure 8. These elements contain global parameters that are defined within the GoldSim input file but are used by WAPDEG.



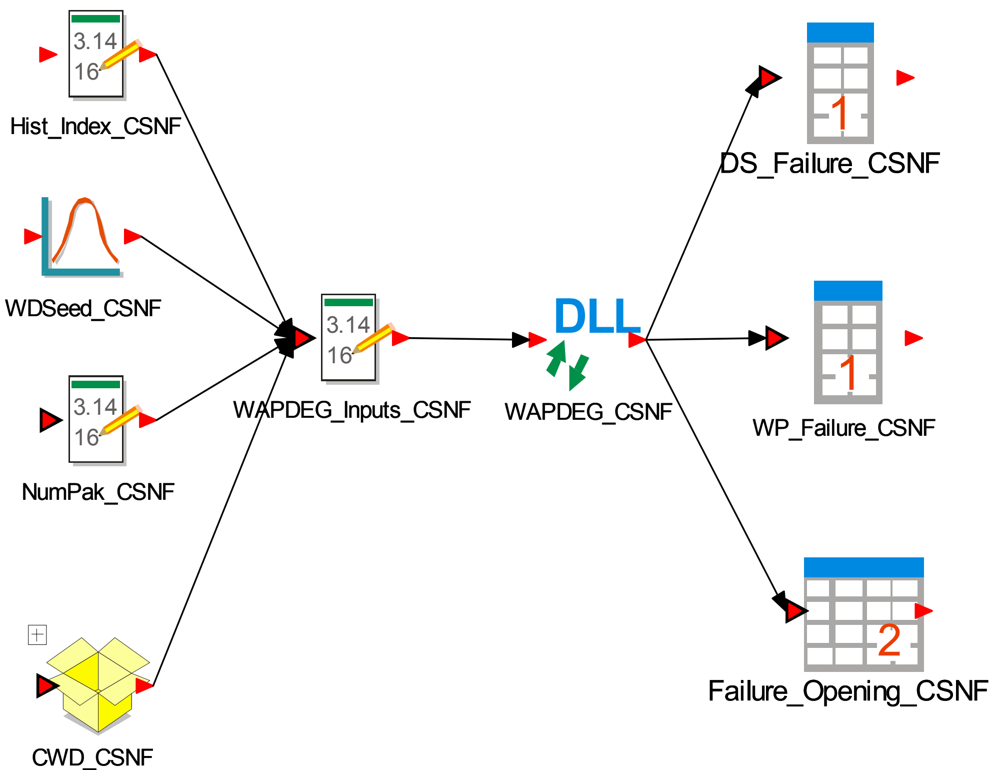
Output DTN: MO0310MWDWAPAN.002.

Figure 8. Contents of the GS_Elements Container Element

The contents of the WP_Degradation container element will be discussed later in this document, in relation to specific degradation modes.

6.4.2 WAPDEG-GoldSim Interface Overview

GoldSim interacts with the WAPDEG DLL through an external element. The TSPA-LA file will typically call the WAPDEG DLL several times per GoldSim realization. The exact number of calls will depend on the scenario class being run. A graphical representation of the interface between the GoldSim software and the WAPDEG DLL is shown in Figure 9, for simulation of CSNF waste package degradation (the interface and input for CDSP waste package degradation are almost identical to those for CSNF waste package degradation, differences will be mentioned when appropriate throughout this section).



Output DTN: MO0310MWDWAPAN.002.

NOTE: These are the contents of the IWPD_CSNF Container Element as depicted in Figure 10.

Figure 9. Interface Between the GoldSim Software and the WAPDEG DLL for CSNF Waste Packages

At each call, the WAPDEG DLL, represented by the external element WAPDEG_CSNF, is passed a vector of 2,000 real numbers, via a vector data element, WAPDEG_Inputs_CSNF. The values in the WAPDEG input vector specify degradation modes and degradation parameters.

The contents of the WAPDEG input vector are reproduced in Appendix I (Table I-1) and will be discussed in more detail in the following sections. All values in the WAPDEG input vector are real numbers. Those that do not change, and are not defined by other TSPA-LA components, are explicitly stated. The rest are represented by variable names, defined in the TSPA-LA itself. Certain parameters in the WAPDEG input vector reproduced in Appendix I (Table I-1) depend on the waste package configuration (CSNF or CDSP) being simulated. The values for the CSNF waste package configuration are shown first, with the corresponding CDSP waste package configuration value given afterwards in brackets.

Since only real numbers are passed between the GoldSim input file and the WAPDEG DLL, and since some of the degradation parameters are represented by distributions and tables, stored in text files, an additional communication mechanism is needed. GoldSim and WAPDEG share a "file index" file, WD4DLL.WAP. The contents of this file, for a typical TSPA-LA input file, are listed in Table 19. Note that the line numbers and the column headings in Table 19 are not part of the WD4DLL.WAP file, but are included for clarity.

Table 19. Contents of WD4DLL.WAP File

Line	File Name
1	WDenv_00_07wheader.ou
2	WDenv_00wh.ou
3	EMPTY
4	WDKIinO.fil
5	WDKIinM.fil
6	WDKISCCO.fil
7	WDStressO.fil
8	WDKISCCM.fil
9	WDStressM.fil
10	WDCWDNDO_CSNF.cdf
11	WDCWDSizeO_CSNF.cdf
12	WDCWDNDM_CSNF.cdf
13	WDCWDSizeM_CSNF.cdf
14	WDCWDNDO_CDSP.cdf
15	WDCWDSizeO_CDSP.cdf
16	WDCWDNDM_CDSP.cdf
17	WDCWDSizeM_CDSP.cdf
18	WDlnRGC.cdf

Using the WD4DLL.WAP file, GoldSim and WAPDEG can share file indices (line numbers in the WD4DLL.WAP file) in place of actual file names. The 2,000 real numbers and the contents of the files identified in the WD4DLL.WAP file are the only inputs to the WAPDEG DLL.

In the TSPA-LA, the drip shield and waste package degradation processes are discretized at the spatial bin/fuel type level. The repository is divided into five spatially defined bins. Each bin contains a different number of waste packages and is subject to different environment conditions. There are two different major types of waste package configurations, designated as commercial spent nuclear fuel (CSNF) and codisposal (CDSP) waste packages.

Figure 9 shows four input links to the WAPDEG_Inputs_CSNF vector. These are all a function of the fuel type and/or thermal history and environment variables. The data element, NumPak_CSNF, defines the number of CSNF waste packages in the bin. The data element, Hist_Index_CSNF, contains the file index linking the file containing the waste package thermal histories to a line number and file name in the WD4DLL.WAP file. WDSeed_CSNF is a stochastic element characterized by a uniform distribution between 1 and 2^{31}-1 (the maximum positive 32-bit integer). WDSeed_CSNF is used to generate a different integer for each WAPDEG DLL call, to seed the random number generator within WAPDEG. The container element, CWD_CSNF, holds some of the parameters required for the calculation of the weld flaw probability for the closure lids. Weld flaws are discussed in Section 6.3.5.2 and the WAPDEG implementation is described in Section 6.4.8.

Figure 9 also illustrates the output produced by the WAPDEG DLL. There are two one-dimensional table elements and one two-dimensional table element linked to the WAPDEG_CSNF external element. The DS_Failure_CSNF element receives a one-dimensional table of drip shield first failure times. The WP_Failure_CSNF element receives a one-dimensional table of waste package first failure times. The waste package first failure time is defined to be the first penetration by any mechanism (patch, pit, or crack) of the waste package inner layer (in this analysis, there are no pit penetration since localized corrosion is not simulated and there will be no crack penetrations of the drip shield since stress corrosion cracking of the drip shield is not simulated). The format of both of these tables is similar; the first column containing the drip shield or waste package first failure times in years (sorted in increasing order) and the second column containing the cumulative fraction of drip shields or waste packages failed. The Failure_Opening_CSNF element receives a two dimensional table containing 33 columns. The number of rows is determined by the input parameter "NumBins." The column contents are explained in Table 20. Note that waste package failure (for the purposes of averaging) is defined as any penetration (patch, pit, or crack) of the waste package layer 2 (the analyzed inner layer in Figure 2). If there are penetrations of layer 1 (the analyzed outer layer in Figure 2) of a waste package, but no waste package failures (penetrations of layer 2), the corresponding average number of patch, pit, or crack failures being reported is set to zero.

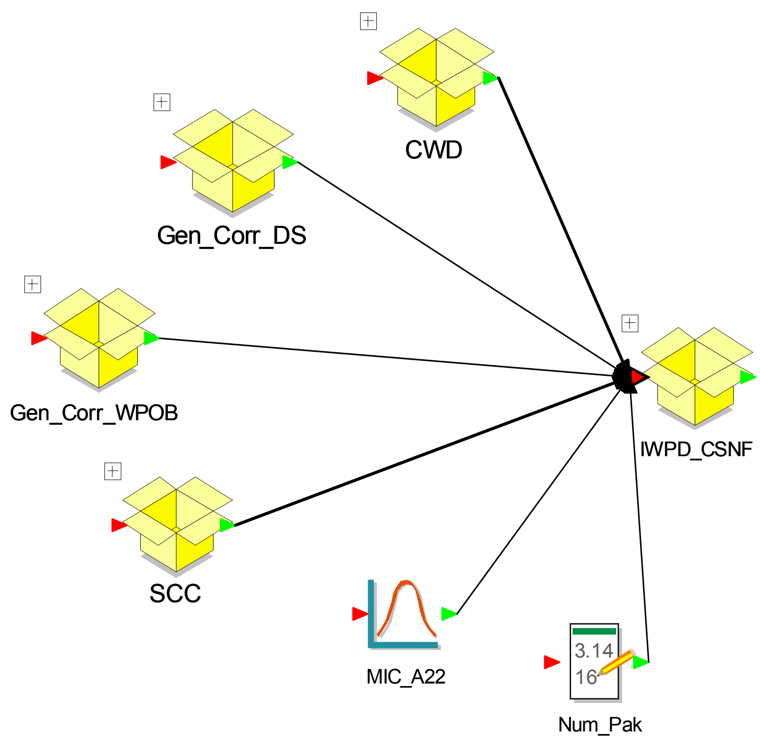
Table 20. Column Contents of the Failure_Opening_CSNF Element

Column Number	Contents
1	average number of patch failures (per failed drip shield) on the drip shield top
2	average number of pit failures (per failed drip shield) on the drip shield top
3	average number of crack failures (per failed drip shield) on the drip shield top
4	average number of patch failures (per failed drip shield) on the drip shield side
5	average number of pit failures (per failed drip shield) on the drip shield side
6	average number of crack failures (per failed drip shield) on the drip shield side
7	the cumulative fraction of first patch failures on the drip shield (top and side)
8	the cumulative fraction of first pit failures on the drip shield (top and side)
9	the cumulative fraction of first crack failures on the drip shield (top and side)
10	average number of patch failures (per failed waste package) on the waste package layer 1 top
11	average number of pit failures (per failed waste package) on the waste package layer 1 top
12	average number of crack failures (per failed waste package) on the waste package layer 1 top
13	average number of patch failures (per failed waste package) on the waste package layer 1 side
14	average number of pit failures (per failed waste package) on the waste package layer 1 side
15	average number of crack failures (per failed waste package) on the waste package layer 1 side
16	average number of patch failures (per failed waste package) on the waste package layer 1 bottom
17	average number of pit failures (per failed waste package) on the waste package layer 1 bottom
18	average number of crack failures (per failed waste package) on the waste package layer 1 bottom
19	the cumulative fraction of first patch failures on the waste package layer 1 (top, side, and bottom)
20	the cumulative fraction of first pit failures on the waste package layer 1 (top, side, and bottom)
21	the cumulative fraction of first crack failures on the waste package layer 1 (top, side, and bottom)
22	average number of patch failures (per failed waste package) on the waste package layer 2 top
23	average number of pit failures (per failed waste package) on the waste package layer 2 top
24	average number of crack failures (per failed waste package) on the waste package layer 2 top
25	average number of patch failures (per failed waste package) on the waste package layer 2 side
26	average number of pit failures (per failed waste package) on the waste package layer 2 side
27	average number of crack failures (per failed waste package) on the waste package layer 2 side

Table 20. Column Contents of the Failure_Opening_CSNF Element (Continued)

Column Number	Contents
28	average number of patch failures (per failed waste package) on the waste package layer 2 bottom
29	average number of pit failures (per failed waste package) on the waste package layer 2 bottom
30	average number of crack failures (per failed waste package) on the waste package layer 2 bottom
31	the cumulative fraction of first patch failures on the waste package layer 2 (top, side, and bottom)
32	the cumulative fraction of first pit failures on the waste package layer 2 (top, side, and bottom)
33	the cumulative fraction of first crack failures on the waste package layer 2 (top, side, and bottom)

There are additional input links to the WAPDEG_Inputs_CSNF vector. Some of these are in the global parameter container, GS_Elements, and were discussed in Section 6.4.1. The implementation of degradation due to general corrosion of Alloy 22 and Titanium Grade 7, and for stress corrosion cracking of Alloy 22 is done in separate container elements. These are shown in Figure 10 (WP_Degradation Container) and discussed in the following sections.



Output DTN: MO0310MWDWAPAN.002.

Figure 10. Other Input Links to IWPD_CSNF (contents of the WP_Degradation Container)

6.4.3 Number of Patches and Number Waste Package-Drip Shields Design Input

The drip shield plate thickness is used directly in the input to the WAPDEG DLL (see line 40 of Table I-1). WAPDEG does not require the drip shield surface area, only the number of drip shield patches need be specified. Since the variation in the general corrosion rate of the drip shield is considered to be due only to uncertainty (Section 6.3.3) each drip shield is analyzed using one patch (see line 52 of Table I-1).

In Section 6.3.2 the CSNF and CDSP waste package surface areas and patch sizes were calculated. The number of waste package patches was determined to be 1,014 for CSNF waste packages and 1,106 for CDSP waste packages (Section 6.3.2). This data is entered on line 29 of Table I-1.

Note that WAPDEG can calculate the number of patches by dividing the waste package surface area entered by the patch area entered. When the number of patches is pre-calculated, as above, the result is entered as the surface area parameter (with value equal to the number of patches in mm^2), and the patch area is entered with the value “1” (see lines 32 to 36 and lines 54 to 58 of Table I-1).

The drip shield and waste container surface areas are also divided into fractions. The drip shield has a top and side fraction. The top fraction is defined in line 53 of the WAPDEG input vector. The waste package has a top, bottom and side fraction. The top fraction and bottom fractions are entered on lines 30 and 31, respectively, of the WAPDEG input vector. The fraction assigned to side patches is obtained by subtracting the data entered for the other fraction(s) from one. The fraction assigned to side patches of the waste container is identified with the closure lid region for analysis purposes.

In the TSPA Model, the drip shield and waste package degradation processes are simulated at the spatial bin/fuel type level. The number of IWPD analysis simulations per TSPA Model realization depends on the scenario class being run. The WAPDEG software runs twice for each of the five spatially fixed bins, once for the CSNF waste packages in that bin and once for CDSP waste packages. If the spatially fixed bin contains fewer than 500 drip shield–waste package pairs, all CSNF and CDSP drip shield–waste package pairs in the bin should be simulated. If the bin contains more than 500 drip shield–waste package pairs, then only up to 500 CSNF and 500 CDSP drip shield–waste package pairs should be simulated. The impact of this is analyzed in the sensitivity studies in Section 6.5.4.

6.4.4 Waste Package Design Input

As discussed in Section 6.3.2, the dual Alloy 22 lid design for the waste package outer barrier requires that outer barrier be analyzed as two layers. The outer analyzed layer is 25-mm thick (the thickness of the outer closure lid) and the inner analyzed layer is 10-mm thick (the thickness of the middle closure lid). The WAPDEG input vector defines these two layer thicknesses in lines 4 and 17 of Table I-1.

In addition, each layer is analyzed as being composed of two different regions, the closure lid region and the shell region. The closure lid thicknesses (both outer and middle) are the same for CSNF and CDSP waste packages, but the thickness of the shell region is different (20 mm for the CSNF waste package, 25 mm for the CDSP waste package). WAPDEG assigns a fraction of the total waste package surface area to top and bottom surfaces. The side fraction is obtained by subtracting the sum of the top and bottom fractions from one. This area assignment, for the waste package outer barrier, is done in lines 30 and 31 of the WAPDEG input vector (Table I-1). The top and bottom area fractions are associated with the shell region and the side fraction is associated with the closure lid region. The fractions are not the same for both waste package types. The area fraction assigned to "side" (closure lid) patches is calculated to be 0.032 (0.038 for CDSP waste packages) in Section 6.3.2.1.

The two-layer implementation of the waste package outer barrier also requires that the general corrosion rate be adjusted. The general corrosion rate applied to the outer layer is set to a large value. The general corrosion rate applied to the inner layer is modified by the ratio of the inner to outer shell layer thicknesses. The effect of this adjustment to general corrosion rate is then removed, for the closure lid regions only. Thus, the original general corrosion rate is applied to both closure lids. However, the outer layer shell region degrades immediately and the inner layer shell region degrades at the correct rate for the 20-mm (or 25-mm) waste package outer barrier shell.

The two-layer implementation of the waste package outer barrier in the WAPDEG software is done in two places. First, the error term in the general linear functional form, used to analyze general corrosion (BSC 2002 [DIRS 162606], Section 4.2.6.5) of the layers, is changed. The second change is to modify the multipliers used in the stress corrosion cracking slip dissolution event used to analyze stress corrosion cracking degradation (BSC 2002 [DIRS 162606], Section 4.2.7.5) of the closure lid regions.

The general linear functional form (BSC 2002 [DIRS 162606], Section 4.2.6.5), in its most general form, is given by:

$$D = \exp\left(c_0 + \sum_{j=1}^{N} c_j E_j + \varepsilon\right)\exp\left(-\frac{Q}{T}\right) t^n \qquad \text{(Eq. 39)}$$

where

D = corrosion depth (mm)
N = number of terms
c_0 = constant
c_j = the j^{th} coefficient
E_j = the j^{th} exposure condition
ε = error term
Q = activation energy
T = temperature (K)
n = time exponent

The general linear functional form is used by WAPDEG to implement the general corrosion model. The general linear functional form defined by Equation 39 includes a constant term, N; terms that depend on exposure conditions; as well as an error term, ε. The general corrosion functional form presented in Equations 17 through 20 (Section 6.3.4) does not require the full generality of Equation 39. The particular form used in the implementation involves a constant term, the activation energy term, and the error term. This implementation is discussed in more detail in Section 6.4.7. The discussion in this section is limited to an explanation of how the error term, ε, is used to implement the two-layer waste package outer barrier analyzed.

The outer layer error term is set to the natural log of 10^{14} in lines 111 to 115 and lines 210 to 214 of the WAPDEG input vector. The error term that applies to the inner layer is set to the natural log of the ratio of 10 to 20 (or the natural log of the ratio of 10 to 25 for CDSP waste packages). The inner layer error term is defined in lines 150 to 154 and lines 249 to 253 of the WAPDEG input vector.

Inspection of the functional form in Equation 39 shows that setting the error term, ε, to a large value effectively causes instantaneous penetration of the outer layer. Using the error term for the inner layer to modify the corrosion rate by the ratio of thicknesses causes the inner layer to degrade at the correct rate for the waste package outer barrier shell region.

The closure lid region stress corrosion cracking degradation is implemented in the WAPDEG input vector using a slip dissolution event (BSC 2002 [DIRS 162606], Section 4.2.7.5). As noted above, the closure lid region of the waste package is identified with the side fraction of the surface area. To maintain the original general corrosion rate in the closure lid region, the effect of the multipliers (imposed by adjusting the error term) is removed in the closure lid region only (i.e., for side patches only).

The input data for the slip dissolution event is contained in lines 331 to 408 of Table I-1, for the outer layer. Examination of lines 337 to 339 of Table I-1 shows that only side patches are impacted by this event data. Examination of line 395 to 406 shows that one of the event effects is to accelerate the general corrosion rate by a factor of 1.00×10^{-14}, which cancels the large multiplier on the general corrosion rate for the closure lid region (side patches).

The input data for the Slip Dissolution event for the inner layer is contained in lines 409 to 486 of Table I-1, for the inner layer. Examination of lines 415 to 417 shows that only side patches are impacted by this event data. Examination of line 473 to 484 shows that one of the event effects is to accelerate the general corrosion rate by a factor of 20/10 = 2 (or 25/10 = 2.5 for CDSP waste packages) This cancels the previously added multiplier on the general corrosion rate.

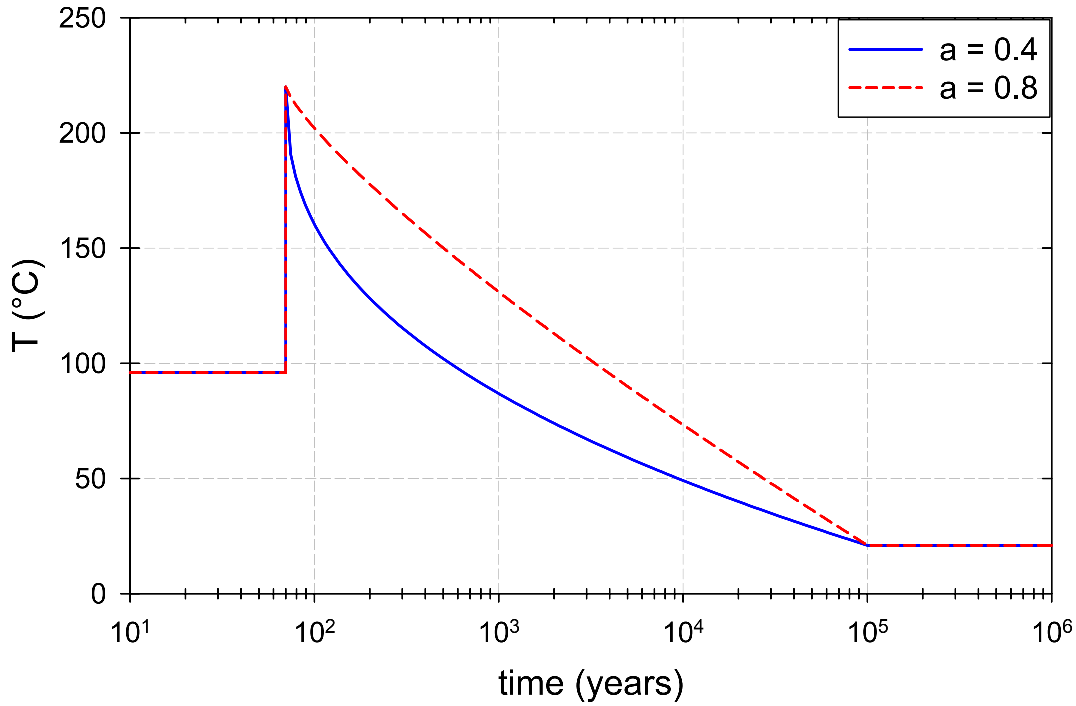
6.4.5 Waste Package and Drip Shield Exposure Conditions Implementation

The exposure condition inputs to the IWPD analysis are representative temperature and relative humidity histories and not the actual thermal hydrologic histories used in TSPA. The representative thermal hydrologic history files are produced to allow the IWPD analysis to be exercised in this report. Analysis outputs presented in Section 6.5 using these inputs are for illustrative purposes only and do not represent output for use in TSPA nor should they be used to evaluate repository performance.

Temperature response is interpolated (on a logarithmic time scale) from a peak temperature at 70 years to a background temperature of 21°C at one hundred thousand years. To study the system response to differing decay rates, a power term in the interpolation is used. The temperature as a function of time is given by:

$$T(t) = T_o + (21°\text{C} - T_o)\left(\frac{\ln\left(\frac{t}{70\text{yr}}\right)}{\ln\left(\frac{10^5\text{ yr}}{70\text{yr}}\right)}\right)^a, \quad 70\text{yr} \le t \le 10^5\text{ yr} \qquad \text{(Eq. 40)}$$

The peak temperature is given by T_o and the decay term is a. Peak temperature values of 160°C and 220°C and decay term values of 0.4 and 0.8 are evaluated. Schematic temperature-versus-time profiles using a peak temperature of 220°C are shown in Figure 11.



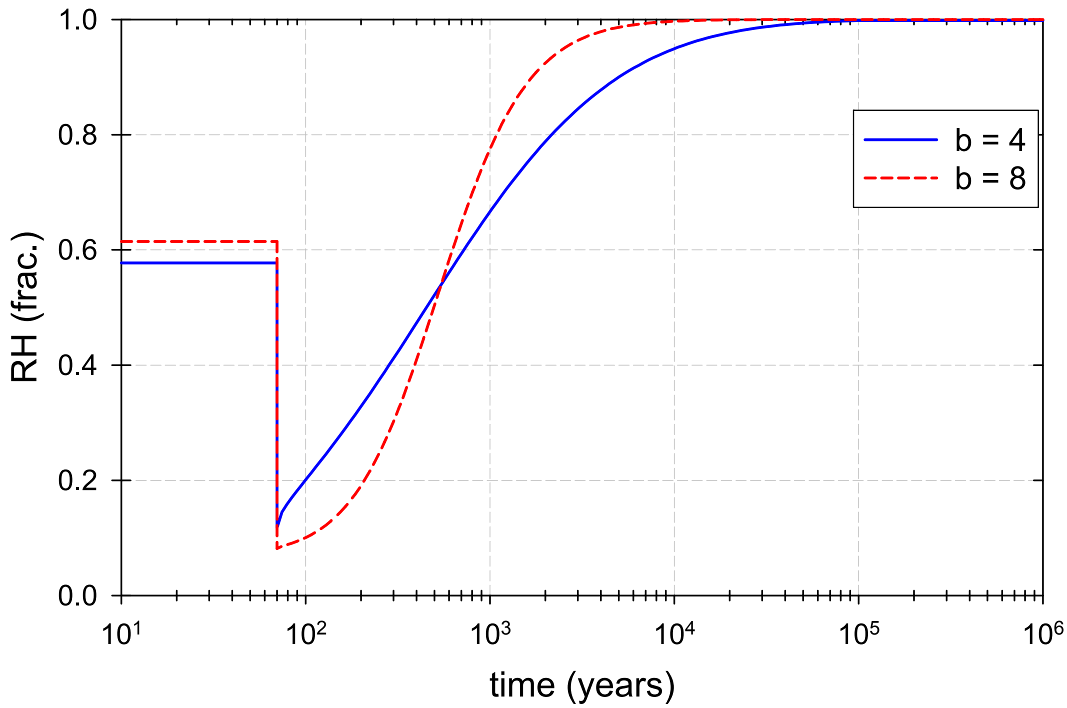
Output DTN: MO0310MWDWAPAN.002.

Figure 11. Schematic Temperature Versus Time Profiles for a Peak Temperature of 220°C and Decay Terms of 0.4 and 0.8

The relative humidity is given by a logistic function of temperature. At low temperature, the fractional RH will reach a limit of one, and at high temperatures, the relative humidity limit will be set at 0.08. The midpoint transition temperature between these limits is set at a temperature of 100°C. The fractional relative humidity as a function of temperature is given by:

$$\mathrm{RH}(T) = 0.08 + \frac{(1.00 - 0.08)}{1 + \left(\frac{T}{100.0°C}\right)^b} \qquad \text{(Eq. 41)}$$

The scaling term, b, is varied to change the rate at which relative humidity, RH, varies with temperature. Scaling term values of 4 and 8 are evaluated. Schematic relative humidity versus time profiles using a peak temperature of 220°C, a decay term of 0.4, and scale terms of 4 and 8 are shown in Figure 12.



Output DTN: MO0310MWDWAPAN.002.

Figure 12. Schematic Relative Humidity Versus Time Profiles for a Peak Temperature of 220°C, Decay Term of 0.4, and Scale Terms of 4 and 8

In this way, a total of eight different thermal hydrologic histories is created; one for each unique combination of the three factors T_o, a, and b. These combinations are summarized in Table 21.

Table 21. Combinations of Peak Temperature, T_o, Decay Term, *a*, and Scaling Term, *b*, Used to Create Representative Thermal Hydrologic Histories

T_o °C	a	b
160	0.4	4
160	0.4	8
160	0.8	4
160	0.8	8
220	0.4	4
220	0.4	8
220	0.8	4
220	0.8	8

All eight thermal hydrologic histories were copied to one exposure file used in the IWPD analysis simulations documented in this report. Each thermal hydrologic history represents the behavior of one-eighth (0.125) of the drip shields and waste packages simulated.

The eight different thermal hydrologic histories were created and combined in one exposure file (WDenv_00_07wheader.ou), to use in the IWPD analysis simulations documented in this report.

Each thermal hydrologic history is considered to represent the behavior of 1/8 (0.125) of the drip shields and waste packages simulated. The format of the thermal hydrology input file conforms to the WAPDEG table format (BSC 2002 [DIRS 162606], Section 4.2.4). The first few lines of the first and second set of exposure histories are shown below:

```
! 1st comment line
! 2nd comment line
! 3rd comment line
#  8  5
#  181
#  0.125
!           t           wpT         wpRH        dsT          dsRH
            1            96      0.577473          96      0.577473
         69.9            96      0.577473          96      0.577473
           70           160     0.2017962         160     0.2017962
     74.40632      139.4507     0.2724015    139.4507     0.2724015
         .             .            .           .             .
         .             .            .           .             .
         .             .            .           .             .
#  181
#  0.125
!           t           wpT         wpRH        dsT          dsRH
            1            96     0.6144519          96     0.6144519
         69.9            96     0.6144519          96     0.6144519
          70            160     0.100933          160     0.100933
     74.40632      139.4507     0.1401267    139.4507     0.1401267
         .             .            .           .             .
         .             .            .           .             .
         .             .            .           .             .
```

The first three lines in the example file (beginning with exclamation points) are comment lines. The user can enter as many comment lines as desired. The WAPDEG software ignores these lines. The user can enter comments designed to enhance traceability and uniquely identify the exposure history file. The next line (# 8 5) is a header line which indicates that the exposure history file contains 8 exposure histories each with five columns. The next line (# 181) is a header line which indicates that the first exposure history contains 181 rows of exposure data. This is followed by (# 0.125) a header line containing the fraction of waste packages to which the exposure history applies (1/8 in this case). The next line again begins with an exclamation point and is a comment line, typically used for column labels. Only one comment line is allowed in this position. The header lines are followed by exposure data, typically consisting of the time, temperature, and relative humidity on the drip shield and waste container surfaces. The next exposure history is preceded by two header lines indicating that it consists of 181 rows and applies to 1/8 of the drip shield waste package pairs.

The WAPDEG input vector (see line 67 of Table I-1) specifies the file index corresponding to the exposure conditions file to be used. In the TSPA-LA, the exposure conditions will vary with spatial bin and fuel type.

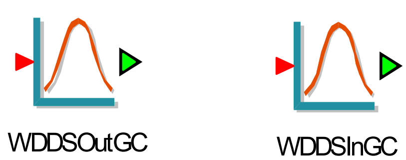
Water conditions (BSC 2002 [DIRS 162606], Sections 3.2.3, 4.2.5.6, 4.2.5.7, and 4.2.5.8) are the mechanism used in WAPDEG to apply corrosion processes to the waste container barriers. The IWPD analysis defines two water conditions. The first, identified by the numerical label “1,” corresponds to the environment under the drip shield and is referred to as the “DSInside” water condition. The second, identified by the numerical label "2," corresponds to the environment above the drip shield and is referred to as the "DSOutside" water condition.

The water condition that applies to the outer (top) surface of the drip shield is defined in the drip sequence data. A drip sequence (BSC 2002 [DIRS 162606], Sections 3.2.2 and 4.2.5.6) is made up of one or more phases, where each phase lasts a specified length of time and is characterized by a constant water contact condition. In the TSPA-LA, only one drip sequence, with one phase, is defined. Lines 68 to 85 of the WAPDEG input vector in Table I-1 define the drip sequence. The water condition number corresponding to this drip sequence is "2" ("DSOutside" water). The drip sequence initially applies to all patches (top and side) on the outer (top) surface of the drip shield. When a drip shield patch penetrates, the drip sequence water condition is transferred to the patches of the underlying waste package outer barrier. Since the drip shield is analyzed with only one patch, when the drip shield fails, all patches of the outer layer of the underlying waste package become subject to the drip sequence water condition ("DSOutside" water).

The water condition that applies to the inner (bottom) surface of the drip shield is defined by the "Drip Shield Initial Water Condition" (BSC 2002 [DIRS 162606], Section 4.2.5.4). For the TSPA-LA, the water condition in effect for the drip shield inner (bottom) surface is specified in line 65 of the WAPDEG input vector to be condition "1" ("DSInside" water condition).

6.4.6 Drip Shield General Corrosion Implementation

General corrosion is the only drip shield degradation process analyzed by integrated waste package degradation (IWPD) analysis (Section 6.3.3). Two cumulative distribution functions were developed for general corrosion of Titanium Grade 7 (Section 4.1.2), one each applicable to the inner surface of the drip shield (Table 4) and for the outer surface (Table 5). These cumulative distribution functions are reproduced in the stochastic elements WDDSOInGC and WDDSOutGC, which are inputs to the WAPDEG DLL (Figure 13).



Output DTN: MO0310MWDWAPAN.002.

Figure 13. Contents of the Gen_Corr_DS Container Element

General corrosion of the drip shield is implemented in WAPDEG using the Power Law functional form (BSC 2002 [DIRS 162606], Section 4.2.6.6). The Power Law functional form has the general representation:

$$D = B\,t^{n} \qquad \text{(Eq. 42)}$$

where

- D = corrosion depth (mm)
- B = Pre-exponent (mm/yr^n)
- t = time (yr)
- n = time exponent

In the current analysis, the time exponent, n, is one.

In WAPDEG, every general corrosion functional form is associated with a single water condition and barrier. Therefore, two implementations of the Power Law functional form are required to define the two possible states of drip shield general corrosion.

The Power Law functional form data is defined in the WAPDEG input vector in lines 165 to 185 ("DSInside" water) and lines 264 to 284 ("DSOutside" water). The B term in Equation 42 is input to WAPDEG as a sampled value from the stochastic WDDSInGC, for the drip shield inner surface and as a sampled value from the stochastic WDDSOutGC, for the drip shield outer surface.

The exponent, n, of the time term, t, in Equation 42 is set to one (lines 180 to 184 and lines 279 to 283).

Note that "inside-out" corrosion of the drip shield proceeds with the water condition defined by the "Drip Shield Initial Water Condition." The water condition defined on line 288 applies only to "inside-out" corrosion of the waste package outer barrier layers (BSC 2002 [DIRS 162606], Sections 4.2.5.4 and 4.2.5.10).

Uncertainty in the general corrosion of titanium is captured by the two stochastics WDDSOutGC and WDDSInGC. These stochastics are sampled once for every TSPA-LA realization and apply to all drip shields.

6.4.7 Waste Package Outer Barrier General Corrosion Implementation

The functional form for the general corrosion rate of the waste package outer barrier is presented in Equation 20 (Section 6.3.4) The rate of general corrosion of the Alloy 22 waste package outer barrier is a function of exposure temperature, with the temperature dependence following an Arrhenius relationship (Section 6.3.4, Equation 17).

General corrosion of Alloy 22 is implemented in WAPDEG using the general linear functional form (BSC 2002 [DIRS 162606], Section 4.2.6.5). The most general form of the general linear functional form is given by Equation 39 (Section 6.4.4). The specific form used for the TSPA-LA implementation of the Alloy 22 corrosion rate is:

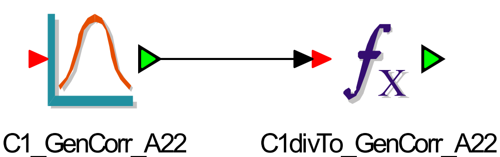
$$D = \exp\left(\ln(R_o) + \frac{C_1}{333.15} + \varepsilon\right)\exp\left(-\frac{C_1}{T}\right)\ t^n \qquad \text{(Eq. 43)}$$

where D is corrosion depth (mm), t is time (yr), and T is exposure temperature (K). This implementation involves a constant term ($\ln(R_o) + C_1/333.15$), the activation energy term (C_1), and an error term, ε. The constant term has two components, $\ln(R_o)$ and $C_1/333.15$. $\ln(R_o)$ is sampled from the (natural logarithm of the) general corrosion rate distribution adjusted for the change of scale (Section 6.3.4). C_1 is normally distributed with a mean of 3,116.47 K and a standard deviation of 296.47 K. The derivation of these two parameters is described in more detail in Section 6.3.4. The error term, ε, is used to adjust the corrosion rate for the dual lid design. This adjustment is required because the lids and outer shell are of different thicknesses.

In WAPDEG, every general corrosion functional form is associated with a single water condition and barrier. "DSInside" and "DSOutside" water conditions can potentially contact the waste package outer barrier. The same general corrosion rate functional form is applied to all surfaces of the waste package outer barrier. Therefore, four almost identical implementations of the general linear functional form are defined, one for each combination of layer and water condition. These four definitions differ only in the error term data.

The general linear functional form data is defined in the WAPDEG input vector in lines 90 to 125 (WPOB outer layer, "DSInside" water), lines 129 to 164 (waste package outer barrier inner layer, "DSInside" water), lines 189 to 224 (waste package outer barrier outer layer, "DSOutside" water), and lines 228 to 263 (WPOB inner layer, "DSOutside" water). Since the same general corrosion functional form applies to both layers and water conditions, these data sections contain essentially the same information. Therefore, only the first (lines 90 to 125) will be discussed in detail.

The first two terms of the general linear functional form specification are defined in lines 100 to 104 ($\ln(R_o)$) and lines 105 to 110 (C_1/ 333.15), respectively. The $\ln(R_o)$ term in Equation 43 is input to WAPDEG as a cumulative distribution functions. Line 101 of the WAPDEG input vector specifies the file index for this cumulative distribution function (line 18 in Table 19). The C_1 term is given by a normal distribution with mean of 3,116.47 K and a standard deviation of 296.47 K truncated at ± 3 standard deviations (Table 7). This normal distribution is defined in the stochastic element C1_GenCorr_A22 (lines 116 to 120). The related term, C_1/333.15, is given by the expression element, C1divTo_GenCorr_A22 (Figure 14). The exponent, n, of the time term, t, in Equation 43 is one (lines 121 to 125). The function of the error term, ε, is explained in Section 6.4.4.



Output DTN: MO0310MWDWAPAN.002.

Figure 14. Contents of the Gen_Corr_WPOB Container Element

Uncertainty in the general corrosion of Alloy 22 is captured by the stochastic C1_GenCorr_A22. This stochastic is sampled once for every TSPA-LA realization and applies to all waste package outer barrier layers.

Variability in the general corrosion of Alloy 22 is represented by the implementation of the $\ln(R_0)$ cumulative distribution functions. The barrier variance sharing for the cumulative distribution function is set to zero (lines 95 to 99). The cumulative distribution function is sampled once, therefore, for every patch of each waste package outer barrier. Each patch on the waste package outer barrier surface will have a different corrosion rate. This captures the variation in the general corrosion rate over the waste package surface.

Variability in the general corrosion of Alloy 22 is also expressed in Equation 43 through the exposure temperature variable, which varies spatially and temporally, according to the thermal hydrologic history files.

6.4.8 Weld Flaw Implementation

Weld flaws in waste package closure lid welds are the only manufacturing defects identified as having the potential to affect waste package performance (Section 6.3.8). The weld flaws in the closure lid welds are likely sites for stress corrosion cracking initiation, and are, therefore, part of the IWPD analysis of stress corrosion cracking (Section 6.3.5.2).

Stress corrosion cracking is implemented in WAPDEG by the use of a slip dissolution event (BSC 2002 [DIRS 162606], Sections 3.3.2.1.1 and 4.2.7.5). The slip dissolution event will be described in more detail in Section 6.4.10. When a slip dissolution event includes defect (weld) flaws, the weld flaw density, and size distribution are defined by a manufacturing defects event (BSC 2002 [DIRS 162606], Sections 3.3.2.1 and 4.2.7.2).

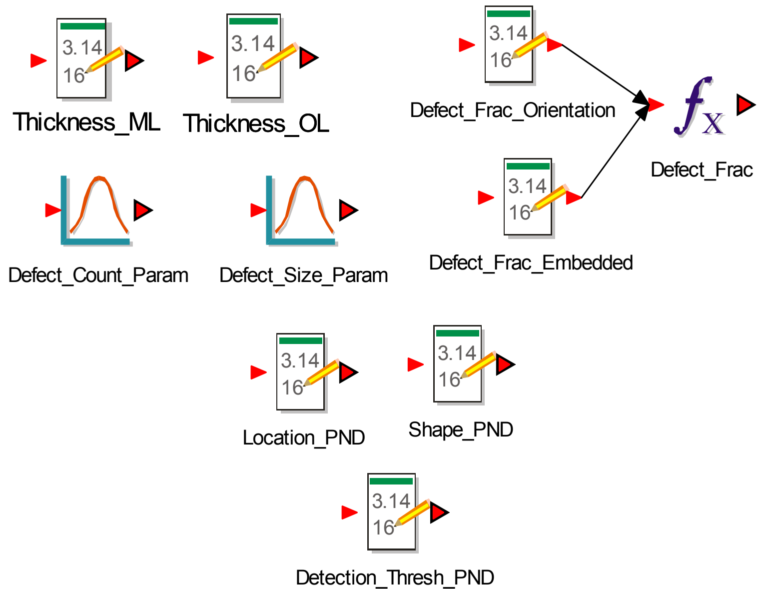
In WAPDEG, a corrosion-affecting event can apply to one barrier and one or more water conditions and can have effects specific to that event, as well as generic effects. The manufacturing defects event has only one specific effect, to introduce manufacturing defects onto patches.

A separate manufacturing defects event must be defined for the outer and middle closure lids. The closure lids can potentially be subject to both exposure conditions; therefore, both water conditions (“DSInside” and “DSOutside” water) are defined. Two manufacturing defect events are defined in lines 291 to 310 (outer closure lid) and lines 311 to 330 (middle closure lid) of the WAPDEG input vector (Table I-1). The inputs to the manufacturing defects event consist of a probability that a barrier has manufacturing defects, a distribution for the number of manufacturing defects per barrier (defect density), and a defect size distribution.

In the TSPA-LA, the defect probability, and the defect density and size distributions are calculated by the CWD DLL (Figure 9 and Figure 10).

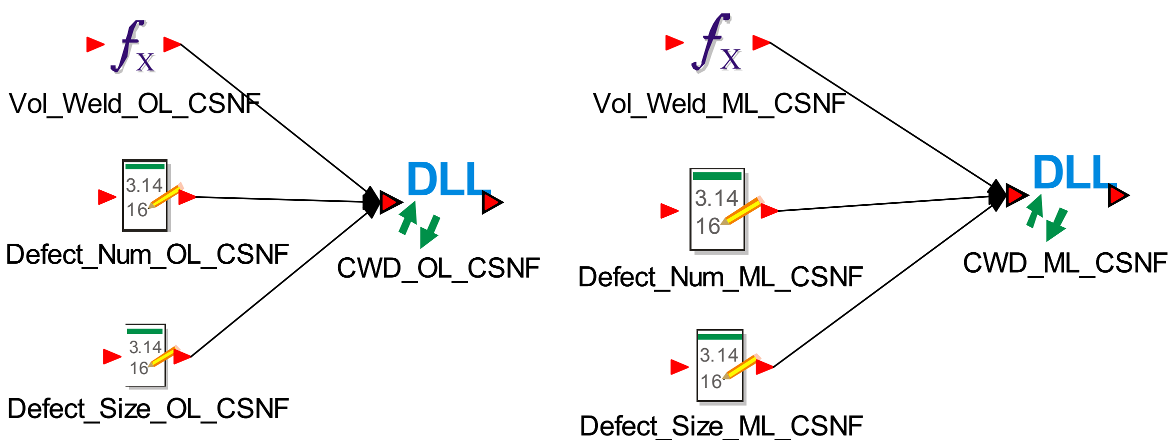
CWD computes the cumulative probability of a manufacturing defect based on the probability for the nondetection of weld flaws. Inputs to this calculation are the weld thickness, the weld volume, the defect fraction considered, a detection threshold, a characteristic flaw size, a shape factor, a defect count parameter, and a defect size parameter. The details of this calculation are provided in Section 6.3.5.2.

The global input parameters to CWD DLL are held in the container element CWD (Figure 15). The weld thickness is given by the data elements Thickness_OL and Thickness_ML (for the outer and middle closure lids). The defect fraction considered is calculated in the expression element, Defect_Frac, as the product of the fraction of defects capable of propagation based on orientation (Defect_Frac_Orientation) and the fraction of embedded manufacturing defects to propagate (Defect_Frac_Embedded). The detection threshold is defined in the data element Detection_Thresh_PND. The characteristic flaw size and shape factor are defined in the data elements Location_PND and Shape_PND, respectively. The defect count parameter is given by a gamma distribution defined in the stochastic element Defect_Count_Param. The defect size parameter is given by a gamma distribution defined in the stochastic element Defect_Size_Param. The values of all of these parameters are taken from Table 8.



Output DTN: MO0310MWDWAPAN.002.

Figure 15. Contents of the CWD Container Element (Global CWD DLL Inputs)



Output DTN: MO0310MWDWAPAN.002.

Figure 16. Contents of the CWD_CSNF Container Element

The local input parameters to the CWD DLL are held in the container CWD_CSNF (CWD_CDSP). The contents of the CWD_CSNF container element are shown in Figure 16. The input parameter, weld volume (Vol_Weld_OL_CSNF and Vol_Weld_ML_CSNF in Figure 16), is not globally defined, but depends on the waste package type. The values for both waste package types and both lids are provided in Table 8.

The output of CWD consists of two tables, and the probability of the occurrence of at least one defect per waste package. The four data elements, Defect_Num_OL_CSNF, Defect_Size_OL_CSNF, Defect_Num_ML_CSNF, and Defect_Size_ML_CSNF contain the file indices for CWD output tables. These output tables contain distributions for the density and size of weld flaws, on the outer and middle closure lids. The CWD outputs are direct inputs to the manufacturing defects event in WAPDEG.

The probability of at least one weld flaw is input at lines 296 and 316 of the WAPDEG input vector (Table I-1), for the outer and middle closure lids, respectively. The file indices corresponding to the number of flaws distribution are input at lines 297 to 301 and lines 317 to 321 of the WAPDEG input vector (Table I-1), for the outer and middle closure lids, respectively. The file indices corresponding to the flaw size distribution are input at lines 302 to 306 and lines 322 to 326 of the WAPDEG input vector (Table I-1), for the outer and middle closure lids, respectively.

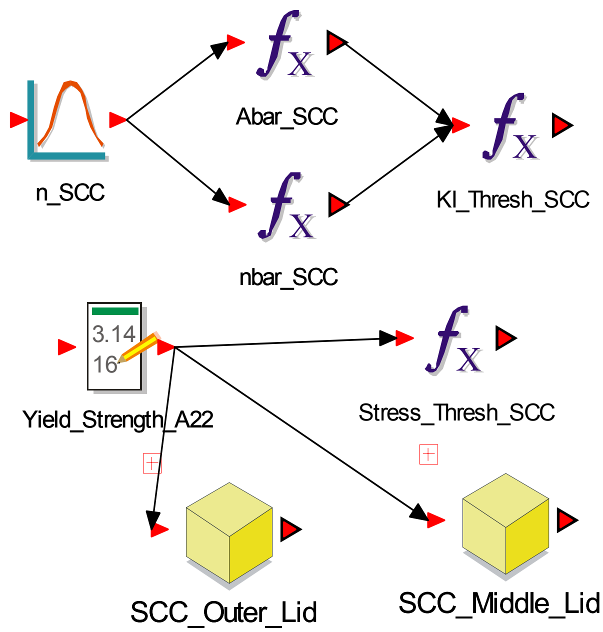
Uncertainty is inherent in the calculation of the probability of at least one weld flaw, via the probability for nondetection (PND) function. The calculation of this function uses the parameters Detection_Thresh_PND, Location_PND, and Shape_PND. Uncertainty in the weld flaw density and size is represented by the uncertain parameters (Defect_Count_Param and Defect_Size_Param) that form components of the calculation of the density and size distributions.

Spatial variability in the weld flaw density and size results from the density and size distributions, which form the input to the manufacturing defects event. These distributions are sampled once for each layer of each waste package. They are then randomly distributed to stress corrosion cracking patches on the waste package outer barrier layers (BSC 2002 [DIRS 162606], Section 4.2.7.2).

6.4.9 Stress and Stress Intensity Factor Profile Implementation

The dominant component of stress in the waste package outer barrier closure lid weld regions has been determined to be hoop stress, which promotes radially oriented crack growth. The stress and stress intensity factor profiles are part of a slip dissolution event (BSC 2002 [DIRS 162606], Section 3.3.2.1.1 and Section 4.2.7.5). The slip dissolution event will be described in more detail in Section 6.4.10. The part of the event data that pertains to the stress and stress intensity factor will be discussed here.

The slip dissolution event requires as input, a stress intensity factor, K_I, versus depth table, and a stress versus depth table. In the TSPA-LA, these tables are produced by the SCCD DLL (Figure 10). In particular, the SCCD software calculates the variation in stress and stress intensity versus depth and angle. Inputs to this calculation are four coefficients used to calculate the stress versus depth, the sine of the fracture angle, the number of angles to be calculated, the yield strength, the yield strength scaling factor, and the angular amplitude of the stress variation. Also required is an uncertain deviation from median yield strength range and a table of stress intensity versus depth. The details of this calculation are given in the SMR for the SCCD software.



Output DTN: MO0310MWDWAPAN.002.

Figure 17. Contents of the SCC Container Element

The input parameters to the SCCD DLL are held in the container element SCC (Figure 17). The global parameter, yield strength, is defined in Table 9 and input via the data element Yield_Strength_A22. The remaining input parameters are barrier-dependent, and are defined for the outer and middle closure lids in the container elements SCC_Outer_Lid and SCC_Middle_Lid. The contents of the container element SCC_Outer_Lid are shown in Figure 18. The contents of the corresponding container for the middle lid are entirely analogous.

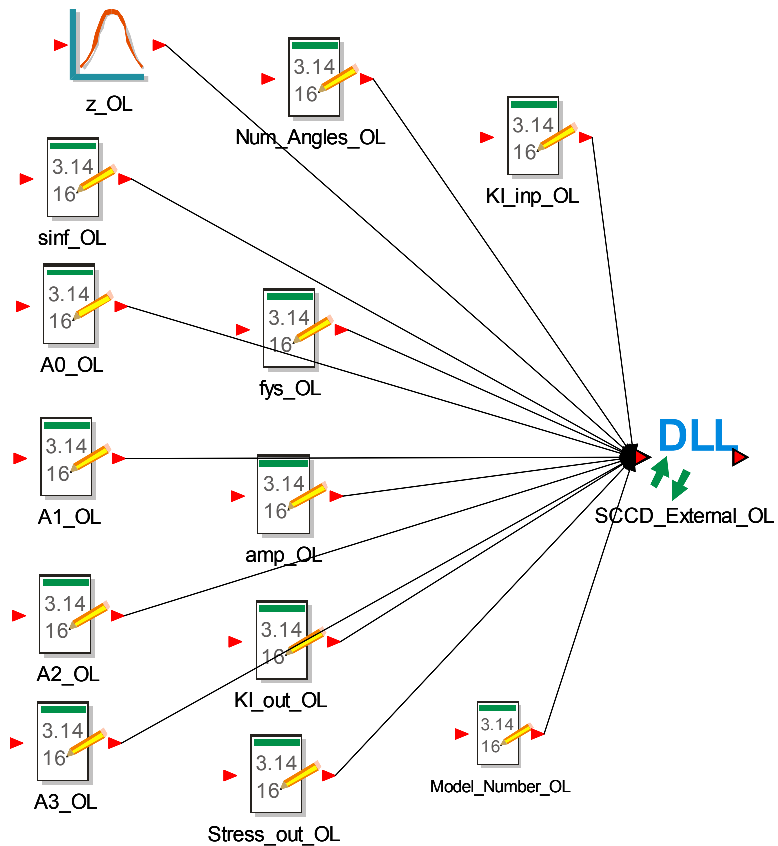
The four coefficients are defined in Table 10, for both lids. The outer lid values are stored in data elements A0_OL, A1_OL, A2_OL, and A3_OL. The sine of the fracture angle is defined in the data element sinf_OL. This value is always one, since only radial cracks are considered. The number of angles for which the calculation will be performed is set in the data element Num_Angles_OL. The yield strength scaling factor, fys_OL, is defined in Section 6.3.5.1 to be 15 percent of the yield strength. The angular amplitude of the stress variation, amp_OL, is defined in Equation 4 (17.236893). The input table of stress intensity factor versus depth is defined in Table 11. The WD4DLL.WAP file index for this table is contained in the data element KI_inp_OL.

Uncertainty in the stress and stress intensity factor profiles is included via an uncertainty scaling factor, z, given by

$$z = \left(\frac{z\_OL \times Yield\_Strength\_A22 \times fys\_OL}{3} \right) \tag{Eq. 44}$$

z_OL represents the uncertain variation away from the median value and is sampled from a truncated normal distribution with a mean of zero, a standard deviation of one, and is truncated at three standard deviations. The uncertainty scaling factor, *z*, then has standard deviation given by 5 percent of yield strength (since fys_OL = 0.15), as specified in Table 9.

Two implementations of the uncertainty are possible, according to the value in the data element, Model_Number_OL. Details of the two uncertainty implementations are given in the SMR for the SCCD software.



Output DTN: MO0310MWDWAPAN.002.

Figure 18. Contents of SCC_Outer_Lid Container Element

Outputs of the SCCD DLL are stress and stress intensity tables, as a function of depth, calculated at a number of angles (equally spaced and in the range 0 to π radians, inclusive). The two data elements, Stress_out_OL and KI_out_OL contain the file indices for the SCCD output tables. The SCCD outputs are direct inputs to the slip dissolution event in WAPDEG.

The WD4DLL.WAP file indices corresponding to the tables of stress intensity-versus-depth and stress-versus-depth tables are input at lines 340 and 341 and lines 418 and 419 of the WAPDEG input vector (Table I-1), for the outer and middle closure lids, respectively.

6.4.10 Slip Dissolution Implementation

Stress corrosion cracking is implemented in WAPDEG by the use of a slip dissolution event (BSC 2002 [DIRS 162606], Sections 3.3.2.1.1 and 4.2.7.5). In WAPDEG, cracking can be initiated at incipient cracks or weld flaws, or both. Stress corrosion cracking due to both incipient cracks and weld flaws is analyzed using the slip dissolution event.

In WAPDEG, a corrosion-affecting event can apply to one barrier and one or more water conditions and can have effects specific to that event, as well as generic effects. The slip dissolution event has one specific effect, to initiate stress corrosion cracking.

A separate slip dissolution event must be defined for each closure lid (outer and middle). The closure lids can potentially be subject to both DSInside and DSOutside exposure conditions; therefore, both water conditions are included. The two slip dissolution events are defined in lines 331 to 408 (outer closure lid) and lines 409 to 486 (middle closure lid) of the WAPDEG input vector (Table I-1). Incipient cracks are automatically included in the event, but weld flaws must be specifically included (lines 336 and 414 of the WAPDEG input vector). Note that the event is restricted to apply only to side patches (closure lid region), by the data entered at lines 337 to 339 and lines 415 to 417.

Using this event, cracks, once initiated, grow at a rate given by:

$$V = \overline{A}\left(K_I\right)^{\overline{n}} \quad \text{(Eq. 45)}$$

where

V = crack velocity
$\overline{A}$ = Pre-exponential factor
K_I = Stress intensity factor
$\overline{n}$ = Repassivation rate (or slope)

The crack growth parameters ($\overline{A}$ and $\overline{n}$) are defined by Equations 10 and 11 (Section 4.1.6) and by the repassivation slope in Table 12. They are input to the WAPDEG input vector at lines 352 to 361 and at lines 430 to 439. The parameters Abar_SCC and nbar_SCC correspond to the TSPA-LA expression elements of the same name, in the SCC container element (Figure 17). Abar_SCC and nbar_SCC are a function of the repassivation slope, n_SCC. The repassivation slope is sampled from the stochastic element, n_SCC, defined by a truncated normal distribution (at ± 2 sds), with a mean of 1.304 and a standard deviation of 0.16 (Table 12).

The number of incipient cracks per patch is defined in the barrier definition data of the WAPDEG input vector. This definition is found in lines 11 to 15, for the outer closure lid and lines 24 to 28 for the middle closure lid. The incipient crack densities are six cracks per patch and 15 cracks per patch, respectively (Section 6.3.5). The number of weld flaws per patch (defect flaw density) is defined by the manufacturing defects event for each closure lid (Section 6.4.8). The stress corrosion cracking slip dissolution event requires data for incipient crack size. The incipient crack size, defined in Table 12, is input at lines 362 to 366 and at lines 440 to lines 444 of the WAPDEG input vector.

The slip dissolution event also requires both a stress threshold or a stress intensity factor threshold or both, for crack growth initiation. These thresholds are defined separately for incipient cracks and weld flaws. The values of stress threshold and stress intensity factor threshold are defined in Table 12. They are contained in the expression elements

Stress_Thresh_SCC and KI_Thresh_SCC. The thresholds for the incipient cracks are defined in lines 373 to 382 and in lines 451 to 460 of the WAPDEG input vector. The thresholds for the weld flaws are entered in lines 383 to 392 and lines 461 to 470 of the WAPDEG input vector. Note that both the incipient cracks and weld flaws use the same stress intensity factor threshold. However, the defect (weld) flaws do not require a stress threshold to nucleate (Section 4.1.6) and, therefore, a relatively large negative number (–600) is input as the stress threshold.

Uncertainty in the crack growth and in the stress intensity factor threshold is represented by the uncertainty in the repassivation slope. The repassivation slope is sampled by the stochastic element n_SCC, once every realization. The stress and stress intensity factor tables, produced by the SCCD DLL, include uncertainty due to the use of a scaling factor that describes the deviation from the median stress/stress intensity profile. This scaling factor is sampled by the stochastic element z_OL, once every realization. Uncertainty in the probability of occurrence and the density and size distributions for weld flaws is included via the stochastic elements (Defect_Count_Param and Defect_Size_Param) that form part of the CWD calculation (Section 6.4.8). Note that there is no uncertainty associated with the density and size distribution of the incipient cracks. These are explicitly defined at lines 12, 25, 363, and 441.

Spatial variability is included in the crack growth analysis via the stress versus depth and stress intensity factor versus depth tables. A new set of tables is calculated for every realization. The tables are sampled for every patch that is subject to stress corrosion cracking. Spatial variability in the density and size of the weld flaws is also included, as described in Section 6.4.8.

6.4.11 Waste Package Outer Barrier Microbially Influenced Corrosion Implementation

The effect of microbially influenced corrosion (MIC) on the general corrosion of the waste package outer barrier is described in Section 6.3.6. Equation 36 defines a MIC general corrosion rate enhancement factor, f_{MIC}. The MIC general corrosion rate enhancement factor is applied to the waste package outer barrier general corrosion rate when the relative humidity at the waste package outer barrier surface is above 90 percent.

MIC is analyzed by the use of a MIC event (BSC 2002 [DIRS 162606], Section 4.2.7.10). The WAPDEG input vector defines two MIC events, one for the outer layer (lines 487 to 520 of Table I-1) and one for the inner layer (lines 521 to 554 of Table I-1).

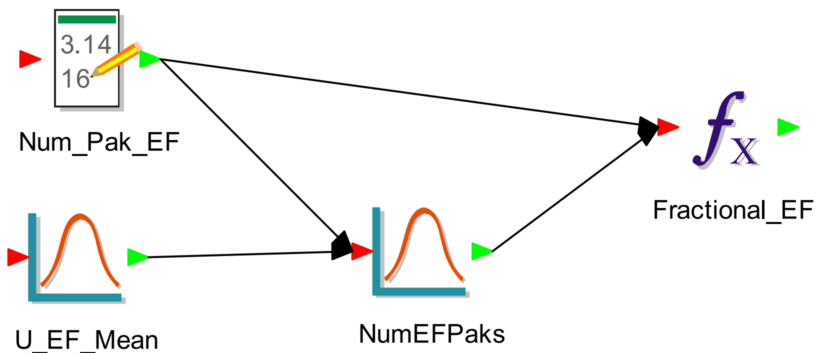
In both cases, the MIC general corrosion rate enhancement factor is applied to the entire surface area (lines 492 and 526 of Table I-1). The threshold relative humidity for initiation of MIC is entered as a fraction (i.e., 0.9) (Table 13) in lines 499 to 503 and lines 533 to 537 of Table I-1.

The MIC general corrosion rate enhancement factor is input to WAPDEG as a sampled value from the stochastic MIC_A22 (Figure 10). This stochastic is defined to be uniformly distributed between 1 and 2 (Table 13). It is entered in lines 514 to 518 of the WAPDEG input vector, for the outer layer, and in lines 548 to 552, for the inner layer. The same value is used for both layers.

Uncertainty in the MIC general corrosion rate enhancement factor is represented by the stochastic element MIC_A22. There is no variability in the MIC general corrosion rate enhancement factor (the factor is applied to the whole waste package outer barrier surface area).

6.4.12 Implementation of Early Failure of Waste Packages

The early failure implementation consists of specifying the number of waste packages to be considered as potentially subject to early failure and the distribution for the failure rate per waste package. The distribution for the failure rate was discussed in Sections 4.1.8 and 6.3.8. A sample GoldSim implementation is shown in Figure 19.



Output DTN: MO0310MWDWAPAN.002.

Figure 19. Example GoldSim Implementation to Determine the Fraction of Early Failed Waste Packages

The values used in the GoldSim elements in Figure 19 are summarized in Table 22.

Table 22. Waste Package Early Failure Parameters and Their Sources

Parameter Name	Parameter Source	Parameter Value	Units
Num_Pak_EF Number of Waste Packages considered	This is a TSPA parameter to be specified by TSPA Model at runtime	e.g., 11,184 (representative value, see discussion under Parameter Source)	N/A
U_EF_Mean Evaluation probability per Waste Package (Uncertain Poisson intensity)	This report (Section 6.3.8)	Log normal distribution with a geometric mean of 7.2×10^{-6} and a geometric sd of $15^{(1/1.645)}$ truncated at an upper-bound of 7.44213×10^{-3}	per waste package
NumEFPaks Number of Early Failed Waste Package in the realization	BSC 2004 [DIRS 170024], Section 7, Table 22	Poisson Distribution with intensity Num_Pak_EF*U_EF_Mean	Number of waste packages per realization
Fractional_EF Fraction of Early Failed Waste Package in the realization	This report (This section)	NumEFPaks/Num_Pak_EF	fraction of waste packages per realization

The value of Num_Pak_EF should be chosen appropriately for the purpose of the study. For example, if one wanted to know how many (or what fraction of) waste packages will undergo early failure in a given realization, one should set Num_Pak_EF equal to the total number of wate packages (i.e., 11,184) (Section 4.1.1). Alternatively, if one wanted to know how many

CDSP waste packages will undergo early failure in a given realiztion, one should set Num_Pak_EF equal to the total number of CDSP waste packages (i.e., 3,412) (Section 4.1.1). Three types of waste packages are considered; CDSP, CSNF with zirconium-based cladding on the waste form, and CSNF with stainless steel-based cladding on the waste form. The separation of CSNF waste package configurations is made for the purposes of incorporating differences in waste form degradation.

A marginal distribution for the number of early failed waste packages which incorporates the uncertainty variation is analysed here. This is evaluated by integrating the Poisson probability density function with the rate of early failure probability density function (given by the log normal distribution) over their given ranges. This integration results in the marginal distribution for number of early failed waste packages given the total number of waste packages ($N = 11{,}184$). The integral is numerically evaluated over its domain from zero to the truncated upper-bound. The log normal probability density function is also adjusted to its truncated upper-bound representation so that the probability density function integrates to one over its effective range. This upper-bound is chosen so that it is as large as any of the rate values from the Monte Carlo study to which the log normal was fitted. The marginal distribution integral is represented below, where *f(x)* and *F(x)* are the probability density function and cumulative distribution function of the lognormal distribution, *N* is the population of packages considered, and *n* is the count of early failed waste packages.

$$p(n) = \int_0^{\lambda_m} (\lambda N)^n \times \frac{\exp(-\lambda N)}{n!} \times \frac{f(\lambda)}{F(\lambda_m)} \times d\lambda \qquad \text{(Eq. 46)}$$

The discrete probability density function, *p(n)*, evaluated for values of $n = 0, 1, 2, \ldots$, gives the probability of *n* packages being failed early. The integral upper-bound, represented by λ_m, is 7.44213×10^{-3} for numerically evaluating the marginal distribution.

Evaluating this marginal probability density function for various values of *n* provides the following results. Only 17 percent of the realizations have early failures, 83 percent of realizations have no early failed waste packages (Table 23). Realizations with only one early failure account for 11.4 percent of realizations and 3 percent of realizations have two early failed waste packages. This leaves 2.6 percent of the remaining realizations having three or more failed waste packages.

Table 23. Early Failure Waste Package Unconditional Probability Values

n (Number of Waste Packages)	p(n)
0	0.830177156
1	0.114170546
2	0.029481907
≥3	0.026170391

Output DTN: MO0310MWDWAPAN.002.

A second probability density function is derived from the probability density function (Equation 46) given that at least one waste package has undergone early failure by renormalizing the probabilities associated with having at least one early failed waste package. This second probability density functions called a conditional distribution (i.e., conditional on the fact that at least one failure has occurred). For purposes of constructing a probability density function table, a maximum value of $n = n_m$ is chosen such that having a value of n larger can be neglected. The maximum count value chosen (n_m = 111) is the count associated with the mean plus three standard deviations. The probability of all count values larger than n_m is small, 1.7×10^{-9}. The conditional probability density function, *pc(n)*, is given below by normalizing the individual probabilities of failure (*p(n)*) by the sum of the probabilities (*p(i)*) for $i = 1, 2, \ldots, n_m$ (Equation 47). Values for this probability density function are in Table 41.

$$pc(n) = \frac{p(n)}{\sum_{i=1}^{n_m} p(i)}, \qquad (n = 1,2,\ldots,n_m) \qquad \text{(Eq. 47)}$$

The distributions above can be sampled directly for unconditional or conditional counts of early failed waste packages, respectively. If it is then required to partition this count between differing package types this may be done by expressing the count as a sample from a multinomial distribution. The parameters for the multinomial distribution would be n and the probabilities of each waste package type, where these probabilities are given by the ratio of the number of packages in the repository for that type (N_i, such that $N = \Sigma N_i$) to the total of number of all package types (i.e., N). To generate a multinomial distribution, a simple way is to work with the marginals since they are binomials. The generation is done sequentially. Each succeeding conditional marginal is a binomial. As an example, an implementation for three (waste form) waste package types would be performed as in Table 24.

Table 24. Multinomial Sampling Algorithm (Three Waste Package Types)

1. Sample a value for n.
2. Sample n_1 as a Binomial(n, $p = N_1/N$).
3. Sample n_2 as a Binomial($n - n_1$, $p = N_2/(N-N_1)$).
4. Sample n_3 as a Binomial($n - n_1 - n_2$, $p = N_3/(N-N_1-N_2) = 1$). That is $n_3 = n - n_1 - n_2$.

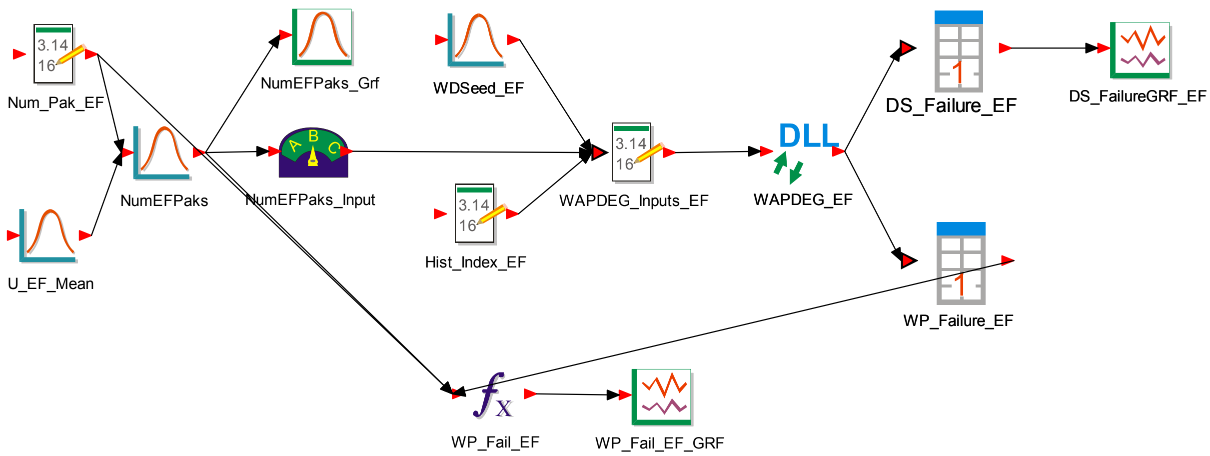
While the analysis above provides counts of early failed waste packages, the effect and time of an early failure are presented in the discussion that follows.

While the failure mechanisms are expected to result in enhanced probability of stress corrosion cracking, the waste packages are treated as failed upon initiation of corrosion processes. The following recommendations are made in *Analysis of Mechanisms for Early Waste Package/Drip Shield Failure* (BSC 2004 [DIRS 170024], Section 6.4.8) for evaluating waste package early failure:

- A failure of the waste package outer barrier shell and outer and middle closure lids should be assumed
- The affected waste packages should be assumed to fail immediately upon initiation of degradation processes

- The entire waste package surface area should be considered affected by improper heat treatment
- The materials of the entire affected area should be assumed lost upon failure of the waste packages, because the affected area could be subjected to stress corrosion cracking and enhanced localized and general corrosion.

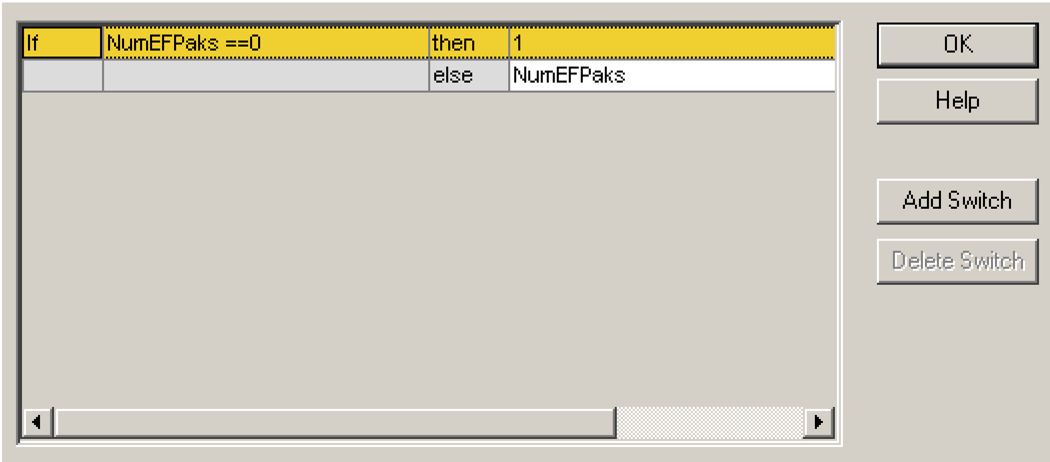
An example GoldSim implementation which determines the number and failure time of early failed waste packages is shown in Figure 20.



Output DTN: MO0310MWDWAPAN.002.

Figure 20. Example GoldSim Implementation to Determine the Number and Failure Time of Early Failed Waste Packages

It is expected that not all of this implementation will be used; it is provided to guide the implementation of the early failure analysis in TSPA. The parameters Num_Pak_EF, U_EF_Mean, and NumEFPaks are familiar from the previous figure. The element labeled NumEFPaks_GRF is merely a graphical element used to show the user a plot of the number of early failed waste packages per realization. It has no effect on the results of the calculation and can be removed. The element labeled NumEFPaks_Input is a switch element whose contents are shown in Figure 21.



Output DTN: MO0310MWDWAPAN.002.

Figure 21. Contents of NumEFPaks_Input Element

The effect of this element is clear; if the number of sampled waste packages subject to early failure is zero, then the number of waste packages analyzed by WAPDEG is set to one; if the number of sampled waste packages subject to early failure is one or more, then the number of waste packages analyzed by WAPDEG is unchanged. This is done so that WAPDEG is not called with zero waste packages (which would result in an error).

The element WDSeed_EF provides WAPDEG with a seed value (through the WAPDEG_Inputs_EF element). Similarly, the Hist_Index_EF provides WAPDEG with the file index for the thermal hydrologic history file index (the line number in the WD4DLL.WAP file) to be used (through the WAPDEG_Inputs_EF element). The contents of the WAPDEG_Inputs_EF element are shown in Table 25.

Table 25. Contents of the WAPDEG_Inputs_EF Element

Row	Value	Input Description	Comments/Units
1	Realization	Realization Number	
2	1	Number of Barriers	
3	1	Barrier Type	A22 OB
4	25	Barrier Thickness	mm
5	0.75	Barrier Mechanical Failure Fraction	fraction
6	1,000	Barrier Pit Density Distribution Index	Fixed
7	0	Parameter1	/mm^2
8	0	Parameter 2	
9	0	Parameter 3	
10	0	Parameter 4	
11	1,000	Barrier Crack Density Distribution Index	Fixed
12	0	Parameter1	/mm^2
13	0	Parameter 2	
14	0	Parameter 3	
15	0	Parameter 4	
16	1	Waste Container Surface Area	mm^2

Table 25. Contents of the WAPDEG_Inputs_EF Element (Continued)

Row	Value	Input Description	Comments/Units
17	1	Waste Container Top Fraction	fraction
18	0	Waste Container Bottom Fraction	fraction
19	1,000	Waste Container Patch Size Distribution Index	Fixed
20	1	Parameter1	mm^2
21	0	Parameter 2	
22	0	Parameter 3	
23	0	Parameter 4	
24	-1	Apply Size Boolean	TRUE
25	-1	Drip Shield Present Boolean	TRUE
26	3	Drip Shield Type	Ti7 DS
27	15	Drip Shield Thickness	mm
28	0.75	Drip Shield Mechanical Failure Fraction	fraction
29	1,000	Drip Shield Pit Density Distribution Index	Fixed
30	0	Parameter1	/mm^2
31	0	Parameter 2	
32	0	Parameter 3	
33	0	Parameter 4	
34	1,000	Drip Shield Crack Density Distribution Index	Fixed
35	0	Parameter1	/mm^2
36	0	Parameter 2	
37	0	Parameter 3	
38	0	Parameter 4	
39	Number_DS_Patches	Drip Shield Surface Area	mm^2
40	1	Drip Shield Top Fraction	fraction
41	1,000	Drip Shield Patch Size Distribution Index	Fixed
42	1	Parameter1	mm^2
43	0	Parameter 2	
44	0	Parameter 3	
45	0	Parameter 4	
46	-1	Drip Shield Apply Size Boolean	TRUE
47	1,000	Drip Shield Fractional Area Affected Distribution Index	Fixed
48	1	Parameter1	fraction
49	0	Parameter 2	
50	0	Parameter 3	
51	0	Parameter 4	
52	1	Initial Water Condition under drip shield	DSInside
53	NumEFPaks_Input	Total Number of Waste Packages	
54	Hist_Index_EF	Index Number of T/H File to Read	
55	1	Number of Drip Sequences	
56	1	Number of Phases - Drip Sequence #1	
57	1,000	Fraction of Top Patches Subject to Sequence Distribution Number	Fixed
58	1	Parameter1	fraction

Table 25. Contents of the WAPDEG_Inputs_EF Element (Continued)

Row	Value	Input Description	Comments/Units
59	0	Parameter 2	
60	0	Parameter 3	
61	0	Parameter 4	
62	1,000	Fraction of Side Patches Subject to Sequence Distribution Number	Fixed
63	1	Parameter1	fraction
64	0	Parameter 2	
65	0	Parameter 3	
66	0	Parameter 4	
67	1,000	Fraction of Bottom Patches Subject to Sequence Distribution Number	Fixed
68	1	Parameter1	fraction
69	0	Parameter 2	
70	0	Parameter 3	
71	0	Parameter 4	
72	2	Water Condition for Last Phase	DSOutside
73	4	Number of Corrosion Functional Forms	
74	1	Water Condition Index Number	DSInside
75	1	Corrosion Mechanism Index (1, 2, or 3)	General
76	1	Layer Composition Index	A22 OB
77	6	Functional Form Index	Power Law
78	2	Number of Levels for Variance Sharing	
79	1,000	Barrier Variance Sharing Distribution Index	Fixed
80	1	Parameter1	fraction
81	0	Parameter 2	
82	0	Parameter 3	
83	0	Parameter 4	
84	1,000	B term distribution	Fixed
85	1.00E+14	Parameter1	
86	0	Parameter 2	
87	0	Parameter 3	
88	0	Parameter 4	
89	1,000	n term distribution	Fixed
90	1	Parameter1	
91	0	Parameter 2	
92	0	Parameter 3	
93	0	Parameter 4	
94	0	Sample Type	
95	1	Water Condition Index	DSInside
96	1	Corrosion Mechanism Index (1, 2, or 3)	General
97	3	Layer Composition Index	Ti7 DS
98	6	Functional Form Index - D = B*t^n	Power Law
99	2	Number of Levels for Variance Sharing	

Table 25. Contents of the WAPDEG_Inputs_EF Element (Continued)

Row	Value	Input Description	Comments/Units
100	1,000	Barrier Variance Sharing Distribution Index	Fixed
101	1	Parameter1	fraction
102	0	Parameter 2	
103	0	Parameter 3	
104	0	Parameter 4	
105	1,000	B Distribution Index	Fixed
106	WDDSInGC	Parameter1	mm/yr
107	0	Parameter 2	
108	0	Parameter 3	
109	0	Parameter 4	
110	1,000	n Distribution Index	Fixed
111	1	Parameter1	
112	0	Parameter 2	
113	0	Parameter 3	
114	0	Parameter 4	
115	0	Sample Type	
116	2	Water Condition Index	DSOutside
117	1	Corrosion Mechanism Index (1, 2, or 3)	General
118	1	Layer Composition Index	A22 OB
119	6	Functional Form Index	Power Law
120	2	Number of Levels for Variance Sharing	
121	1,000	Barrier Variance Sharing Distribution Index	Fixed
122	1	Parameter1	fraction
123	0	Parameter 2	
124	0	Parameter 3	
125	0	Parameter 4	
126	1,000	B term distribution	Fixed
127	1.00E+14	Parameter1	
128	0	Parameter 2	
129	0	Parameter 3	
130	0	Parameter 4	
131	1,000	n term distribution	Fixed
132	1	Parameter1	
133	0	Parameter 2	
134	0	Parameter 3	
135	0	Parameter 4	
136	0	Sample Type	
137	2	Water Condition Index	DSOutside
138	1	Corrosion Mechanism Index (1, 2, or 3)	General
139	3	Layer Composition Index	Ti7 DS
140	6	Functional Form Index - D = B*t^n	Power Law
141	2	Number of Levels for Variance Sharing	
142	1,000	Barrier Variance Sharing Distribution Index	Fixed

Table 25. Contents of the WAPDEG_Inputs_EF Element (Continued)

Row	Value	Input Description	Comments/Units
143	1	Parameter1	
144	0	Parameter 2	
145	0	Parameter 3	
146	0	Parameter 4	
147	1,000	B Distribution Index	Fixed
148	WDDSOutGC	Parameter1	mm/yr
149	0	Parameter 2	
150	0	Parameter 3	
151	0	Parameter 4	
152	1,000	n Distribution Index	Fixed
153	1	Parameter1	
154	0	Parameter 2	
155	0	Parameter 3	
156	0	Parameter 4	
157	0	Sample Type	
158	0	Number of General Thresholds	
159	0	Number of Pit Temperature Thresholds	
160	-1	Inside Out Corrosion Logical	TRUE
161	2	Water Condition for Inside Out Corrosion	DSOutside
162	0	Interface Corrosion Logical	FALSE
163	0	Number of Events	
164	WDSeed_EF	Seed for the random number generator	
165	NumBins	Number of bins for reporting penetrations with time	
166	BinStart	Bin Start Time	
167	0	Number of summary times for reporting penetrations	
168	0	Do Subset of Total Package Logical	FALSE
169	1	Number of First Package	
170	1	Number of Last Package	
171	SimTime	Simulation Time	
172	11	Number of Output files	
173	0	Generate OUT file logical	
174	0	Generate AUX file logical	
175	0	Generate PIT file logical	
176	0	Generate CRK file logical	
177	0	Generate PAT file logical	
178	0	Generate THK file logical	
179	0	Generate EVN file logical	
180	0	Generate DET file logical	
181	0	Generate INA file logical	
182	0	Generate OUA file logical	
183	0	Generate PDZ file logical	

Output DTN: MO0310MWDWAPAN.002.

This WAPDEG input vector is much simplified compared to the nominal WAPDEG input vector. The WAPDEG_Inputs_EF vector contains input for analyzing NumEFPaks_Input number of drip shield–waste package pairs. The drip shield is analyzed with the same general corrosion rates used in the nominal IWPD analysis (lines 106 and 147 in Table 25). A very high (10^{14} mm/yr general corrosion rate is chosen for the single-barrier waste package (line 126 of Table 25) resulting in immediate failure of the entire waste package barrier upon initiation of degradation. The DS_Failure_EF and WP_Failure_EF elements contain the output of the WAPDEG software. The WP_Fail_EF element contains WP_Failure_EF* (NumEFPaks/Num_Pak_EF), which is zero when NumEFPaks is zero and gives the fraction of early failed waste packages failed versus time. The WP_Fail_EF_GRF element is a graph element, which has no effect on the simulation results.

6.5 BASE-CASE ANALYSIS RESULTS

6.5.1 Overview

The previous sections of this report have documented the inputs to the integrated waste package degradation (IWPD) nominal-case analysis. In this section, the results of a representative IWPD analysis for waste package and drip shield degradation are presented. Waste package early failure is not included in the representative analysis presented in this section. The information in this section is provided only as a demonstration of an example set of analysis outputs. The waste package and drip shield degradation analyses to be presented in this section are for 300 realizations of the IWPD analysis to account for the uncertainty analysis of the uncertain simulation parameters. Each IWPD analysis realization corresponds to a complete IWPD analysis run to represent the variability in the degradation processes for a given number of waste package and drip shield pairs. Sensitivities using other choices of number of waste package and drip shield pairs are discussed in the next section.

The input parameters and their values were discussed in Section 6.4. Further specification of analysis inputs and recommendations for implementation can be found in Section 7.1. The IWPD analysis results (i.e., fraction of drip shields and waste packages failed versus time and the number of crack and patch penetrations per failed drip shield or waste package versus time) are reported as a group of "degradation profile curves" that represent the potential range of the output parameters.

The analysis results are presented for the upper- and lower-bounds, mean, and 95^{th}, 75^{th}, 25^{th}, and 5^{th} percentiles as a function of time for the following output parameters:

- Waste package first breach (or failure)
- Drip shield first breach (or failure)
- Waste package first crack penetration
- Waste package first patch penetration
- Waste package number of crack penetrations per failed waste package
- Waste package number of patch penetrations per failed waste package
- Drip shield number of patch penetrations per failed drip shield

Note that localized corrosion is not analyzed in this report. Also, stress corrosion cracking of the drip shield is not analyzed; thus, no crack penetration failures for the drip shield are calculated. Therefore, for the drip shield, the first patch penetration versus time profile is equivalent to the first breach versus time profile.

The upper- and lower-bounds, mean, and 95th, 75th, 25th, and 5th percentile curves do not correspond to single realizations. They are summary statistics related to consideration of all 300 realizations. In the bullets below, the origin of the upper- and lower-bound, mean, and 95th, 75th, 25th, and 5th percentile curves for first breach of the waste package are discussed. Similar wording (not included for the sake of brevity) applies to the origins of the drip shield first breach curves, waste package first crack penetration curves, etc.

- At each time, the upper-bound curve shows the realization with the greatest fraction of waste packages failed calculated in any one of the 300 realizations. This may not be the same realization at each point in time. The upper-bound curve becomes nonzero at the time of failure of first waste package in all of the 300 realizations.

- At each time, the 95th-percentile curve shows the realization with the 285th greatest fraction of waste packages failed (i.e., 3 × 95 = 285 realizations out of 300 have smaller fraction of waste packages failed calculated in any one of the 300 realizations. This may not be the same realization at each point in time. The 95th-percentile curve becomes nonzero at the time when at least 3 × 5 = 15 realizations have at least one waste package failure.

- At each time, the 75th-percentile curve shows the realization calculated in any one of the 300 realizations with the 225th greatest fraction of waste packages failed (i.e., 3 × 75 = 225 realizations out of 300 have smaller fraction of waste packages failed). This may not be the same realization at each point in time. The 75th-percentile curve becomes nonzero at the time when at least 3 × 25 = 75 realizations have at least one waste package failure.

- At each time, the 25th-percentile curve shows the realization calculated in any one of the 300 realizations with the 75th greatest fraction of waste packages failed (i.e., 3 × 25 = 75 realizations out of 300 have smaller fraction of waste packages failed). This may not be the same realization at each point in time. The 25th-percentile curve becomes nonzero at the time when at least 3 × 75 = 225 realizations have at least one waste package failure.

- At each time, the 5th-percentile curve shows the realization calculated in any one of the 300 realizations with the 15th greatest fraction of waste packages failed (i.e., 3 × 5 = 15 realizations out of 300 have smaller fraction of waste packages failed). This may not be the same realization at each point in time. The 5th-percentile curve becomes nonzero at the time when at least 3 × 95 = 285 realizations have at least one waste package failure.

- At each time, the mean curve shows the mean of all the fractions of waste packages failed in all of the 300 realizations. The mean curve becomes nonzero at the time of failure of first waste package in all of the 300 realizations.

6.5.2 Commercial Spent Nuclear Fuel Integrated Waste Package Degradation Analysis Base-Case Results

The commercial spent nuclear fuel (CSNF) waste packages are simulated using 1,014 patches (Section 6.3.2). The CSNF waste package outer barrier shell thickness is 20 mm (Section 4.1.1).

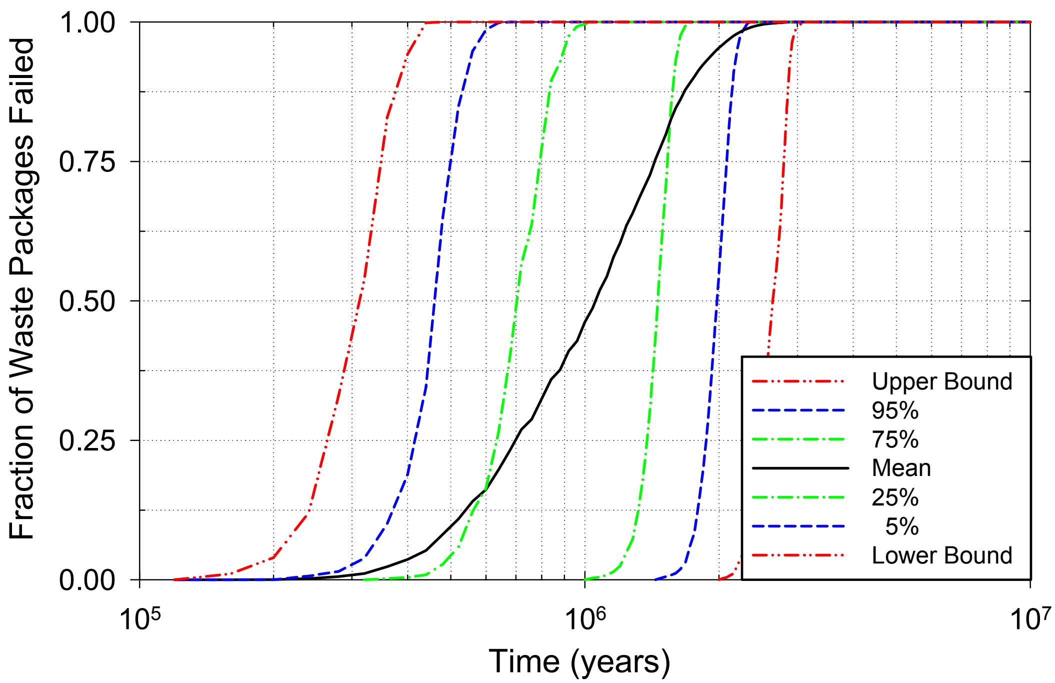
Figure 22 shows the upper- and lower-bounds, mean, and 95th, 75th, 25th, and 5th percentile confidence intervals of the first breach profile for CSNF waste packages versus time. The upper-bound profile, which is the upper extreme of the probable range of the first breach time, indicates that the earliest possible first breach time for a waste package is about 120,000 years. Note that the estimated earliest possible first breach time has a very low probability. It can be shown by comparing with the upper-bound profile in Figure 24 (showing the first crack breach profiles of waste packages with time) that the first breach is by stress corrosion crack penetration (Figure 24 and Figure 25). The median estimate (50 percent of waste packages failed) of the first breach time of the upper-bound profile is about 310,000 years. The median estimate of the first breach time of the mean profile is about 1.06 million years. The time to fail 10 percent of waste packages for the upper-bound and mean profiles is about 230,000 and 320,000 years, respectively.

Figure 23 shows the first breach profiles of CSNF drip shields with time. Because stress corrosion cracking and localized corrosion of the drip shields are not analyzed in this report, the first breach profiles shown in the figure are all by general corrosion only. Both the upper and under sides of the drip shield are exposed to the exposure conditions in the emplacement drift and are subject to general corrosion. Thus, in the analysis, the general corrosion rate for the drip shields is sampled twice independently, once for the upper side and the once for the under side. There is no variability in drip shield failure times. This is shown in the failure profiles in that the fraction of failed drip shields rises quickly from zero to one. For the upper-bound drip shield failure profile, the drip shields fail at about 47,500 years. For the 95th-percentile profile, the drip shields fail at about 92,500 years. The median estimate of the first breach time of the mean profile is about 310,000 years. Note that the lower-bound curve for drip shield breach is not shown in Figure 23 because the lower-bound breach curve lies beyond 10 million years. The lower-bound entry is left in the graph legend for consistency with the other figures in this report. Because the drip shields are analyzed with one patch, the entire surface of a failed drip shield fails at one time.

Figure 24 and Figure 25 show respectively the first crack penetration and patch penetration profiles of the CSNF waste packages with time. The first crack breach times of the upper-bound and 95th-percentile profiles are about 120,000 and 240,000 years, respectively (Figure 24), and the first patch breach times of the upper-bound and 95th-percentile profiles are about 480,000 and 560,000 years, respectively (Figure 25). Comparison of the first crack and patch breach profiles with the first breach profiles in Figure 22 indicates that the initial breach (or failure) of the waste packages is generally by stress corrosion crack penetration in the Alloy 22 waste package outer barrier middle closure lid welds. For the 75th-percentile profiles in the figures, the first crack and patch penetration times are about 360,000 and 840,000 years, respectively.

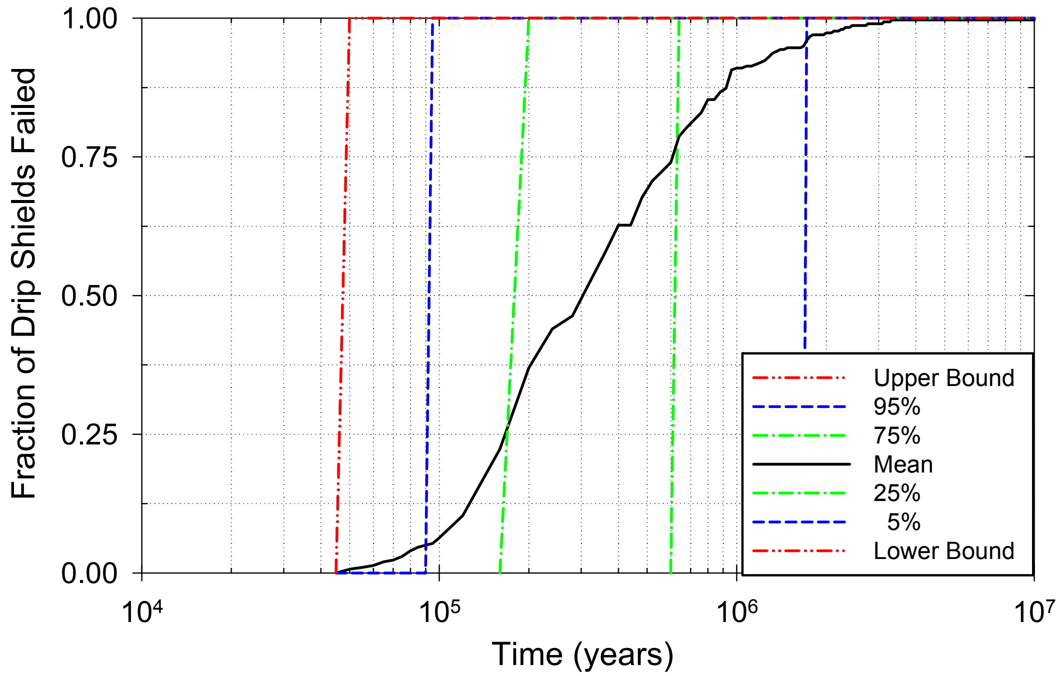
Figure 26 shows the profile for the average number of crack penetrations per failed CSNF waste package. As discussed for Figure 24, the upper-bound and 95th-percentile profiles show the first crack penetration at about 120,000 and 240,000 years, respectively. The mean profile never develops more than about 382 cracks.

Figure 27 presents the profile for the average number of patch openings per failed waste package. For the upper-bound profile, which again represents an extremely low probability case, the average first patch breach occurs at about 480,000 years (Figure 25), and about 10 patches on average (about 1 percent of the waste package surface area) are breached by 825,000 years. For the mean profile, there will be only about 2.5 patch openings (on average) in each of the failed waste packages by 1 million years.



Output DTN: MO0310MWDWAPAN.002.

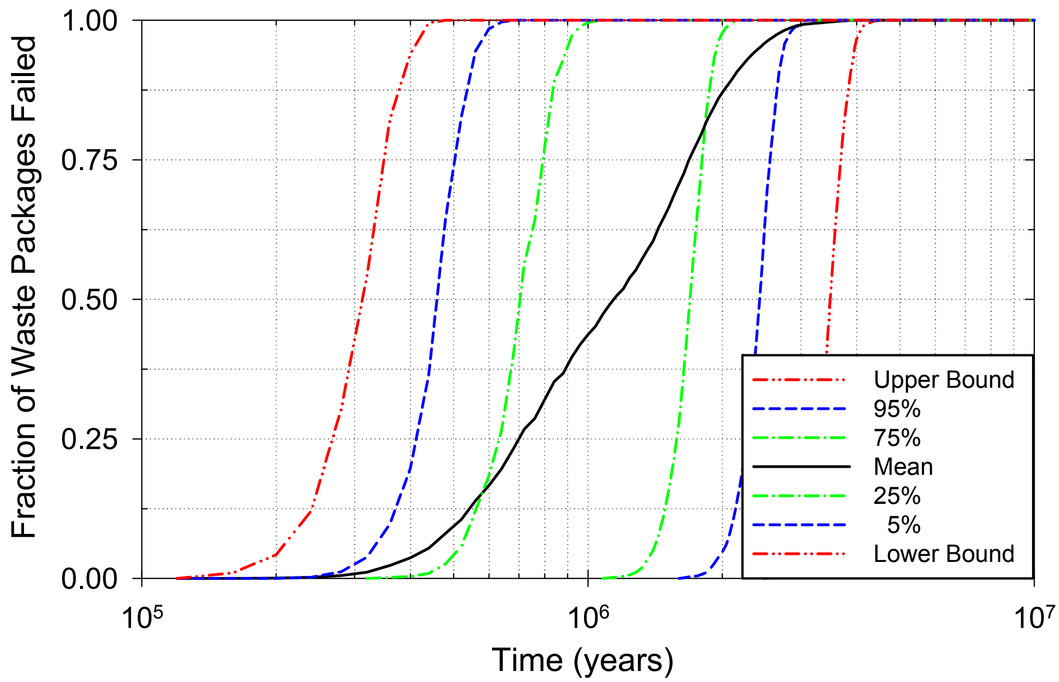
Figure 22. The Upper- and Lower-Bounds, Mean, and 95th, 75th, 25th, and 5th Percentile Confidence Intervals of the First Breach Profile of CSNF Waste Packages With Time for the IWPD Analysis



Output DTN: MO0310MWDWAPAN.002.

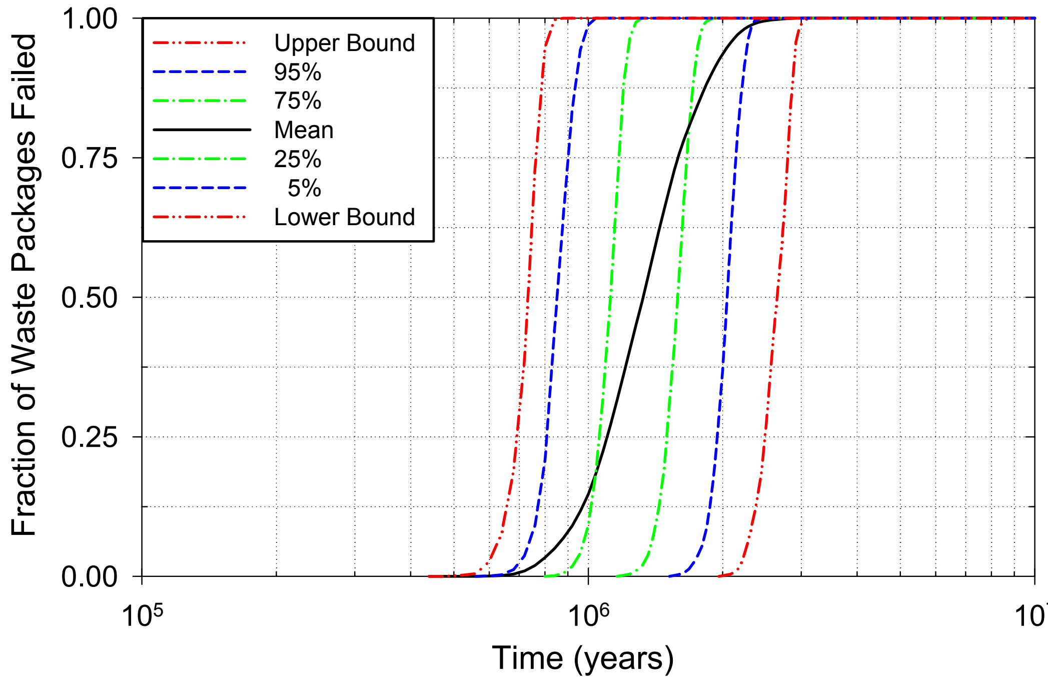
Note: The lower-bound curve for drip shield breach is not shown because the lower-bound breach curve lies beyond 10 million years

Figure 23. The Upper-Bound, Mean, and 95th, 75th, 25th, and 5th Percentile Confidence Intervals of the First Breach Profile of CSNF Drip Shields With Time for the IWPD Analysis



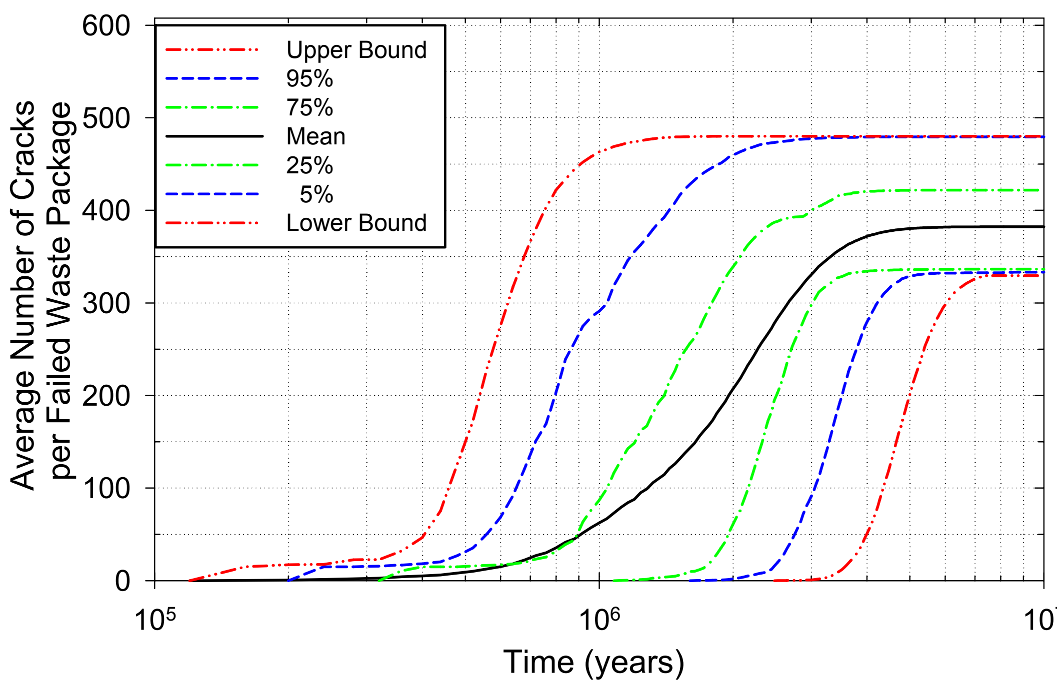
Output DTN: MO0310MWDWAPAN.002.

Figure 24. The Upper- and Lower-Bounds, Mean, and 95th, 75th, 25th, and 5th Percentile Confidence Intervals of the First Crack Breach Profile of CSNF Waste Packages With Time for the IWPD Analysis



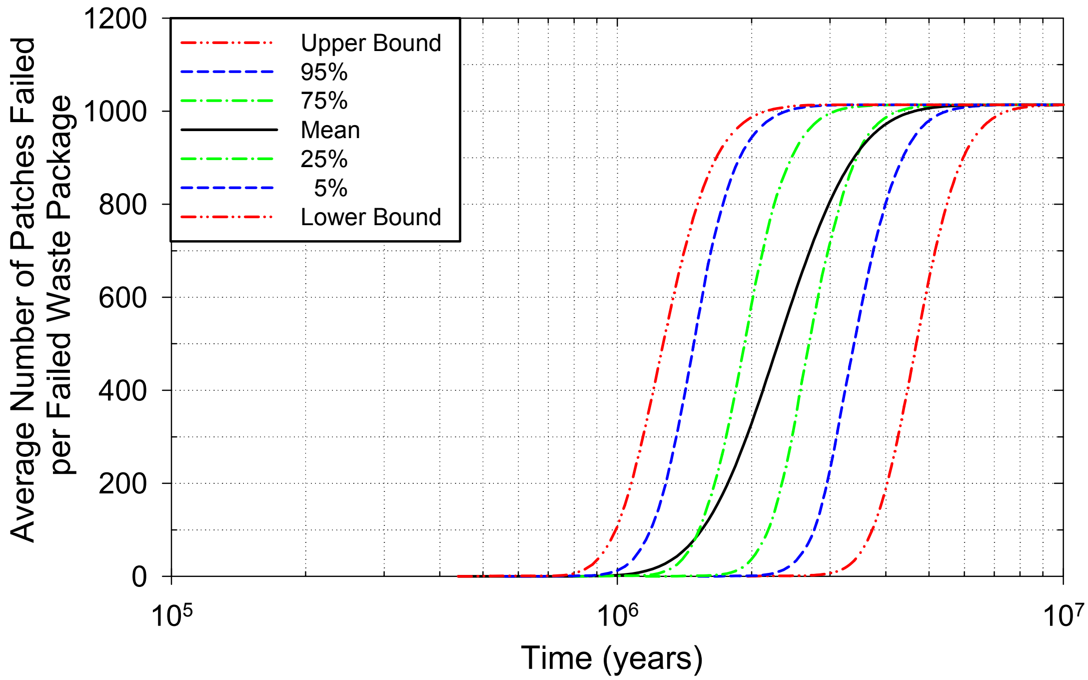
Output DTN: MO0310MWDWAPAN.002.

Figure 25. The Upper- and Lower-Bounds, Mean, and 95th, 75th, 25th, and 5th Percentile Confidence Intervals of the First Patch Breach Profile of CSNF Waste Packages With Time for the IWPD Analysis



Output DTN: MO0310MWDWAPAN.002.

Figure 26. The Upper- and Lower-Bounds, Mean, and 95th, 75th, 25th, and 5th Percentile Confidence Intervals of the Average Number of Crack Penetrations per Failed CSNF Waste Package Profile With Time for the IWPD Analysis



Output DTN: MO0310MWDWAPAN.002.

Figure 27. The Upper- and Lower-Bounds, Mean, and 95th, 75th, 25th, and 5th Percentile Confidence Intervals of the Average Number of Patch Penetrations per Failed CSNF Waste Package Profile With Time for the IWPD Analysis

6.5.3 Codisposal Waste Package Integrated Waste Package Degradation Analysis Base-Case Results

The codisposal (CDSP) waste packages are simulated using 1,106 patches (Section 6.3.2). The CDSP waste package outer barrier shell thickness is 25 mm (Section 4.1.1).

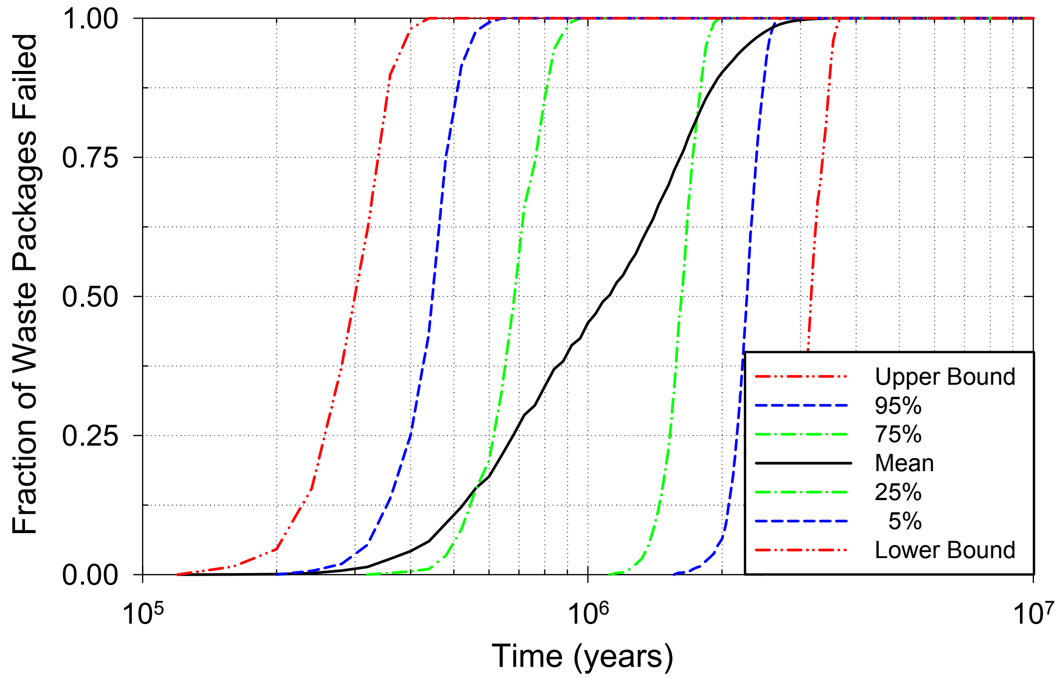
Figure 28 shows the upper- and lower-bounds, mean, and 95th, 75th, 25th, and 5th percentile confidence intervals of the first breach profile for CDSP waste packages versus time. The upper-bound profile, which is the upper extreme of the probable range of the first breach time, indicates that the earliest possible first breach time for a waste package is about 120,000 years. The estimated earliest possible first breach time has a very low probability. It can be shown by comparing with the upper-bound profile in Figure 30 (showing the first crack breach profiles of waste packages with time) that the first breach is by stress corrosion crack penetration (see the discussion of the results in Figure 30 and Figure 31 later in this section). The median estimate (50 percent of waste packages failed) of the first breach time of the upper-bound profile is about 310,000 years. The median estimate of the first breach time of the mean profile is about 1.12 million years. The time to fail 10 percent of waste packages for the upper-bound and mean profiles is about 220,000 and 485,000 years, respectively.

Figure 29 shows the first breach profiles of CDSP drip shields with time. Because stress corrosion cracking and localized corrosion of the drip shields are not analyzed in this report, the first breach profiles shown in the figure are all by general corrosion only. Both the upper and under sides of the drip shield are exposed to the exposure conditions in the emplacement drift and are subject to general corrosion. Thus, in the analysis, the general corrosion rate for the drip shields is sampled twice independently, once for the upper side and the once for the under side. There is no variability in drip shield failure times. This is shown in the failure profiles in that the fraction of failed drip shields rises quickly from zero to one. For the upper-bound drip shield failure profile, the drip shields all fail at about 47,500 years. For the 95th-percentile profile, the drip shields all fail at about 92,500 years. The median estimate of the first breach time of the mean profile is about 310,000 years. Note that the lower-bound curve for drip shield breach is not shown in Figure 29 because the lower-bound breach curve lies beyond 10 million years. The lower-bound entry is left in the graph legend for consistency with the other figures in this report. Because the drip shields are analyzed with one patch, the entire surface of a failed drip shield fails at one time. Note that the CSNF and CDSP drip shield failure curves are identical since there is no difference between the drip shields for the two waste package types.

Figure 30 and Figure 31 show, respectively, the first crack penetration and patch penetration profiles of the CDSP waste packages with time. The first crack breach times of the upper-bound and 95th-percentile profiles are about 120,000 and 200,000 years respectively (Figure 30), and the first patch breach times of the upper- and 95th-percentile profiles are about 560,000 and 720,000 years, respectively (Figure 31). Comparison of the first crack and patch breach profiles with the first breach profiles in Figure 28 indicates that the initial breach (or failure) of the waste packages is generally by stress corrosion cracking crack penetration in the Alloy 22 waste package outer barrier middle closure lid welds. For the 75th-percentile profiles in the figures, the first crack and patch penetration times are about 360,000 and 920,000 years, respectively.

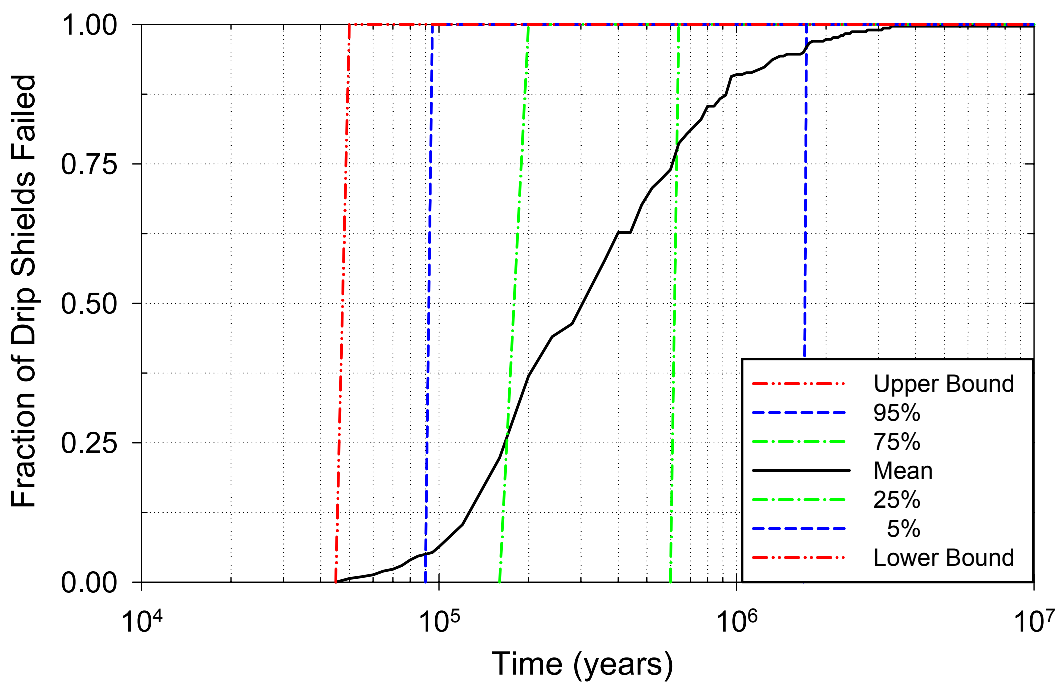
Figure 32 shows the profile for the average number of crack penetrations per failed CDSP waste package. As discussed for Figure 30, the upper-bound and 95th-percentile profiles show the first crack penetration at about 120,000 and 200,000 years, respectively. The mean profile never develops more than about 522 cracks.

Figure 33 presents the profile for the average number of patch openings per failed waste package. For the upper-bound profile, which again represents an extremely low probability case, the first patch breach occurs at about 560,000 years (Figure 31), and about 13 patches (on average) (about 1 percent of the waste package surface area) are breached by 1 million years. For the mean profile, there will be only about 0.28 of a patch opening (on average) in each of the failed waste packages by 1 million years.



Output DTN: MO0310MWDWAPAN.002.

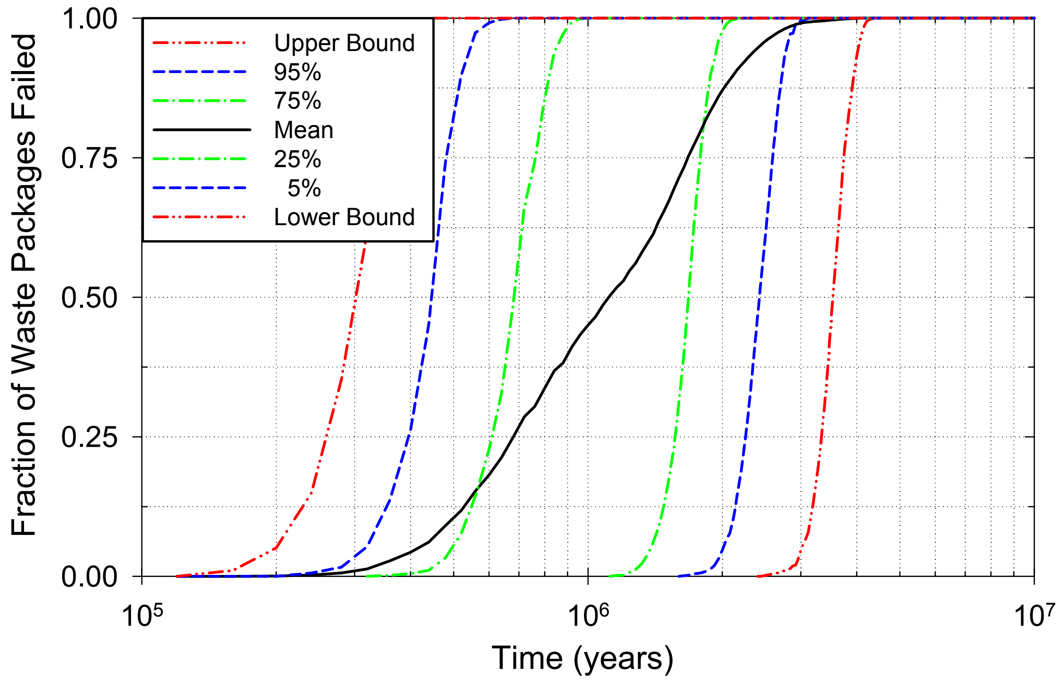
Figure 28. The Upper- and Lower-Bounds, Mean, and 95th, 75th, 25th, and 5th Percentile Confidence Intervals of the First Breach Profile of CDSP Waste Packages With Time for the IWPD Analysis



Output DTN: MO0310MWDWAPAN.002.

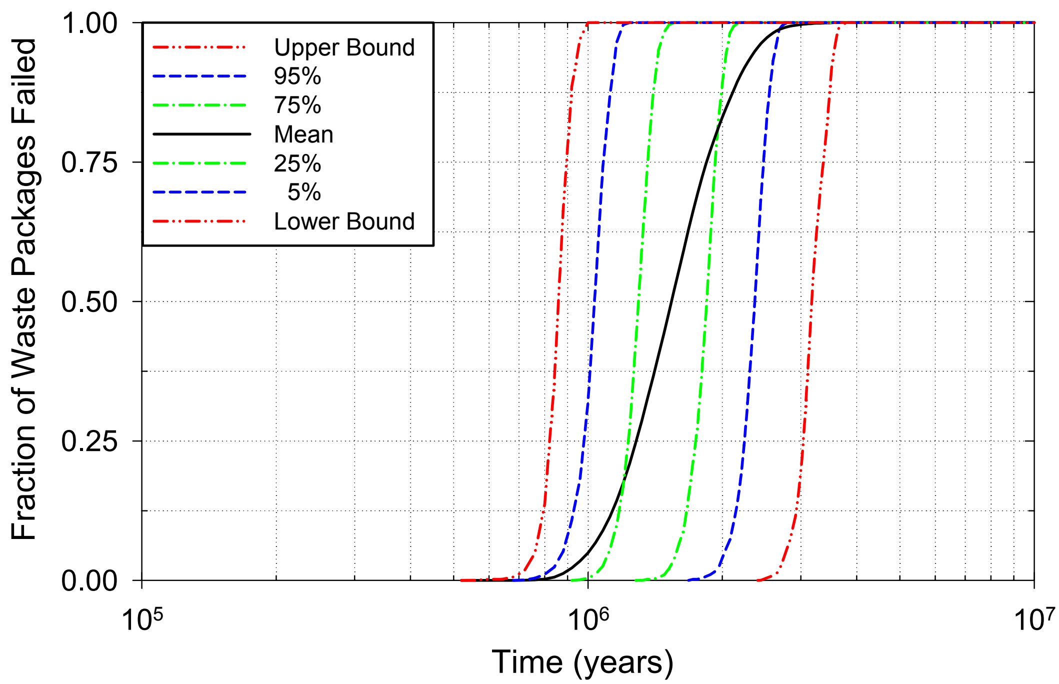
NOTE: The lower-bound curve for drip shield breach is not shown because the lower-bound breach curve lies beyond 10 million years.

Figure 29. The Upper-Bound, Mean, and 95th, 75th, 25th, and 5th Percentile Confidence Intervals of the First Breach Profile of CDSP Drip Shields With Time for the IWPD Analysis



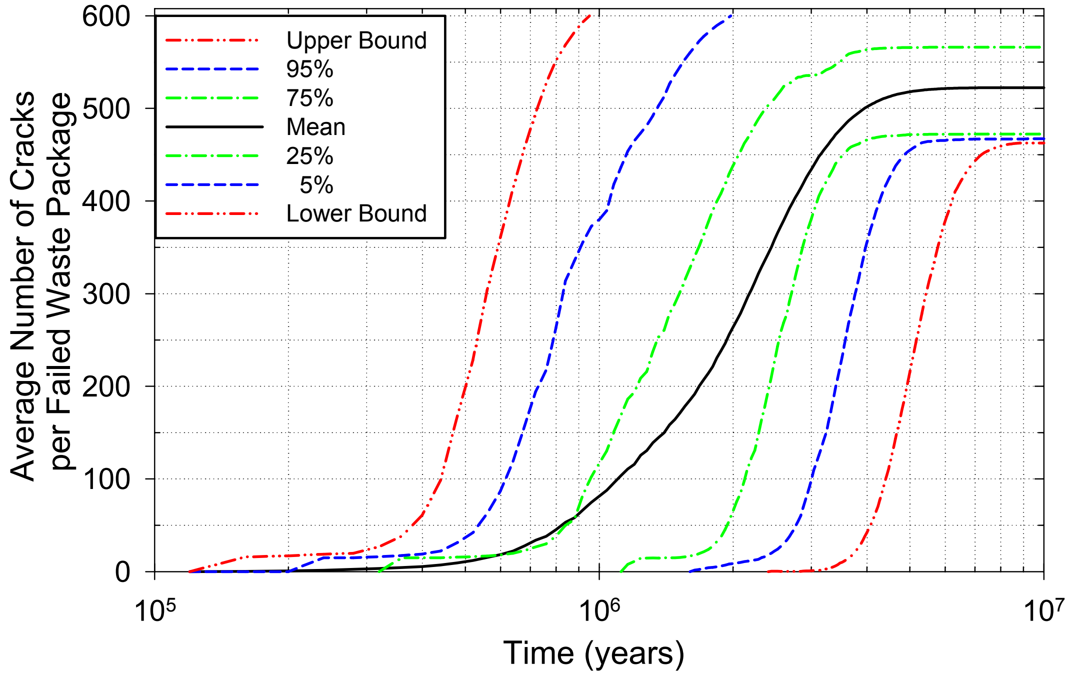
Output DTN: MO0310MWDWAPAN.002.

Figure 30. The Upper- and Lower-Bounds, Mean, and 95th, 75th, 25th, and 5th Percentile Confidence Intervals of the First Crack Breach Profile of CDSP Waste Packages With Time for the IWPD Analysis



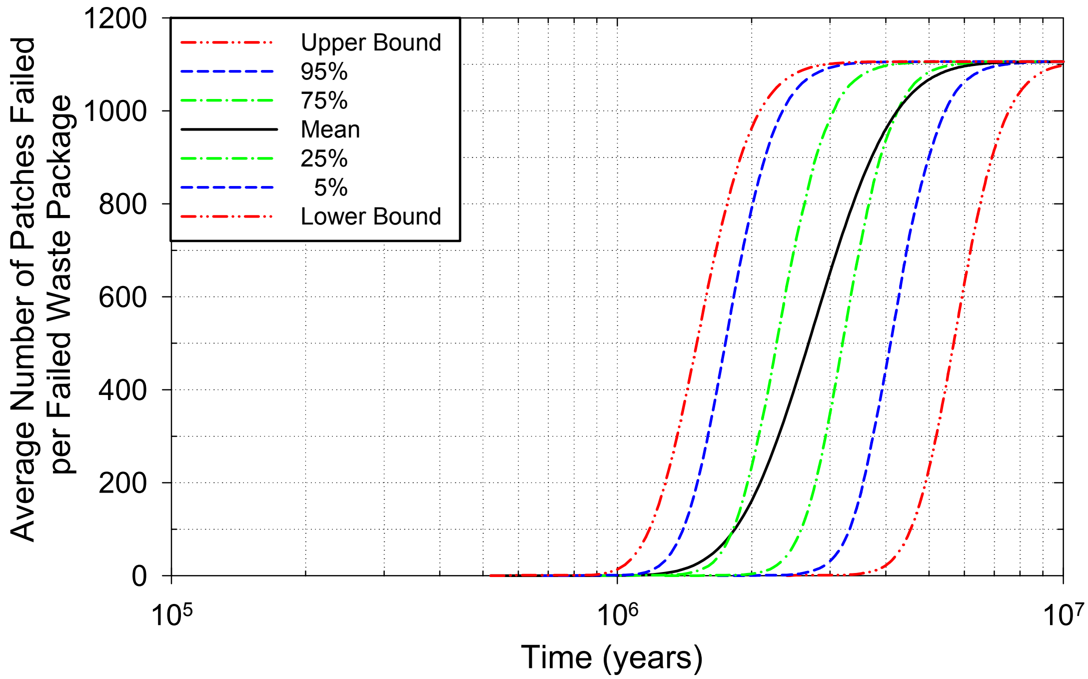
Output DTN: MO0310MWDWAPAN.002.

Figure 31. The Upper- and Lower-Bounds, Mean, and 95th, 75th, 25th, and 5th Percentile Confidence Intervals of the First Patch Breach Profile of CDSP Waste Packages With Time for the IWPD Analysis



Output DTN: MO0310MWDWAPAN.002.

Figure 32. The Upper- and Lower-Bounds, Mean, and 95th, 75th, 25th, and 5th Percentile Confidence Intervals of the Average Number of Crack Penetrations per Failed CDSP Waste Package Profile With Time for the IWPD Analysis



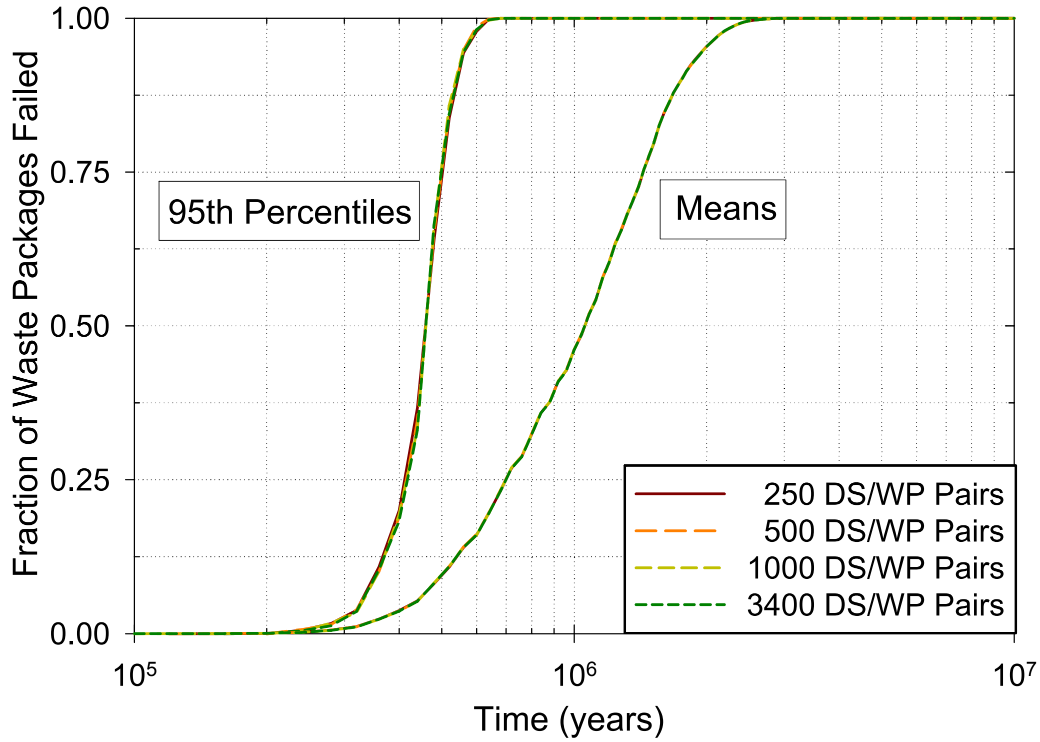
Output DTN: MO0310MWDWAPAN.002.

Figure 33. The Upper- and Lower-Bounds, Mean, and 95th, 75th, 25th, and 5th Percentile Confidence Intervals of the Average Number of Patch Penetrations per Failed CDSP Waste Package Profile With Time for the IWPD Analysis

6.5.4 Number of Drip Shield and Waste Package Pairs Sensitivity Study

A sensitivity study using various numbers of waste package and drip shield pairs was conducted to determine the appropriate number of waste package and drip shield pairs to use in nominal simulations. Simulations with various numbers of waste package and drip shield patches are not necessary since the analyses in this report have developed a technical basis for the particular choice of the number of patches used in nominal integrated waste package degradation (IWPD) analysis simulations (Section 6.3.4).

The IWPD analysis was executed with 250, 500, 1,000, and 3,400 drip shield and waste package pairs. The mean and 95th percentile waste package first failure curves are shown in Figure 34 for all cases. Figure 34 shows that the IWPD analysis results are not very sensitive to the number of drip shield and waste package pairs simulated over the range investigated. However, it should be noted that the TSPA will use thermal hydrologic history files which differ from those used in these analyses. On this basis, it is recommended that the TSPA use the lesser of the number of drip shield–waste package pairs to be simulated and 500 drip shield–waste package pairs. This choice is obviously appropriate when less than 500 drip shield–waste package pairs are to be simulated and balances the need for accuracy with the need for reasonable execution time when more than 500 drip shield–waste package pairs are to be simulated. In the TSPA, the drip shield and waste package degradation processes will be simulated at the spatial bin/fuel type level. The number of IWPD analysis simulations per TSPA realization depends on the scenario class being run. The IWPD analysis is evaluated twice for each of the five spatially fixed bins, once for the CSNF waste packages in that bin and once for CDSP waste packages. If the spatially fixed bin contains fewer than 500 drip shield–waste package pairs, all CSNF and CDSP drip shield–waste package pairs in the bin should be simulated. If the bin contains more than 500 drip shield–waste package pairs, then only 500 CSNF and 500 CDSP drip shield–waste package pairs need to be simulated.



Output DTN: MO0310MWDWAPAN.002.

Figure 34. The 95th Percentile Confidence Intervals and Means Using 250, 500, 1,000, and 3,400 Drip Shield–Waste Package Pairs of the First Breach of CSNF Waste Package Profile With Time for the IWPD Analysis

6.6 SUMMARY OF BARRIER ANALYSIS

The reader should note that the results of the analyses documented in Section 6.5 are for illustrative purposes only. The drip shield and waste package degradation profiles presented in this Section 6.5 result from the use of representative thermal hydrologic history files (Section 6.4.5) produced to allow the IWPD analysis to be exercised in this report. The drip shield and waste package degradation profiles, which will be generated in TSPA, will make use of the thermal hydrologic history files appropriate for the repository. Nonetheless, the drip shield and waste package degradation profiles presented in this Section 6.5 provide evidence that the IWPD analysis implementation functions properly.

The effects of igneous and seismic events and localized corrosion on drip shield and waste package performance were not evaluated in this report.

7. CONCLUSIONS

7.1 ANALYSIS OUTPUTS

The results of all outputs documented in this report are tracked by DTN: MO0310MWDWAPAN.002. All distributions sampled within GoldSim are uncertainty distributions and all distributions sampled within the WAPDEG DLL are variability distributions.

7.1.1 Developed Outputs

The outputs discussed in this section are inputs to the TSPA integrated waste package degradation (IWPD) analysis implementation.

7.1.1.1 Nominal Integrated Waste Package Degradation Analysis Outputs

Since the integrated waste package degradation (IWPD) analysis is implemented directly in the TSPA, the inputs to the IWPD analysis are also inputs to the TSPA. For example, the files identified in the Linked_Files container element (Figure 7), are inputs to the IWPD analysis and must accompany the TSPA Model if the IWPD analysis is to be run properly within the TSPA. Therefore, the files identified in the Linked_Files container element (Figure 7) would also be documented in the TSPA documentation since they serve as inputs to the IWPD analysis component of the larger TSPA Model. The primary outputs of this report are the WAPDEG input vector (Table I-1) and the external input files that must accompany the IWPD analysis GoldSim implementation (Appendix II). In addition, the contents of the IWPD analysis GoldSim implementation are outputs of this report.

The elements in the Linked_Files container element (Figure 7) and their values are listed in Table 26.

Table 26. Contents of Linked_Files Container

Element Name	Description	Value
WAP_File	List of filenames	WD4DLL.WAP (Appendix II)
WDKIinO	Stress intensity vs depth for outer lid	WDKIinO.fil (Appendix II)
WDKIinM	Stress intensity vs depth for middle lid	WDKIinM.fil (Appendix II)
WDhist	List of T/RH files	WDenv_00_07wheader.ou (it is expected that TSPA will generate their own list of T/RH files)
LnRo	Cumulative distribution function for the natural logarithm of the general corrosion rate for Alloy 22	WDlnRGC.cdf (Appendix II)

The elements in the GS_Elements container element (Figure 8) and their values are listed in Table 27.

Table 27. Contents of GS_Elements Container

Element Name	Description	Value
Number_DS_Patches	Number of patches per drip shield	1
SimTime	Length of Simulation (years)	1.0E7
BinStart	Start time for bins (years)	1,000
NumBins	Number of log-spaced time bins in WAPDEG tables	300
Cracks_per_Patch_Factor	Number of cracks per patch for middle lid	15

The GoldSim elements, which do not vary with waste package configuration (i.e., CSNF or CDSP), are treated in separate container elements as illustrated in Figure 10. The elements in Figure 10 and their values are listed in Table 28.

Table 28. Contents of WP_Degradation Container

Element Name	Description	Value
MIC_A22	MIC general corrosion enhancement factor	Uniform between 1 and 2
Gen_Corr_DS (Container)	General corrosion of the Drip Shield	Table 29
Gen_Corr_WPOB (Container)	General corrosion of the waste package outer barrier	Table 30
CWD (Container)	Closure Weld Defect treatment	Table 31
SCC (Container)	SCC Inputs	Table 32
IWPD_CSNF (Container)	Inputs for CSNF Waste Package analysis	Table 35
IWPD_CDSP (Container) (not shown in Figure 10)	Inputs for CDSP Waste Package analysis	Table 36

NOTE: See Figure 10

The elements in the Gen_Corr_DS container element (Figure 13) and their values are listed in Table 35.

Table 29. Contents of the Gen_Corr_DS Container Element

Element Name	Description	Value
WDDSOutGC	Outside surface general corrosion rate for Drip Shield	Cumulative distribution function in Table 5
WDDSInGC	Inside surface general corrosion rate for Drip Shield	Cumulative distribution function in Table 4

The elements in the Gen_Corr_WPOB container element (Figure 14) and their values are listed in Table 30.

Table 30. Contents of the Gen_Corr_WPOB Container Element

Element Name	Description	Value
C1_GenCorr_A22	Slope term for T-dependent Alloy 22 general corrosion	Table 7
C1divTo_GenCorr_A22	Constant term (per realization) for Alloy 22 general corrosion rate	C1_GenCorr_A22/333.15

The elements in the CWD container element (Figure 15) and their values are listed in Table 31.

Table 31. Contents of the CWD Container Element

Element Name	Description	Value
Thickness_ML	Middle lid thickness (mm) (CWD input)	10
Thickness_OL	Outer lid thickness (mm) (CWD input)	25
Defect_Count_Param	Flaw density parameter (flaws per mm^3 of weld) (CWD input)	Gamma distribution with a mean of 7.5/18610540.3277924 and a standard deviation of sqrt(7.5)/18610540.3277924
Defect_Size_Param	Flaw size parameter (1/mm) (CWD input)	Gamma distribution with a mean of 7/31.75 and a standard deviation of sqrt(7)/31.75
Location_PND	Characteristic flaw size for NDE PND (mm) (CWD input)	2.5
Shape_PND	Shape factor for probability of nondetection (CWD input)	3
Detection_Thresh_PND	Lower limit for NDE probability of nondetection (CWD input)	0.005
Defect_Frac_Orientation	Fraction of defects capable of propagation based on orientation	0.008
Defect_Frac_Embedded	Fraction of embedded manufacturing defect flaws to propagate	0.25
Defect_Frac	Fraction of defects capable of propagation (CWD input)	Defect_Frac_Embedded*Defect_Frac_Orientation

The elements in the SCC container element (Figure 17) and their values are listed in Table 32.

Table 32. Contents of the SCC Container Element

Element Name	Description	Value
n_SCC	Stress corrosion cracking growth rate exponent (repassivation rate)	Truncated normal (at ±2 sd) with a mean of 1.304 and sd of 0.16.
Abar_SCC	Stress corrosion cracking growth rate pre-exponent	(7.8E-2) * ((n_SCC)^3.6) * ((4.1E-14)^(n_SCC)) *60*60*24*365.25
nbar_SCC	4*n	4*n_SCC
KI_Thresh_SCC	Stress Intensity Factor Threshold	(7.23E-06/Abar_SCC)^(1/nbar_SCC)
Yield_Strength_A22	Yield Strength of Alloy 22 (MPa)	285
Stress_Thresh_SCC	Stress threshold for stress corrosion cracking nucleation (MPa)	0.9*Yield_Strength_A22
SCC_Outer_Lid (Container)	Stress corrosion cracking Inputs for Outer Lid	Table 33
SCC_Middle_Lid (Container)	Stress corrosion cracking Inputs for Middle Lid	Table 34

The elements in the SCC_Outer_Lid container element (Figure 18) and their values are listed in Table 33.

Table 33. Contents of the SCC_Outer_Lid Container Element

Element Name	Description	Value
z_OL	Uncertain deviation from median yield strength range for outer lid (SCCD input)	Truncated normal (at ±3 sd) with a mean of 0 and sd of 1
Num_Angles_OL	Number of angles at which stress intensity factor will be evaluated for outer lid (SCCD input)	5
KI_inp_OL	Line number in WD4DLL.WAP file of the stress intensity factor (KI) versus depth profiles for the outer lid (WDKIinO.fil) (SCCD input)	4
sinf_OL	Sine of the angle of projection that the crack path makes with the outer lid normal (SCCD input)	1
A0_OL	Outer lid stress coefficient (SCCD input)	-292.607
A1_OL	Outer lid stress coefficient (SCCD input)	178.277
A2_OL	Outer lid stress coefficient (SCCD input)	-14.135
A3_OL	Outer lid stress coefficient (SCCD input)	0.320
fys_OL	Outer lid yield strength scaling factor (SCCD input)	0.15
amp_OL	Amplitude of the stress variation with angle, for the outer lid (SCCD input)	17.236893
KI_out_OL	Line number in WD4DLL.WAP file of the filename outer lid KI vs depth profile (SCCD output, WAPDEG input)	6
Stress_out_OL	Line number in WD4DLL.WAP file of the filename for outer lid stress vs depth profile (SCCD output, WAPDEG input)	7
Model_Number_OL	SCC uncertainty model number for outer lid (SCCD input)	1

The elements in the SCC_Middle_Lid container element and their values are listed in Table 34.

Table 34. Contents of the SCC_Middle_Lid Container Element

Element Name	Description	Value
z_ML	Uncertain deviation from median yield strength range for middle lid (SCCD input)	Truncated normal (at ±3 sd) with a mean of 0 and sd of 1
Num_Angles_ML	Number of angles at which stress intensity factor will be evaluated for middle lid (SCCD input)	5
KI_inp_ML	Line number in WD4DLL.WAP file of the stress intensity factor (KI) versus depth profiles for the middle lid (WDKIinO.fil) (SCCD input)	5
sinf_ML	Sine of the angle of projection that the crack path makes with the middle lid normal (SCCD input)	1
A0_ML	Middle lid stress coefficient (SCCD input)	219.908
A1_ML	Middle lid stress coefficient (SCCD input)	56.494
A2_ML	Middle lid stress coefficient (SCCD input)	-20.848
A3_ML	Middle lid stress coefficient (SCCD input)	1.083
fys_ML	Middle lid yield strength scaling factor (SCCD input)	0.15
amp_ML	Amplitude of the stress variation with angle, for the middle lid (SCCD input)	17.236893
KI_out_ML	Line number in WD4DLL.WAP file of the filename outer lid KI vs depth profile (SCCD output, WAPDEG input)	8
Stress_out_ML	Line number in WD4DLL.WAP file of the filename for middle lid stress vs depth profile (SCCD output, WAPDEG input)	9
Model_Number_ML	SCC uncertainty model number for middle lid (SCCD input)	1

The elements in the IWPD_CSNF container element (Figure 9) and their values are listed in Table 35.

Table 35. Contents of IWPD_CSNF Container

Element Name	Description	Value
Hist_Index_CSNF	Line number in WD4DLL.WAP file of the filename for the thermal hydrologic and chemistry time history file	1
WDSeed_CSNF	WAPDEG Seed CSNF	Uniform between 1 and $2^{31}-1$
NumPak_CSNF	Number of CSNF waste packages	Expected to be set by TSPA
CWD_CSNF (Container)	Closure weld defects treatment for CSNF Waste Packages	See Table 37
WAPDEG_Inputs_CSNF	Input vector to WAPDEG.DLL CSNF	See Appendix I, Table I-1

The elements in the IWPD_CDSP container element and their values are listed in Table 36.

Table 36. Contents of IWPD_CDSP Container Element

Element Name	Description	Value
Hist_Index_CDSP	Line number in WD4DLL.WAP file of the filename for the thermal hydrologic and chemistry time history file	1
WDSeed_CDSP	WAPDEG Seed CDSP	Uniform between 1 and $2^{31}-1$
NumPak_CDSP	Number of CDSP waste packages	Expected to be set by TSPA
CWD_CDSP (Container)	Closure weld defects treatment for CDSP	See Table 38
WAPDEG_Inputs_CDSP	Input vector to WAPDEG.DLL CDSP	See Appendix I, Table I-1

The elements in the CWD_CSNF container element (Figure 16) and their values are listed in Table 37.

Table 37. Contents of CWD_CSNF Container Element

Element Name	Description	Value
Vol_Weld_OL_CSNF	Volume of outer lid weld for CSNF Waste Packages (CWD input) (mm^3)	1,350,189
Defect_Num_OL_CSNF	Line number in WD4DLL.WAP file of the filename for CDF of the number of outer lid manufacturing defect flaws for CSNF Waste Packages (CWD output)	10
Defect_Size_OL_CSNF	Line number in WD4DLL.WAP file of the filename for CDF of the length of outer lid manufacturing defect flaws for CSNF Waste Packages (CWD output)	11
Vol_Weld_ML_CSNF	Volume of middle lid weld for CSNF Waste Packages (CWD input) (mm^3)	490,478
Defect_Num_ML_CSNF	Line number in WD4DLL.WAP file of the filename for CDF of the number of middle lid manufacturing defect flaws for CSNF Waste Packages (CWD output)	12
Defect_Size_ML_CSNF	Line number in WD4DLL.WAP file of the filename for CDF of the length of middle lid manufacturing defect flaws for CSNF Waste Packages (CWD output)	13

The elements in the CWD_CDSP container element and their values are listed in Table 38.

Table 38. Contents of CWD_CDSP Container Element

Element Name	Description	Value
Vol_Weld_OL_CDSP	Volume of outer lid weld for CDSP Waste Packages (CWD input) (mm^3)	1,753,091
Defect_Num_OL_CDSP	Line number in WD4DLL.WAP file of the filename for CDF of the number of outer lid manufacturing defect flaws for CDSP Waste Packages (CWD output)	14
Defect_Size_OL_CDSP	Line number in WD4DLL.WAP file of the filename for CDF of the length of outer lid manufacturing defect flaws for CDSP Waste Packages (CWD output)	15
Vol_Weld_ML_CDSP	Volume of middle lid weld for CDSP Waste Packages (CWD input) (mm^3)	639,901
Defect_Num_ML_CDSP	Line number in WD4DLL.WAP file of the filename for CDF of the number of middle lid manufacturing defect flaws for CDSP Waste Packages (CWD output)	16
Defect_Size_ML_CDSP	Line number in WD4DLL.WAP file of the filename for CDF of the length of middle lid manufacturing defect flaws for CDSP Waste Packages (CWD output)	17

It is recommended that the WAPDEG DLL be called twice (i.e., once each for CSNF and for CDSP waste packages) for each region of the repository (i.e., each unique set of thermal hydrologic history files) to be simulated. The input to the WAPDEG DLL consists of the elements in the IWPD_CSNF (Figure 9) (or IWPD_CDSP) container element and the external files created by calls to the CWD DLL (for outer lid of CSNF waste packages: WDCWDNDO_CSNF.cdf and WDCWDSizeO_CSNF.cdf; for middle lid of CSNF waste packages: WDCWDNDM_CSNF.cdf and WDCWDSizeM_CSNF.cdf; for outer lid of CDSP waste packages: WDCWDNDO_CDSP.cdf and WDCWDSizeO_CDSP.cdf; for middle lid of CDSP waste packages: WDCWDNDM_CDSP.cdf and WDCWDSizeM_CDSP.cdf) and SCCD DLL (for outer lid: WDKISCCO.fil and WDStressO.fil; for middle lid: WDKISCCM.fil and WDStressM.fil).

7.1.1.2 Waste Package Early Failure Analysis Outputs

An implementation of the waste package early failure analysis involves the full uncertainty and variability specification as outlined in Section 4.1.8 and developed in Section 6.3.8. Alternatively, use of the marginal probability distribution, developed in Section 6.4.12, allows results to be used in a conditional or stratified approach, which allows for computational efficiencies.

Table 39. Waste Package Early Failure Parameters and Their Sources

Parameter Name	Parameter Source	Parameter Value	Units
Num_Pak_EF Number of packages considered	This is a TSPA parameter to be specified by TSPA at runtime	e.g., 11,184 (representative value, see discussion under Parameter Source)	N/A
U_EF_Mean Evaluation probability per WP (Uncertain Poisson intensity)	This report (Section 6.3.8)	Log normal distribution with a geometric mean of 7.2×10^{-6} and a geometric sd of $15^{(1/1.645)}$ truncated at an upper-bound of 7.44213×10^{-3}	per Waste Package
NumEFPaks Number of Early Failed WP in the realization	BSC 2004 [DIRS 170024], Section 7, Table 22	Poisson distribution with intensity Num_Pak_EF*U_EF_Mean	number of waste packages per realization
Fractional_EF Fraction of Early Failed WP in the realization	This report (Section 6.4.12)	NumEFPaks/Num_Pak_EF	fraction of waste packages per realization

Table 40. Early Failure Waste Package Unconditional Probability Values

n (Number of Waste Packages)	p(n)
0	0.830177156
1	0.114170546
2	0.029481907
≥3	0.026170391

Table 41. Early Failure Waste Package Conditional Probability Density Function

Conditional Probability	Number of Waste Packages
6.72292043249447E-01	1
1.73603896475176E-01	2
6.62102251738378E-02	3
3.16781457051218E-02	4
1.74664265480460E-02	5
1.05986309693713E-02	6
6.88874646926455E-03	7
4.71473222137090E-03	8
3.35923480253975E-03	9
2.47181818957650E-03	10
1.86749677986347E-03	11
1.44237040765972E-03	12
1.13503969252866E-03	13
9.07649803289940E-04	14
7.36008651370934E-04	15
6.04171817640069E-04	16
5.01345905459817E-04	17
4.20051218756154E-04	18
3.54995977674767E-04	19

Table 41. Early Failure Waste Package Conditional Probability Density Function (Continued)

Conditional Probability	Number of Waste Packages
3.02366678546451E-04	20
2.59369367847244E-04	21
2.23926363184013E-04	22
1.94471645187147E-04	23
1.69810267359572E-04	24
1.49020132777530E-04	25
1.31382319712795E-04	26
1.16330965064662E-04	27
1.03416750621992E-04	28
9.22799833021864E-05	29
8.26305297934502E-05	30
7.42327072291007E-05	31
6.68937973539920E-05	32
6.04552375285604E-05	33
5.47858084815550E-05	34
4.97763250833152E-05	35
4.53354681692636E-05	36
4.13864895817636E-05	37
3.78645905269958E-05	38
3.47148228178331E-05	39
3.18903989250389E-05	40
2.93513236906451E-05	41
2.70632806669899E-05	42
2.49967211722396E-05	43
2.31261156125399E-05	44
2.14293353591146E-05	45
1.98871401733203E-05	46
1.84827513472259E-05	47
1.72014947430197E-05	48
1.60305010475418E-05	49
1.49584530155581E-05	50
1.39753714138465E-05	51
1.30724329177318E-05	52
1.22418144452487E-05	53
1.14765594142005E-05	54
1.07704622310122E-05	55
1.01179680120012E-05	56
9.51408513147726E-06	57
8.95430871137521E-06	58
8.43455362935730E-06	59
7.95109603336955E-06	60
7.50052270944795E-06	61

Table 41. Early Failure Waste Package Conditional Probability Density Function (Continued)

Conditional Probability	Number of Waste Packages
7.07968794836482E-06	62
6.68567778292314E-06	63
6.31578160673403E-06	64
5.96747122389443E-06	65
5.63838730892199E-06	66
5.32633307799113E-06	67
5.02927469761981E-06	68
4.74534760973451E-06	69
4.47286756875376E-06	70
4.21034481259677E-06	71
3.95649947572606E-06	72
3.71027614758051E-06	73
3.47085542520984E-06	74
3.23766043150573E-06	75
3.01035657795550E-06	76
2.78884332947732E-06	77
2.57323734345134E-06	78
2.36384705234588E-06	79
2.16113947409198E-06	80
1.96570069703811E-06	81
1.77819203158221E-06	82
1.59930419528470E-06	83
1.42971206779268E-06	84
1.27003250396409E-06	85
1.12078743904329E-06	86
9.82374090487728E-07	87
8.55043505290756E-07	88
7.38888077500076E-07	89
6.33838028935228E-07	90
5.39666263494115E-07	91
4.56000518554527E-07	92
3.82341378459289E-07	93
3.18084501625250E-07	94
2.62545345353809E-07	95
2.14984738019739E-07	96
1.74633823455080E-07	97
1.40717156867760E-07	98
1.12473032823898E-07	99
8.91704420953614E-08	100
7.01223580113182E-08	101
5.46953228642639E-08	102
4.23155263966068E-08	103

Table 41. Early Failure Waste Package Conditional Probability Density Function (Continued)

Conditional Probability	Number of Waste Packages
3.24717339289036E-08	104
2.47155300757037E-08	105
1.86593991019425E-08	106
1.39731722870978E-08	107
1.03793457798317E-08	108
7.64771967930777E-09	109
5.58974043798139E-09	110
4.05285294051235E-09	111

7.2 SUMMARY

A nominal case analysis of degradation of drip shield and waste package in the Yucca Mountain repository was presented, incorporating the data and analyses of the individual degradation processes documented in the companion process-level reports (BSC 2004 [DIRS 169985]; BSC 2004 [DIRS 169984]; BSC 2004 [DIRS 169845]). The IWPD analysis was conducted to provide the TSPA with inputs and methodologies, which are used to evaluate waste package and drip shield degradation as a function of exposure time under exposure conditions anticipated in the repository.

It should be noted that the results of the analyses documented in Section 6.5 are for illustrative purposes only. The drip shield and waste package degradation profiles presented in Section 6.5 result from the use of representative thermal hydrologic history files (Section 6.4.5) produced to allow the IWPD analysis to be exercised in this report. The drip shield and waste package degradation profiles, which will be used in the TSPA-LA will make use of the thermal hydrologic history files appropriate for the repository. The drip shield and waste package degradation profiles presented in this Section 6.5 provide evidence that the IWPD analysis implementation functions properly.

The waste package and drip shield degradation analyses documented in this report have shown that based on the current general corrosion and stress corrosion cracking analysis, neither the drip shields nor the waste packages fail within the regulatory time period (10,000 years). The effects of igneous and seismic events and localized corrosion on drip shield and waste package performance were not evaluated in this report. Both the drip shield and waste package degrade by general corrosion at very low passive dissolution rates. The current experimental data and detailed process-level analyses, upon which the IWPD Analyses are based, are consistent with this conclusion. With the exception of early failure processes (Section 6.3.8), only the closure-lid welds of the waste package, for which complete stress mitigation may not be possible, are subject to rapidly penetrating corrosion modes under repository conditions (BSC 2004 [DIRS 169985]). Because of potential residual stresses, the closure-lid welds would be subject to stress corrosion cracking.

A dual closure-lid design for the waste package outer barrier is used, and stress mitigation techniques is used on the outer closure lid weld region. The analyses in this report show that the hoop stress (driving radial cracks) is the dominant stress in the closure-lid welds that causes stress corrosion cracking failure of waste package. The analyses also show that stress mitigation techniques achieve a substantial stress relief for the closure-lid welds (BSC 2004 [DIRS 169985]).

7.3 YUCCA MOUNTAIN REVIEW PLAN CRITERIA

Yucca Mountain Review Plan, Final Report (YMRP) (NRC 2003 [DIRS 163274]) contains Acceptance Criteria that are intended to establish the basis for the review of the material contained in the License Application. As this report serves, in part, as the basis for the License Application, it is important to show how the information contained herein addresses each of the applicable YMRP Acceptance Criteria.

The drip shield limits the water contacting the waste package and the water available for advective transport through the waste package and drift invert. The waste package limits the water contacting the waste form. Therefore, the drip shield and waste package must help meet criteria specific to *Technical Work Plan For: Regulatory Integration Modeling and Analysis of the Waste Form and Waste Package* (BSC 2004 [DIRS 171583]), which has identified acceptance criteria (AC) based on the requirements mentioned in *Project Requirements Document* (Canori and Leitner 2003 [DIRS 166275]) and *Yucca Mountain Review Plan, Final Report* (NRC 2003 [DIRS 163274]).

7.3.1 System Description and Demonstration of Multiple Barriers

For the Yucca Mountain Review Plan criterion entitled System Description and Demonstration of Multiple Barriers (NRC 2003 [DIRS 163274], Section 2.2.1.1.3; Canori and Leitner 2003 [DIRS 166275], PRD-002/T-014, PRD-002/T-016), the acceptance criteria (AC) AC1, AC2, and AC3 do not apply because the purpose of this report is not to describe the performance of the barriers but to describe the analysis process as used by TSPA-LA. The barriers are adequately identified and described in Sections 4.1, 6.1, and 6.3.

7.3.2 Degradation of Engineered Barriers

For the Yucca Mountain Review Plan criterion entitled Degradation of Engineered Barriers (NRC 2003 [DIRS 163274], Section 2.2.1.3.1.3; Canori and Leitner 2003 [DIRS 166275], PRD-002/T-015), the following acceptance criteria (AC) were addressed:

AC 1 – System Description and Model Integration are Adequate

> *(1) TSPA adequately incorporates important design features, physical phenomena and couplings and uses consistent assumptions throughout the degradation of engineered barriers abstraction process;*
>
> *(2) Abstraction uses assumptions, technical bases, data and models that are appropriate and consistent with [those used] in other abstractions.*
>
> *(3) The descriptions of the engineered barriers, design features, degradation processes, physical phenomena, and couplings that may affect the degradation of the engineered barriers are adequate.*

(4) Initial and boundary conditions are propagated consistently throughout the abstraction process.

(5) Sufficient technical basis for the inclusion and exclusion of FEPs are provided;

(6) Adequate technical bases are provided, for selecting the design criteria, that mitigate any potential impact of in-package criticality on repository performance, including considering all features, events, and processes that may increase the reactivity of the system inside the waste package.

(7) Guidance in NUREG 1297 and NUREG 1298 [re: Expert Elicitation] are followed.

The drip shield and waste package barriers that this report addresses are described in Sections 4.1 and 6.6. This report documents how important design features, physical phenomena and couplings, and consistent assumptions are incorporated throughout the degradation of engineered barriers analysis process are incorporated into the total system performance. assessment. Adequate description of the engineered barriers, design features, physical phenomena and couplings are addressed in Section 6.3. Assumptions used are identified in Section 5 and are consistent with those used in other abstractions. A description of how these elements are incorporated into the total system performance assessment is presented in Section 6.4 and analyses of (illustrative) results are presented in Section 6.5. The models and analyses used in this report are implemented in a manner consistent with their sources (BSC 2004 [DIRS 169845]; BSC 2004 [DIRS 169984]; BSC 2004 [DIRS 169985]; BSC 2004 [DIRS 170024]) and all initial and boundary conditions identified in these sources as described in Section 6.3.

The features, events, and processes (FEPs) treated in this report are identified in Section 6.2. Sufficient technical basis for the inclusion of FEPs are provided in Section 6.3 as part of the conceptual discussion for drip shield and waste package degradation. See also DTN: MO0407SEPFEPLA.000 [DIRS 170760] for a description of these FEPs and *FEPs Screening of Processes and Issues in Drip Shield and Waste Package Degradation* (BSC 2004 [DIRS 169997]) for a complete list of all FEPs related to waste package and drip shield degradation.

Those sections of the acceptance criterion that relate to the selection of design criteria are not applicable to this report because design criteria are not selected in this report. Those sections of the acceptance criterion that relate to the use of expert elicitation are not applicable to this report because expert elicitation was not used in this report.

AC 2 – Data Are Sufficient for Model Justification

(1) Parameters used to evaluate the degradation of EBS are adequately justified;

(2) Sufficient data have been collected to establish initial and boundary conditions;

(3) Data on the degradation of the engineered barriers (e.g. – general and localized corrosion, microbially induced corrosion, galvanic interactions, hydrogen embrittlement and phase stability) are based on laboratory measurements, site-specific field measurements, industrial and/or natural analogs and tests designed to replicate anticipated conditions. As appropriate, sensitivity or uncertainty analyses are provided and are shown to be adequate.

(4) Degradation models for the applicable processes are adequate. For example, general and localized corrosion, microbially induced corrosion, galvanic interactions, hydrogen embrittlement and phase stability are given appropriate consideration and treatment.

The data used in the IWPD analysis are adequately justified in Section 4.1. The models and analyses used in this report (BSC 2004 [DIRS 169845]; BSC 2004 [DIRS 169984]; BSC 2004 [DIRS 169985]; BSC 2004 [DIRS 170024]) were developed based on laboratory measurements, site-specific field measurements, industrial and/or natural analogs and tests designed to replicate anticipated conditions sufficient to establish initial and boundary conditions. The degradation models for applicable processes are validated for their intended use (this analysis) in their respective reports. These data were sufficient to develop the integrated waste package degradation (IWPD) analysis described in Sections 6.3 and 6.4. The data and parameters result from activities conducted under a quality assurance program. On this basis, the data used are sufficient for justification of the IWPD analysis.

AC 3 – Data Uncertainty is Characterized and Propagated Through The Model Abstraction

(1) Models use parameter values, assumed ranges, probability distributions and/or bounding assumptions that are technically defensible, reasonably account for uncertainties and variabilities, and do not result in under-representation of the risk estimate.

(2) Appropriate parameters, based on techniques that may include laboratory experiments, field measurements, and industrial analogs are used.

(3) Assumed range of values and probability distributions for parameters used in conceptual and process-level models are not likely to underestimate the actual degradation and failure of engineered barriers.

(4) Appropriate methods of NDE of fabricated-engineered barriers are used to assess the type, size and location of fabrication defects that may lead to premature failure of engineered barriers.

(5) Where sufficient data do not exist, the definition of parameter values and conceptual models is based on appropriate use of other sources, such as expert elicitation.

The models and analyses used in this report (BSC 2004 [DIRS 169845]; BSC 2004 [DIRS 169984]; BSC 2004 [DIRS 169985]; BSC 2004 [DIRS 170024]) were developed based on laboratory measurements, industrial and/or natural analogs and tests designed to replicate anticipated conditions. The degradation models for applicable processes are validated for their intended use (this analysis) in their respective reports. The models used in this analysis make use of parameter values, assumed ranges, probability distributions or bounding assumptions that are technically defensible, reasonably account for uncertainties and variabilities, and do not result in under-representation of the risk estimate. The uncertainties in the parameter ranges and uncertainty distributions in the models used in this report are discussed in Sections 4.1 and 6.3. The uncertainty distributions are implemented in Section 6.4. The effect of uncertainty on (illustrative) analysis results are presented in Section 6.5.

The uncertainty treatments in this analysis do not result in under-representation of the risk estimate. The rationale for this statement is discussed below:

- The analysis does not make use of a relative humidity threshold for corrosion initiation (i.e., corrosion is allowed to occur at any exposure relative humidity) although a relative humidity threshold for corrosion initiation clearly exists (ASM International 1987 [DIRS 133378, p. 82). Use of a relative humidity threshold would delay the start time for corrosion processes.

- In this report (Section 6.3), the only performance credit taken for the Stainless Steel Type 316 inner vessel is for the structural support it provides to the waste package outer barrier before waste package breach. Although the waste package inner vessel would also provide some performance for waste containment and potentially act as a barrier to radionuclide transport after waste package outer barrier breach, the potential performance of this barrier is far less than that of the more corrosion resistant Alloy 22 waste package outer barrier. For this reason, the corrosion performance of the waste package inner vessel is conservatively ignored in this report.

- The general corrosion rate of the waste package outer barrier (at a given temperature) is time independent. This is conservative (will not result in an under-representation of the risk estimate) because the general corrosion rates of the waste package outer barrier decrease with time (BSC 2004 [DIRS 169984], Section 7.2.1).

- The general corrosion rates used for the waste package outer barrier are derived from weight loss measurements of creviced geometry specimens which showed a higher distribution of corrosion rates than did the weight loss geometry specimens (BSC 2004 [DIRS 169984], Section 6.4.3). This is conservative because it is unlikely that the entire waste package surface has a creviced geometry.

- In Section 6.3.4, the waste package outer barrier general corrosion rates are conservatively adjusted for the change of scale between a creviced geometry specimen and the patch size (which is about four times larger than the creviced geometry specimen size) used in this analysis. The technique used is equivalent to using the highest of four sampled values for the overall patch general corrosion rate.

On these bases, the uncertainty treatments in this analysis do not result in under-representation of the risk estimate.

Those sections of the acceptance criterion that relate to NDE of fabricated engineered barriers are not applicable to this report because no analyses of nondestructive examination of fabricated engineered barriers were analyzed in this report. Those sections of the acceptance criterion that relate to the use of other sources, such as expert elicitation, are not applicable to this report because no other sources were used in the creation of this report.

AC 4 – Model Uncertainty is Characterized and Propagated Through the Model Abstraction

> *(1) Alternative modeling approaches are considered and are consistent with available data and current scientific understanding.*
>
> *(2) Consideration of conceptual model uncertainty is consistent with available site characterization data, laboratory experiments, . . . and the treatment of uncertainty does not result in under-estimation of the risk estimate.*
>
> *(3) Alternative modeling approaches, consistent with available data and current scientific understanding, are used and the modeling results are evaluated using tests that are sensitive to the processes modeled.*

Conceptual model uncertainty was adequately considered in the models used in this report (BSC 2004 [DIRS 169845]; BSC 2004 [DIRS 169984]; BSC 2004 [DIRS 169985]). Objective evidence of this is their approval in accordance with the applicable procedures under which they were produced. The uncertainty treatments in these reports are inputs to this report, meaning that the uncertainty treatments are implemented within the IWPD analysis (Sections 4.1 and 6.3). On this basis model uncertainty is appropriately characterized and propagated through the IWPD analysis. As discussed in acceptance criterion 3, these uncertainty treatments do not result in underestimation of the risk estimate.

Those sections of the acceptance criterion that relate to consideration of alternative conceptual models are not applicable to this report because no analyses of alternative conceptual models were undertaken in this report.

AC 5 – Model Abstraction Output Is Supported By Objective Comparisons

> *(1) Models implemented in this total system performance assessment abstraction provide results consistent with output from detailed process-level models and or empirical observations (laboratory and field testing, and/or natural analogs).*
>
> *(2) Numerical corrosion models used to calculate the lifetime of the engineered barriers are adequate representations, considering the associated uncertainties in long term behavior, range of conditions (including residual stresses) and the variability in fabrication processes.*
>
> *(3) Evidence is sufficient to show that models will not underestimate the actual degradation and failure of engineered barriers.*

> *(4) Mathematical degradation models are based on the same environmental parameters, material factors, assumptions and approximations shown to be appropriate for closely analogous applications.*
>
> *(5) Accepted and well documented procedures are used to construct and test the numerical models that simulate the EBS chemical environment and degradation of EBS;*
>
> *(6) Sensitivity analyses or bounding analyses are provided to support the abstraction of the degradation of engineered barriers.*

The models used in the IWPD analysis, including their uncertainty treatments, are listed in Section 4.1. The uncertainty treatments are inputs to this report meaning that the uncertainty treatments are implemented within the IWPD analysis consistent with the process or abstraction models feeding this report (BSC 2004 [DIRS 169845]; BSC 2004 [DIRS 169984]; BSC 2004 [DIRS 169985]). Numerical corrosion models used to calculate the lifetime of the engineered barriers are adequate representations, considering the associated uncertainties in long term behavior, range of conditions (including residual stresses) and the variability in fabrication processes. Objective evidence of this is the approval of the process or abstraction models feeding this report in accordance with the applicable procedures under which they were produced. Sufficient evidence to show that models will not underestimate the actual degradation and failure of engineered barriers is provided in the response to acceptance criterion 3.

One input (the waste package outer barrier general corrosion rate distribution) was manipulated in this report using a technique evident from standard scientific practices, approaches, or methods. The IWPD analysis makes use of a patch size which is about four times the size of the creviced geometry specimens used to generate the distribution of rates used to analyze general corrosion of the waste package outer barrier (Section 6.3.4). In this instance, a comparison was made between the input general corrosion rate distribution and that resulting from the methodology (Figure 3). The results of that comparison are that the implementation methodology is conservative and does not result in underestimation of the risk estimate. The models used in the IWPD analysis are discussed in Sections 6.3 and 6.4. Illustrative analysis results are presented in Section 6.5. On this basis, analysis output is supported by objective comparisons (where necessary) in this report.

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APPENDIX I

CONTENTS OF WAPDEG INPUT VECTOR

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I. CONTENTS OF WAPDEG INPUT VECTOR

The contents of the WAPDEG input vector are reproduced below (Table I-1). All values in the WAPDEG input vector are real numbers. Those that do not change, and are not defined by TSPA-LA components, are explicitly stated. The rest are represented by variable names, defined in the TSPA-LA itself. Certain of the parameters in the WAPDEG input vector reproduced in Table I-1 depend on the waste package configuration (CSNF or CDSP) being simulated. In this case, the value for the CSNF waste package is shown first, with the corresponding CDSP waste package value given afterwards in brackets.

The DLL links at the end of the vector (i.e., elements 700 and 701) are used to control the calling sequence of the DLLs. Inclusion in the WAPDEG input vector assures that those DLLs are called before WAPDEG is called.

For details of construction of the WAPDEG input vector consult (BSC 2002 [DIRS 162606]).

Table I-1. Contents of WAPDEG Input Vector

Row	Value	Parameter Description	Comments
1	Realization	**Realization Number**	
2	2	**Number of Barriers**	
3	1	**Barrier Type**	**A22 OB**
4	25	Barrier Thickness	mm
5	0.75	Barrier Mechanical Failure Fraction	fraction
6	1000	Barrier Pit Density Distribution Index	Fixed
7	0	Parameter 1	/mm^2
8	0	Parameter 2	
9	0	Parameter 3	
10	0	Parameter 4	
11	1000	Barrier Crack Density Distribution Index	Fixed
12	6	Parameter 1	/mm^2
13	0	Parameter 2	
14	0	Parameter 3	
15	0	Parameter 4	
16	2	**Barrier Type**	**A22 IB**
17	10	Barrier Thickness	mm
18	0.75	Barrier Mechanical Failure Fraction	fraction
19	1000	Barrier Pit Density Distribution Index	Fixed
20	0	Parameter 1	/mm^2
21	0	Parameter 2	
22	0	Parameter 3	
23	0	Parameter 4	
24	1000	Barrier Crack Density Distribution Index	Fixed
25	15	Parameter 1	/mm^2
26	0	Parameter 2	
27	0	Parameter 3	
28	0	Parameter 4	
29	1014 (1106)	Waste Container Surface Area	mm^2
30	0.484 (0.481)	Waste Container Top Fraction	fraction
31	0.484 (0.481)	Waste Container Bottom Fraction	fraction
32	1000	Waste Container Patch Area Distribution Index	Fixed
33	1	Parameter 1	mm^2
34	0	Parameter 2	
35	0	Parameter 3	
36	0	Parameter 4	

Row	Value	Parameter Description	Comments
37	-1	Apply Size Boolean	TRUE
38	-1	**Drip Shield Present Boolean**	TRUE
39	3	Drip Shield Type	**Ti7 DS**
40	15	Drip Shield Thickness	mm
41	0.75	Drip Shield Mechanical Failure Fraction	fraction
42	1000	Drip Shield Pit Density Distribution Index	Fixed
43	0	Parameter 1	/mm^2
44	0	Parameter 2	
45	0	Parameter 3	
46	0	Parameter 4	
47	1000	Drip Shield Crack Density Distribution Index	Fixed
48	0	Parameter 1	/mm^2
49	0	Parameter 2	
50	0	Parameter 3	
51	0	Parameter 4	
52	Number_DS_Patches	Drip Shield Surface Area	mm^2
53	1	Drip Shield Top Fraction	fraction
54	1000	Drip Shield Patch Size Distribution Index	Fixed
55	1	Parameter 1	mm^2
56	0	Parameter 2	
57	0	Parameter 3	
58	0	Parameter 4	
59	-1	Drip Shield Apply Size Boolean	TRUE
60	1000	Drip Shield Fractional Area Affected Distribution Index	Fixed
61	1	Parameter 1	fraction
62	0	Parameter 2	
63	0	Parameter 3	
64	0	Parameter 4	
65	1	Initial Water Condition under drip shield	**DSInside**
66	NumPak_CSNF (NumPak_CDSP)	Total Number of Waste Packages	
67	Hist_Index_CSNF (Hist_Index_CDSP)	Index Number of T/H File to Read	
68	1	**Number of Drip Sequences**	
69	1	**Number of Phases - Drip Sequence #1**	
70	1000	Fraction of Top Patches Subject to Sequence Distribution Number	Fixed
71	1	Parameter 1	fraction
72	0	Parameter 2	
73	0	Parameter 3	
74	0	Parameter 4	
75	1000	Fraction of Side Patches Subject to Sequence Distribution Number	Fixed
76	1	Parameter 1	fraction
77	0	Parameter 2	
78	0	Parameter 3	
79	0	Parameter 4	
80	1000	Fraction of Bottom Patches Subject to Sequence Distribution Number	Fixed
81	1	Parameter 1	fraction
82	0	Parameter 2	
83	0	Parameter 3	
84	0	Parameter 4	
85	2	Water Condition for Last Phase	**DSOutside**
86	6	**Number of Corrosion Functional Forms**	
87	1	**Water Condition Index Number**	**DSInside**
88	1	Corrosion Mechanism Index (1, 2, or 3)	**General**

Row	Value	Parameter Description	Comments
89	1	Layer Composition Index	**A22 OB**
90	5	Functional Form Index	General Linear
91	2	Number of terms in form	
92	0	Column number for term 1	
93	0	Column number for term 2	
94	2	Number of Levels for Variance Sharing	
95	1000	Barrier Variance Sharing Distribution Index	Fixed
96	0	Parameter1	fraction
97	0	Parameter 2	
98	0	Parameter 3	
99	0	Parameter 4	
100	2500	Term 1 distribution - ln(R)	File CDF
101	18	Parameter 1	WDlnRGC.cdf
102	0	Parameter 2	
103	0	Parameter 3	
104	0	Parameter 4	
105	1000	Term 2 distribution - C1/To	Fixed
106	C1divTo_GenCorr_A22	Parameter 1	
107	0	Parameter 2	
108	0	Parameter 3	
109	0	Parameter 4	
110	0	Sample Type	
111	1000	Error Term Distribution Index	Fixed
112	3.2236191301917E+01	Parameter 1	ln(10^14)
113	0	Parameter 2	
114	0	Parameter 3	
115	0	Parameter 4	
116	1000	Q Term Distribution Index - C1	Fixed
117	C1_GenCorr_A22	Parameter 1	K
118	0	Parameter 2	
119	0	Parameter 3	
120	0	Parameter 4	
121	1000	n Distribution Index	Fixed
122	1	Parameter 1	
123	0	Parameter 2	
124	0	Parameter 3	
125	0	Parameter 4	
126	1	**Water Condition Index Number**	**DSInside**
127	1	Corrosion Mechanism Index Number (1, 2, or 3)	**General**
128	2	Layer Composition Index	**A22 IB**
129	5	Functional Form Index	General Linear
130	2	Number of terms in form	
131	0	Column number for term 1	
132	0	Column number for term 2	
133	2	Number of Levels for Variance Sharing	
134	1000	Barrier Variance Sharing Distribution Index	Fixed
135	0	Parameter1	fraction
136	0	Parameter 2	
137	0	Parameter 3	
138	0	Parameter 4	
139	2500	Term 1 distribution - ln(R)	File CDF
140	18	Parameter 1	WDlnRGC.cdf
141	0	Parameter 2	
142	0	Parameter 3	
143	0	Parameter 4	
144	1000	Term 2 distribution - C1/To	Fixed
145	C1divTo_GenCorr_A22	Parameter 1	
146	0	Parameter 2	

Row	Value	Parameter Description	Comments
147	0	Parameter 3	
148	0	Parameter 4	
149	0	Sample Type	
150	1000	Error Term Distribution Index	Fixed
151	-6.93147180559945E-01 (-9.16290731874155E-01)	Parameter 1	ln(10/20) (ln(10/25))
152	0	Parameter 2	
153	0	Parameter 3	
154	0	Parameter 4	
155	1000	Q Term Distribution Index	Fixed
156	C1_GenCorr_A22	Parameter 1	K
157	0	Parameter 2	
158	0	Parameter 3	
159	0	Parameter 4	
160	1000	n Distribution Index	Fixed
161	1	Parameter 1	
162	0	Parameter 2	
163	0	Parameter 3	
164	0	Parameter 4	
165	1	**Water Condition Index**	**DSInside**
166	1	Corrosion Mechanism Index (1, 2, or 3)	**General**
167	3	Layer Composition Index	**Ti7 DS**
168	6	Functional Form Index - D = B*t^n	Power Law
169	2	Number of Levels for Variance Sharing	
170	1000	Barrier Variance Sharing Distribution Index	Fixed
171	1	Parameter 1	fraction
172	0	Parameter 2	
173	0	Parameter 3	
174	0	Parameter 4	
175	1000	B Distribution Index	Fixed
176	WDDSInGC	Parameter 1	mm/yr
177	0	Parameter 2	
178	0	Parameter 3	
179	0	Parameter 4	
180	1000	n Distribution Index	Fixed
181	1	Parameter 1	
182	0	Parameter 2	
183	0	Parameter 3	
184	0	Parameter 4	
185	0	Sample Type	
186	2	**Water Condition Index**	**DSOutside**
187	1	Corrosion Mechanism Index (1, 2, or 3)	**General**
188	1	Layer Composition Index	**A22 OB**
189	5	Functional Form Index	General Linear
190	2	Number of terms in form	
191	0	Column number for term 1	
192	0	Column number for term 2	
193	2	Number of Levels for Variance Sharing	
194	1000	Barrier Variance Sharing Distribution Index	Fixed
195	0	Parameter1	fraction
196	0	Parameter 2	
197	0	Parameter 3	
198	0	Parameter 4	
199	2500	Term 1 distribution - ln(R)	File CDF
200	18	Parameter 1	WDlnRGC.cdf
201	0	Parameter 2	
202	0	Parameter 3	
203	0	Parameter 4	

Row	Value	Parameter Description	Comments
204	1000	Term 2 distribution - C1/To	Fixed
205	C1divTo_GenCorr_A22	Parameter 1	
206	0	Parameter 2	
207	0	Parameter 3	
208	0	Parameter 4	
209	0	Sample Type	
210	1000	Error Term Distribution Index	Fixed
211	3.2236191301917E+01	Parameter 1	ln(10^14)
212	0	Parameter 2	
213	0	Parameter 3	
214	0	Parameter 4	
215	1000	Q Term Distribution Index	Fixed
216	C1_GenCorr_A22	Parameter 1	K
217	0	Parameter 2	
218	0	Parameter 3	
219	0	Parameter 4	
220	1000	n Distribution Index	Fixed
221	1	Parameter 1	
222	0	Parameter 2	
223	0	Parameter 3	
224	0	Parameter 4	
225	2	**Water Condition Index Number**	**DSOutside**
226	1	Corrosion Mechanism Index Number (1, 2, or 3)	**General**
227	2	Layer Composition Index	**A22 IB**
228	5	Functional Form Index	General Linear
229	2	Number of terms in form	
230	0	Column number for term 1	
231	0	Column number for term 2	
232	2	Number of Levels for Variance Sharing	
233	1000	Barrier Variance Sharing Distribution Index	Fixed
234	0	Parameter1	
235	0	Parameter 2	
236	0	Parameter 3	
237	0	Parameter 4	
238	2500	Term 1 distribution - ln(R)	File CDF
239	18	Parameter 1	WDlnRGC.cdf
240	0	Parameter 2	
241	0	Parameter 3	
242	0	Parameter 4	
243	1000	Term 2 distribution - C1/To	Fixed
244	C1divTo_GenCorr_A22	Parameter 1	
245	0	Parameter 2	
246	0	Parameter 3	
247	0	Parameter 4	
248	0	Sample Type	
249	1000	Error Term Distribution Index	Fixed
250	-6.9314718055995E-01 (-9.1629073187416E-01)	Parameter 1	ln(10/20) (ln(10/25))
251	0	Parameter 2	
252	0	Parameter 3	
253	0	Parameter 4	
254	1000	Q Term Distribution Index	Fixed
255	C1_GenCorr_A22	Parameter 1	K
256	0	Parameter 2	
257	0	Parameter 3	
258	0	Parameter 4	
259	1000	n Distribution Index	Fixed
260	1	Parameter 1	

Row	Value	Parameter Description	Comments
261	0	Parameter 2	
262	0	Parameter 3	
263	0	Parameter 4	
264	2	**Water Condition Index**	**DSOutside**
265	1	Corrosion Mechanism Index (1, 2, or 3)	**General**
266	3	Layer Composition Index	**Ti7 DS**
267	6	Functional Form Index - D = B*t^n	Power Law
268	2	Number of Levels for Variance Sharing	
269	1000	Barrier Variance Sharing Distribution Index	Fixed
270	1	Parameter 1	
271	0	Parameter 2	
272	0	Parameter 3	
273	0	Parameter 4	
274	1000	B Distribution Index	Fixed
275	WDDSOutGC	Parameter 1	mm/yr
276	0	Parameter 2	
277	0	Parameter 3	
278	0	Parameter 4	
279	1000	n Distribution Index	Fixed
280	1	Parameter 1	
281	0	Parameter 2	
282	0	Parameter 3	
283	0	Parameter 4	
284	0	Sample Type	
285	0	**Number of General Thresholds**	
286	0	**Number of Pit Temperature Thresholds**	
287	-1	Inside Out Corrosion Logical	TRUE
288	2	Water Condition for Inside Out Corrosion	**DSOutside**
289	0	Interface Corrosion Logical	FALSE
290	6	**Number of Events**	
291	2	**Manufacturing Defects Event Index**	
292	1	Barrier Type	**A22 OB**
293	2	Number of Water Conditions	
294	1	Condition Number	**DSInside**
295	2	Condition Number	**DSOutside**
296	CWD_OL_CSNF.FlawProb (CWD_OL_CDSP.FlawProb)	Probability that a Waste Package Has Defects	
297	2600	Number of Flaws Distribution Index	
298	10 (14)	Parameter 1	WDCWDNDO_CSNF.cdf (WDCWDNDO_CDSP.cdf)
299	0	Parameter 2	
300	0	Parameter 3	
301	0	Parameter 4	
302	2500	Flaw Size Distribution Index	File CDF
303	11 (15)	Parameter 1	WDCWDSizeO_CSNF.cdf (WDCWDSizeO_CDSP.cdf)
304	0	Parameter 2	
305	0	Parameter 3	
306	0	Parameter 4	
307	0	Immediate Failure Flag (-1 or 0 for true or false)	FALSE
308	0	Number of Localized Corrosion Modes Initiated (0, 1, or 2)	
309	0	Number of Corrosion Modes Accelerated (0, 1, 2, or 3)	
310	0	Number of Thresholds Reduced (0, 1, or 2)	
311	2	**Manufacturing Defects Event Index**	
312	2	Barrier Type	**A22 IB**
313	2	Number of Water Conditions	

Row	Value	Parameter Description	Comments
314	1	Condition Number	**DSInside**
315	2	Condition Number	**DSOutside**
316	CWD_ML_CSNF.FlawProb (CWD_ML_CDSP.FlawProb)	Probability that a Waste Package Has Defects	
317	2600	Number of Flaws Distribution Index	Discrete probability density function
318	12 (16)	Parameter 1	WDCWDNDM_CSNF.cdf (WDCWDNDM_CDSP.cdf)
319	0	Parameter 2	
320	0	Parameter 3	
321	0	Parameter 4	
322	2500	Flaw Size Distribution Index	File CDF
323	13 (17)	Parameter 1	WDCWDSizeM_CSNF.cdf (WDCWDSizeM_CDSP.cdf)
324	0	Parameter 2	
325	0	Parameter 3	
326	0	Parameter 4	
327	0	Immediate Failure Flag (-1 or 0 for true or false)	FALSE
328	0	Number of Localized Corrosion Modes Initiated (0, 1, or 2)	
329	0	Number of Corrosion Modes Accelerated (0, 1, 2, or 3)	
330	0	Number of Thresholds Reduced (0, 1, or 2)	
331	5	**SCC (Slip Dissolution) Event Index**	
332	1	Barrier Type	**A22 OB**
333	2	Number of Water Conditions	
334	1	Condition Number	**DSInside**
335	2	Condition Number	**DSOutside**
336	-1	Include MFD and rockfall cracks?	TRUE
337	0	Fraction of top surface area subject to SCC	fraction
338	1	Fraction of side surface area subject to SCC	fraction
339	0	Fraction of bottom surface area subject to SCC	fraction
340	6	File Index for Lookup Table [KI (col1) vs depth (col2)]	WDKISCCO.fil
341	7	File Index for Lookup Table [stress (col1) vs depth (col2)]	WDStressO.fil
342	1000	Barrier Variance Share Distribution Index (A, n)	Fixed
343	1	Parameter 1	fraction
344	0	Parameter 2	
345	0	Parameter 3	
346	0	Parameter 4	
347	1000	Patch Variance Share Distribution Index (A, n)	Fixed
348	0	Parameter 1	fraction
349	0	Parameter 2	
350	0	Parameter 3	
351	0	Parameter 4	
352	1000	A Distribution Index (velocity = A (KI)**n)	Fixed
353	Abar_SCC	Parameter 1	
354	0	Parameter 2	
355	0	Parameter 3	
356	0	Parameter 4	
357	1000	n Distribution Index	Fixed
358	nbar_SCC	Parameter 1	
359	0	Parameter 2	
360	0	Parameter 3	
361	0	Parameter 4	
362	1000	Incipient Crack Size Distribution Index	Fixed
363	0.05	Parameter 1	mm

Row	Value	Parameter Description	Comments
364	0	Parameter 2	
365	0	Parameter 3	
366	0	Parameter 4	
367	0	Sample Type	
368	1000	Barrier Variance Share Distribution Index (for thresholds)	Fixed
369	1	Parameter 1	fraction
370	0	Parameter 2	
371	0	Parameter 3	
372	0	Parameter 4	
373	1000	Stress Threshold Distribution Index (Incipient)	Fixed
374	Stress_Thresh_SCC	Parameter 1	MPa
375	0	Parameter 2	
376	0	Parameter 3	
377	0	Parameter 4	
378	1000	KI Threshold Distribution Index (Incipient)	Fixed
379	KI_Thresh_SCC	Parameter 1	MPa*sqrt(m)
380	0	Parameter 2	
381	0	Parameter 3	
382	0	Parameter 4	
383	1000	Stress Threshold Distribution Index (MFD)	Fixed
384	-600	Parameter 1	MPa
385	0	Parameter 2	
386	0	Parameter 3	
387	0	Parameter 4	
388	1000	KI Threshold Distribution Index (MFD)	Fixed
389	KI_Thresh_SCC	Parameter 1	MPa*sqrt(m)
390	0	Parameter 2	
391	0	Parameter 3	
392	0	Parameter 4	
393	0	Immediate Failure Flag (-1 or 0 for true or false)	FALSE
394	0	Number of Localized Corrosion Modes Initiated (0, 1, or 2)	
395	1	Number of Corrosion Modes Accelerated (0, 1, 2, or 3)	
396	1	General Corrosion Accelerated	
397	1000	Barrier Variance Share Distribution Index	Fixed
398	1	Parameter 1	fraction
399	0	Parameter 2	
400	0	Parameter 3	
401	0	Parameter 4	
402	1000	Acceleration Factor	Fixed
403	1.00E-14	Parameter 1	
404	0	Parameter 2	
405	0	Parameter 3	
406	0	Parameter 4	
407	0	Sample Type	
408	0	Number of Thresholds Reduced (0, 1, or 2)	
409	5	**SCC (Slip Dissolution) Event Index**	
410	2	Barrier Type	**A22 IB**
411	2	Number of Water Conditions	
412	1	Condition Number	**DSInside**
413	2	Condition Number	**DSOutside**
414	1	Include MFD and rockfall cracks?	TRUE
415	0	Fraction of top surface area subject to SCC	fraction
416	1	Fraction of side surface area subject to SCC	fraction
417	0	Fraction of bottom surface area subject to SCC	fraction

Row	Value	Parameter Description	Comments
418	8	File Index for Lookup Table [KI (col1) vs depth (col2)]	WDKISCCM.fil
419	9	File Index for Lookup Table [stress (col1) vs depth (col2)]	WDStressM.fil
420	1000	Barrier Variance Share Distribution Index (A, n)	Fixed
421	1	Parameter 1	
422	0	Parameter 2	
423	0	Parameter 3	
424	0	Parameter 4	
425	1000	Patch Variance Share Distribution Index (A, n)	Fixed
426	0	Parameter 1	
427	0	Parameter 2	
428	0	Parameter 3	
429	0	Parameter 4	
430	1000	A Distribution Index (velocity = A (KI)**n)	Fixed
431	Abar_SCC	Parameter 1	
432	0	Parameter 2	
433	0	Parameter 3	
434	0	Parameter 4	
435	1000	n Distribution Index	Fixed
436	nbar_SCC	Parameter 1	
437	0	Parameter 2	
438	0	Parameter 3	
439	0	Parameter 4	
440	1000	Incipient Crack Size Distribution Index	Fixed
441	0.05	Parameter 1	mm
442	0	Parameter 2	
443	0	Parameter 3	
444	0	Parameter 4	
445	0	Sample Type	
446	1000	Barrier Variance Share Distribution Index (for thresholds)	Fixed
447	1	Parameter 1	fraction
448	0	Parameter 2	
449	0	Parameter 3	
450	0	Parameter 4	
451	1000	Stress Threshold Distribution Index (Incipient)	Fixed
452	Stress_Thresh_SCC	Parameter 1	MPa
453	0	Parameter 2	
454	0	Parameter 3	
455	0	Parameter 4	
456	1000	KI Threshold Distribution Index (Incipient)	Fixed
457	KI_Thresh_SCC	Parameter 1	MPa*sqrt(m)
458	0	Parameter 2	
459	0	Parameter 3	
460	0	Parameter 4	
461	1000	Stress Threshold Distribution Index (MFD)	Fixed
462	-600	Parameter 1	MPa
463	0	Parameter 2	
464	0	Parameter 3	
465	0	Parameter 4	
466	1000	KI Threshold Distribution Index (MFD)	Fixed
467	KI_Thresh_SCC	Parameter 1	MPa*sqrt(m)
468	0	Parameter 2	
469	0	Parameter 3	
470	0	Parameter 4	
471	0	Immediate Failure Flag (-1 or 0 for true or false)	FALSE

Row	Value	Parameter Description	Comments
472	0	Number of Localized Corrosion Modes Initiated (0, 1, or 2)	
473	1	Number of Corrosion Modes Accelerated (0, 1, 2, or 3)	
474	1	General Corrosion Accelerated	
475	1000	Barrier Variance Share Distribution Index	Fixed
476	1	Parameter 1	fraction
477	0	Parameter 2	
478	0	Parameter 3	
479	0	Parameter 4	
480	1000	Acceleration Factor	Fixed
481	2 (2.5)	Parameter 1	20/10 (25/10)
482	0	Parameter 2	
483	0	Parameter 3	
484	0	Parameter 4	
485	0	Sample Type	
486	0	Number of Thresholds Reduced (0, 1, or 2)	
487	10	**MIC Event Index**	
488	1	Barrier Type	**A22 OB**
489	2	Number of Water Conditions	
490	1	Condition Number	**DSInside**
491	2	Condition Number	**DSOutside**
492	1	Fraction of surface area subject to MIC	
493	0	Use SCC patches first?	
494	1000	Barrier Variance Share Distribution Index	Fixed
495	1	Parameter 1	fraction
496	0	Parameter 2	
497	0	Parameter 3	
498	0	Parameter 4	
499	1000	MIC RHcrit Distribution Index	Fixed
500	0.9	Parameter 1	fraction
501	0	Parameter 2	
502	0	Parameter 3	
503	0	Parameter 4	
504	0	Sample Type (only one variable so not used, but must be specified)	
505	0	Immediate Failure Flag (- 1 or 0 for true or false)	FALSE
506	0	Number of Localized Corrosion Modes Initiated (0, 1, or 2)	
507	1	Number of Corrosion Modes Accelerated (0, 1, 2, or 3)	
508	1	Corrosion Mode Number (1, 2, or 3)	General Corrosion Accelerated
509	1000	Barrier Variance Share Distribution Index	Fixed
510	1	Parameter 1	fraction
511	0	Parameter 2	
512	0	Parameter 3	
513	0	Parameter 4	
514	1000	Acceleration Factor Distribution Index	Fixed
515	MIC_A22	Parameter 1	
516	0	Parameter 2	
517	0	Parameter 3	
518	0	Parameter 4	
519	0	Sample Type	
520	0	Number of Thresholds Reduced (0, 1, or 2)	
521	10	**MIC Event Index**	
522	2	Barrier Type	**A22 IB**

Row	Value	Parameter Description	Comments
523	2	Number of Water Conditions	
524	1	Condition Number	**DSInside**
525	2	Condition Number	**DSOutside**
526	1	Fraction of surface area subject to MIC	
527	0	Use SCC patches first?	
528	1000	Barrier Variance Share Distribution Index	Fixed
529	1	Parameter 1	fraction
530	0	Parameter 2	
531	0	Parameter 3	
532	0	Parameter 4	
533	1000	MIC RHcrit Distribution Index	Fixed
534	0.9	Parameter 1	fraction
535	0	Parameter 2	
536	0	Parameter 3	
537	0	Parameter 4	
538	0	Sample Type (only one variable so not used, but must be specified)	
539	0	Immediate Failure Flag (- 1 or 0 for true or false)	FALSE
540	0	Number of Localized Corrosion Modes Initiated (0, 1, or 2)	
541	1	Number of Corrosion Modes Accelerated (0, 1, 2, or 3)	
542	1	Corrosion Mode Number (1, 2, or 3)	General Corrosion Accelerated
543	1000	Barrier Variance Share Distribution Index	Fixed
544	1	Parameter 1	fraction
545	0	Parameter 2	
546	0	Parameter 3	
547	0	Parameter 4	
548	1000	Acceleration Factor Distribution Index	Fixed
549	MIC_A22	Parameter 1	
550	0	Parameter 2	
551	0	Parameter 3	
552	0	Parameter 4	
553	0	Sample Type	
554	0	Number of Thresholds Reduced (0, 1, or 2)	
555	WDSeed_CSNF (WDSeed_CDSP)	**Seed for the random number generator**	
556	NumBins	Number of bins for reporting penetrations with time	
557	BinStart	Bin Start Time	
558	0	Number of summary times for reporting penetrations	
559	0	Do Subset of Total Package Logical	FALSE
560	1	Number of First Package	
561	1	Number of Last Package	
562	SimTime	Simulation Time	
563	11	Number of Output files	
564	0	Generate OUT file logical	
565	0	Generate AUX file logical	
566	0	Generate PIT file logical	
567	0	Generate CRK file logical	
568	0	Generate PAT file logical	
569	0	Generate THK file logical	
570	0	Generate EVN file logical	
571	0	Generate DET file logical	
572	0	Generate INA file logical	

Row	Value	Parameter Description	Comments
573	0	Generate OUA file logical	
574	0	Generate PDZ file logical	
575	*(rows 575 to 699 are not referenced and contain zeros)*		
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.	.		
.	.		
699	0		
700	SCC_Outer_Lid.Output1		
701	SCC_Middle_Lid.Output1		
702	0		
703	0		
704	*(rows 704 to 2,000 are not referenced and contain zeros)*		
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.	.		
2,000	0		

APPENDIX II

OTHER SUPPORTING FILES

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II. OTHER SUPPORTING FILES

The integrated waste package degradation (IWPD) analysis uses several external files that must accompany the GoldSim input file in which it is run. The first of these is the WD4DLL.WAP file listed in Table II-1. Note that the line numbers and the column headings in Table II-1 are not part of the WD4DLL.WAP file, but are included for clarity.

Table II-1. Contents of WD4DLL.WAP File

Line	File Name
1	WDenv_00_07wheader.ou
2	WDenv_00wh.ou
3	EMPTY
4	WDKIinO.fil
5	WDKIinM.fil
6	WDKISCCO.fil
7	WDStressO.fil
8	WDKISCCM.fil
9	WDStressM.fil
10	WDCWDNDO_CSNF.cdf
11	WDCWDSizeO_CSNF.cdf
12	WDCWDNDM_CSNF.cdf
13	WDCWDSizeM_CSNF.cdf
14	WDCWDNDO_CDSP.cdf
15	WDCWDSizeO_CDSP.cdf
16	WDCWDNDM_CDSP.cdf
17	WDCWDSizeM_CDSP.cdf
18	WDlnRGC.cdf

WDenv_00_07wheader.ou and WDenv_00wh.ou are used only in this report. It is expected that another file will actually be used in the TSPA.

There is a dummy filename in position 3.

The contents of WDKIinO.fil are reproduced below. The first three lines in the WDKIinO.fil file (beginning with exclamation points) are comment lines. The comment lines have no effect on the calculations performed in the SCCD and WAPDEG software. The comment lines allow the user to enhance traceability by uniquely identifying the contents of the file. In this instance (and for the WDKIinM.fil discussed next), the contents of the comment lines are not correct. The first comment line should contain "`! WDKIinO.fil`". The second comment line should contain "`! Laser peened Outer lid DIRS: 169985, Table 8-3`" to be consistent with the *Stress Corrosion Cracking of the Drip Shield, the Waste Package Outer Barrier, and the Stainless Steel Structural Material* (BSC 2004 [DIRS 169985]). The file listing presented is consistent with the output DTN from this report (DTN: MO0310MWDWAPAN.002).

```
! KIinO.fil
! Laser peened Outer lid DIRS: 161234, Table 8-5
!
#  1  2
```

```
#  50
#  1.0
! KI (MPA*m½)  depth (mm)
-5.6943         0.3988
-6.4965         0.8001
-6.1528         1.1989
-5.1372         1.6002
-3.6697         1.9990
-1.8824         2.4003
0.1212          2.7991
2.2821          3.2004
4.5533          3.5992
6.8939          3.9980
9.2702          4.3993
11.6543         4.7981
14.0165         5.1994
16.3364         5.5982
18.6024         5.9995
20.8003         6.3983
22.9177         6.7970
24.9441         7.1984
26.9023         7.5971
28.8612         7.9985
30.7287         8.3972
32.5008         8.7986
34.1745         9.1973
35.7479         9.5987
37.2200         9.9974
38.4530         10.3962
39.5674         10.7975
40.5636         11.1963
41.4432         11.5976
42.2086         11.9964
42.8627         12.3977
43.4439         12.7965
43.9342         13.1978
44.3269         13.5966
44.6272         13.9954
44.8409         14.3967
44.9743         14.7955
45.0329         15.1968
45.0208         15.5956
44.9464         15.9969
44.8182         16.3957
44.6449         16.7945
44.4361         17.1958
44.2112         17.5946
43.9968         17.9959
43.7750         18.3947
43.5578         18.7960
43.3569         19.1948
43.1853         19.5961
43.0560         19.9949
```

The contents of WDKIinM.fil are reproduced below. Similar to the case of WDKIinO.fil discussed above, the first two comment lines in the WDKIinM.fil file (beginning with exclamation points) are not correct. The first comment line should contain "`! WDKIinM.fil`". The second comment line should contain "`!As-Welded Middle Lid DIRS: 169985, Table 8-2`" to be consistent with *Stress Corrosion Cracking of the Drip Shield, the Waste Package Outer Barrier, and the Stainless Steel Structural Material* (BSC 2004 [DIRS 169985]). The file listing presented is consistent with the output DTN from this report (DTN: MO0310MWDWAPAN.002).

```
! KIinM.fil
! As-Welded Middle Lid DIRS: 161234, Table 8-5
!
```

```
#  1  2
#  50
#  1.0
! KI (MPa*m½)   depth (mm)
7.5754          0.1593
10.9665         0.3203
13.7144         0.4797
16.1330         0.6407
18.3358         0.8000
20.3775         0.9593
22.3816         1.1203
24.3197         1.2797
26.1726         1.4407
27.9459         1.6000
29.6433         1.7593
31.2668         1.9203
32.8922         2.0797
34.5292         2.2407
36.1060         2.4000
37.6220         2.5593
39.0762         2.7203
40.4676         2.8797
41.8264         3.0407
43.2168         3.2000
44.5479         3.3593
45.8181         3.5203
47.0265         3.6797
48.1718         3.8407
49.2531         4.0000
50.3451         4.1593
51.3729         4.3203
52.3351         4.4797
53.2313         4.6407
54.0602         4.8000
54.8214         4.9593
55.4811         5.1203
56.0586         5.2797
56.5637         5.4407
56.9965         5.6000
57.3567         5.7593
57.6444         5.9203
57.7587         6.0797
57.6946         6.2407
57.5522         6.4000
57.3322         6.5593
57.0353         6.7203
56.6626         6.8797
56.1419         7.0407
55.3276         7.2000
54.4422         7.3593
53.4878         7.5203
54.6294         7.6797
56.2191         7.8407
57.7865         8.0000
```

The files WDKISCCO.fil, WDStressO.fil, WDKISCCM.fil, WDStressM.fil, WDCWDNDO_CSNF.cdf, WDCWDSizeO_CSNF.cdf, WDCWDNDM_CSNF.cdf, WDCWDSizeM_CSNF.cdf, WDCWDNDO_CDSP.cdf, WDCWDSizeO_CDSP.cdf, WDCWDNDM_CDSP.cdf, and WDCWDSizeM_CDSP.cdf are all files that are produced at run time and change their contents for each realization of the IWPD analysis.

The contents of WDlnRGC.cdf are reproduced below (column 1 is the natural logarithm of the general corrosion rate, column 2 is the cumulative probability values, column 3 is the general corrosion rate in mm/yr (not used but provided for illustration)).

```
125  ! WDlnRGC.cdf - CDF for Ln[Rate (mm/yr)] for Alloy 22
```

-16.961712197361	1e-015	4.3015204214735e-008
-16.606332266861	1e-014	6.1370764287394e-008
-16.250919072358	1e-013	8.7561969415836e-008
-15.895446698814	1e-012	1.2493819039048e-007
-15.539869004983	1e-011	1.7828739590043e-007
-15.184103757973	1e-010	2.5446468878913e-007
-14.828004150476	1e-009	3.6331189726815e-007
-14.471307289094	1e-008	5.1902837174783e-007
-14.113539817716	1e-007	7.4227962051286e-007
-13.753841023008	1e-006	1.0636108004554e-006
-13.390617861005	1e-005	1.529426298765e-006
-13.020824635104	0.0001	2.2137456007201e-006
-12.638272586363	0.001	3.2453979309883e-006
-12.228771288622	0.01	4.8877851647675e-006
-12.095541575836	0.02	5.5843552467729e-006
-12.014176485059	0.03	6.0577235210094e-006
-11.95450274756	0.04	6.4302139435167e-006
-11.906896320413	0.05	6.7437371027708e-006
-11.867014466231	0.06	7.0181250237782e-006
-11.832515828457	0.07	7.2644655516632e-006
-11.801989899202	0.08	7.4896394493125e-006
-11.774519377179	0.09	7.6982357619692e-006
-11.749473240538	0.1	7.8934816984425e-006
-11.726398285935	0.11	8.0777411437344e-006
-11.704957708673	0.12	8.25280257971e-006
-11.684894157232	0.13	8.4200553404489e-006
-11.666006404304	0.14	8.5806026817397e-006
-11.648134015655	0.15	8.7353371663517e-006
-11.631146932008	0.16	8.8849925752487e-006
-11.614938185062	0.17	9.0301806512331e-006
-11.599418678305	0.18	9.1714177309772e-006
-11.584513366555	0.19	9.3091444514342e-006
-11.570158406341	0.2	9.4437405995513e-006
-11.556298994738	0.21	9.5755364846527e-006
-11.542887705779	0.22	9.7048217747851e-006
-11.529883192646	0.23	9.8318524528176e-006
-11.51724916292	0.24	9.9568563577574e-006
-11.504953560484	0.25	1.0080037647227e-005
-11.492967905824	0.26	1.0201580427299e-005
-11.481266759108	0.27	1.0321651732614e-005
-11.46982727947	0.28	1.0440403994467e-005
-11.458628860377	0.29	1.0557977101684e-005
-11.447652825708	0.3	1.0674500134987e-005
-11.43688217469	0.31	1.0790092837602e-005
-11.42630136642	0.32	1.0904866871379e-005
-11.415896136709	0.33	1.1018926897439e-005
-11.405653341471	0.34	1.1132371512535e-005
-11.39556082205	0.35	1.1245294066247e-005
-11.385607288762	0.36	1.1357783379422e-005
-11.375782219648	0.37	1.1469924380546e-005
-11.366075771986	0.38	1.1581798673867e-005
-11.356478704522	0.39	1.1693485050718e-005
-11.346982308768	0.4	1.1805059953714e-005
-11.337578347973	0.41	1.1916597901966e-005
-11.328259002589	0.42	1.2028171884343e-005
-11.319016821266	0.43	1.2139853726833e-005
-11.309844676534	0.44	1.225171443934e-005
-11.300735724457	0.45	1.2363824546659e-005
-11.29168336764	0.46	1.2476254407934e-005
-11.282681221066	0.47	1.2589074528536e-005
-11.27372308027	0.48	1.2702355868114e-005
-11.264802891481	0.49	1.2816170148356e-005
-11.255914723223	0.5	1.2930590163975e-005

-11.247052739247	0.51	1.3045690100432e-005
-11.238211172251	0.52	1.3161545861962e-005
-11.229384298222	0.53	1.3278235413665e-005
-11.220566411044	0.54	1.3395839141646e-005
-11.21175179711	0.55	1.3514440235511e-005
-11.202934709625	0.56	1.3634125097966e-005
-11.194109342302	0.57	1.3754983786796e-005
-11.185269802139	0.58	1.3877110495173e-005
-11.176410080918	0.59	1.4000604077062e-005
-11.167524025069	0.6	1.4125568625509e-005
-11.15860530346	0.61	1.4252114112813e-005
-11.149647372663	0.62	1.4380357103089e-005
-11.140643439142	0.63	1.4510421549568e-005
-11.131586417741	0.64	1.4642439691204e-005
-11.12246888575	0.65	1.4776553065942e-005
-11.113283031688	0.66	1.4912913661378e-005
-11.104020597771	0.67	1.5051685227771e-005
-11.094672814858	0.68	1.5193044783627e-005
-11.085230328375	0.69	1.5337184350634e-005
-11.075683113423	0.7	1.5484312963077e-005
-11.066020376864	0.71	1.5634659007344e-005
-11.05623044364	0.72	1.5788472960683e-005
-11.046300623925	0.73	1.5946030615688e-005
-11.036217056846	0.74	1.610763689963e-005
-11.025964525342	0.75	1.6273630427313e-005
-11.015526235268	0.76	1.6444388965399e-005
-11.004883549816	0.77	1.6620336038545e-005
-10.994015667647	0.78	1.6801948978702e-005
-10.982899229434	0.79	1.6989768816026e-005
-10.971507832438	0.8	1.7184412544673e-005
-10.959811425593	0.81	1.7386588486316e-005
-10.947775547458	0.82	1.7597115745295e-005
-10.935360354661	0.83	1.7816949143246e-005
-10.922519366853	0.84	1.8047211604704e-005
-10.909197821533	0.85	1.8289236847896e-005
-10.895330481956	0.86	1.8544626601422e-005
-10.880838661918	0.87	1.8815328738574e-005
-10.865626102186	0.88	1.9103746273212e-005
-10.849573116212	0.89	1.9412893170728e-005
-10.832528043575	0.9	1.9746623493742e-005
-10.814294357166	0.91	2.0109979829965e-005
-10.794610437982	0.92	2.0509744608982e-005
-10.773116302859	0.93	2.0955355687502e-005
-10.74929553616	0.94	2.1460521153888e-005
-10.722365979358	0.95	2.2046295397764e-005
-10.69105213255	0.96	2.2747572249932e-005
-10.653038849576	0.97	2.3628927628531e-005
-10.603337771639	0.98	2.4832984417707e-005
-10.526951407683	0.99	2.6804214973517e-005
-10.325849053552	0.999	3.2774851685675e-005
-10.174589906086	0.9999	3.8126922194693e-005
-10.053211136624	0.99999	4.3047296134484e-005
-9.9518237288526	0.999999	4.7640670996241e-005
-9.8647635039768	0.9999999	5.1974179853622e-005
-9.7884780416973	0.99999999	5.6094205379008e-005
-9.7205916556578	0.999999999	6.0034470302955e-005
-9.6594369250961	0.9999999999	6.3820447508563e-005
-9.603798439259	0.99999999999	6.7471960981027e-005
-9.552764757972	0.999999999999	7.1004680683796e-005
-9.5056107132096	0.9999999999999	7.4433033708262e-005
-9.4614083903465	0.99999999999999	7.7796945354491e-005
-9.4189122120715	1	8.1174271693367e-005

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