DOC.20071003.0015

Scientific Analysis/Calculation Administrative Change Notice

QA:QA
Page 1 of 2

Complete only applicable items.

1. Document Number:	ANL-EBS-MD-000076	**2. Revision:**	00	**3. ACN:**	01
4. Title:	Analysis of Mechanisms for Early Waste Package / Drip Shield Failure				
5. No. of Pages Attached:	31				

6. Approvals:

Preparer: Russell Jarek Russell Jarek — Print Name and Sign — Date: 9/28/07

Checker: John McClure John McClure — Print name and sign — Date: 9/28/07

QCS/Lead Lab QA Reviewer: Charles Beach Charles P. Beach — Print name and sign — Date: 9-28-07

Responsible Manager: Cliff Howard For Paul R. Dixon Paul — Print name and sign — Date: 9-28-07

7. Affected Pages	**8. Description of Change:**
1-1, 6-20, 6-26	The cited SCC AMR has been revised, updated references to DIRS 181953.
4-4 to 4-7, 5-1 to 5-3, and 5-5	Citation to design information in SNL 2007 [DIRS 179394] updated to the correct title and parameter number.
6-9 and 6-10	Clarified the usage of "Improper heat treatment" process as applicable to both the outer corrosion barrier shell and outer corrosion barrier closure lid. Deleted footnote as its clarification is no longer necessary. Improved the description of how the waste package related processes are dispositioned.
6-11, 6-14, 6-16, 6-19, 6-38, 6-50, 6-52, 6-53, and A-1	Citation to design information in SNL 2007 [DIRS 179394] updated to the correct title, table number and/or parameter number.
6-12	Citation to design information in SNL 2007 [DIRS 179394] updated to the correct parameter number. Title update to most recent SNL 2007 [DIRS 179354].

Scientific Analysis/Calculation Administrative Change Notice

Complete only applicable items.

1. Document Number:	ANL-EBS-MD-000076	**2. Revision**:	00	**3. ACN**:	01
4. Title:	Analysis of Mechanisms for Early Waste Package / Drip Shield Failure				

6-17	For consistency with changes on pp. 6-9 and 6-10, updated bulleted list to match. Deleted footnote as it is no longer necessary to clarify. Title update to DIRS 179354.
6-36	Clarified the TSPA usage of weld flaw analysis.
6-39, 6-40, and 6-46	Updated the waste package Alloy 22 annealing temperature to 2,050°F.
6-45	Citation to design information in SNL 2007 [DIRS 179394] updated to the correct parameter number. Updated the waste package Alloy 22 annealing temperature to 2,050°F.
7-3	Emphasized the separate treatment of weld flaw failures. Adjusted the description of weld flaw alignment that is required for through-crack SCC propagation.
8-5	References updated for the titles and ACC of design reports, and to the latest REV 04 of SCC AMR.

1. PURPOSE

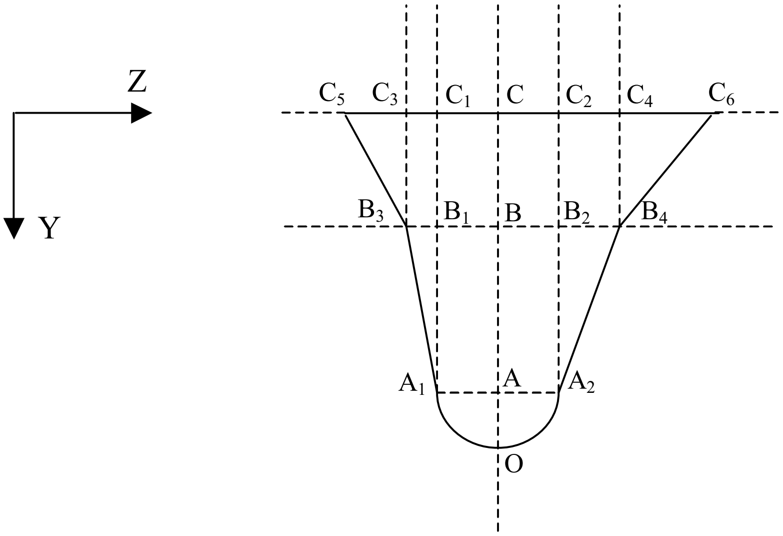
The purpose of this analysis is to evaluate the types of defects or imperfections that could occur in a waste package or a drip shield and potentially lead to its early failure, and to estimate a probability of undetected occurrence for each type. An early failure is defined as the through-wall penetration of a waste package or drip shield due to manufacturing or handling-induced defects, at a time earlier than would be predicted by mechanistic degradation models for a defect-free waste package or drip shield. A single waste package design has been specified with several configurations for the various waste forms as cited in *Total System Performance Assessment Data Input Package for Requirements Analysis for DOE SNF/HLW and Navy SNF Waste Package Physical Attributes Basis for Performance Assessment* (SNL 2007 [DIRS 179567], Table 4-1, Item 03-02). The waste package consists of a stainless steel inner shell and an outer corrosion barrier. For this analysis, the transportation, aging, and disposal (TAD) canister type waste package is a surrogate for all of the waste package configurations since all the configurations are subject to the same fabrication and handling processes. The scope of this analysis is limited to the manufacturing or handling-induced defects that might lead to the early failure of the waste package outer corrosion barrier and drip shield. The structural (stainless steel) vessel of the waste package was not analyzed.

This document was developed in accordance with the *Technical Work Plan for Postclosure Engineered Barrier Degradation Modeling* (SNL 2007 [DIRS 178849]), except for deviations as noted.

1. All of the acceptance criteria from Section 2.2.1.3.1.3 of *Yucca Mountain Review Plan, Final Report* (YMRP) (NRC 2003 [DIRS 163274]) were designated in the technical work plan (TWP) for consideration in this analysis. However, most of the criteria in Section 2.2.1.3.1.3 relate to degradation of the engineered barriers model abstraction that is beyond the scope of this analysis. The one subsection from Section 2.2.1.3.1.3 of *Yucca Mountain Review Plan, Final Report* (NRC 2003 [DIRS 163274]) applicable to this analysis is Acceptance Criterion 3, subsection 4, addressed in Section 4.2.

2. The TWP cites the procedure IM-PRO-001, *Managing Electronic Mail Records,* as the procedure for handling electronic information. The correct procedure is IM-PRO-002, *Control of the Electronic Management of Information*, as cited in Section 2.

If a waste package is affected by a type of defect that may lead to its early failure, it does not mean that this waste package is due to fail at emplacement in the repository. Failure of the waste package will only occur after degradation processes take place, which may happen hundreds or even thousands of years after emplacement. If a waste package were to fail early because of a defect, its radionuclide inventory would not necessarily be available for transport. This is because most through-wall penetrations, especially cracks from stress corrosion cracking (SCC), are usually tight and of limited length. Likewise, for drip shields, these types of failures do not necessarily lead to a loss of function, as seepage ingress through stress corrosion cracks is expected to be minimal (SNL 2007 [DIRS 181953], Section 6.7).



Source: Combination of Figures 1 and 2 from the drawing cited in SNL 2007 [DIRS 179394], Section 4.1.2.3.

Figure 4-1. Schematic Representation of the Cross Section of the Alloy 22 Weld

4.1.2.2 Parameters for Ultrasonic Inspection and Flaw Characteristics

Several nondestructive examination (NDE) techniques were used to detect weld flaws in the specimen rings. Surface examinations included liquid penetrant and eddy current inspections. Volumetric examinations included radiographic and ultrasonic testing. The surface indications, which consisted of nonwelding-related indications such as tooling marks, were irrelevant as discussed in the drawing cited in *Total System Performance Assessment Data Input Package for Requirements Analysis for TAD Canister and Related Waste Package Physical Attributes Basis for Performance Assessment* (SNL 2007 [DIRS 179394], Section 4.1.2.3) and are eliminated from further consideration in this analysis. For volumetric inspection, the radiographic testing was mainly used for a secondary check of the ultrasonic testing inspections. Therefore, only the volumetric indications of the ultrasonic testing are further considered.

Discussion in the "Study Summary" from the drawing cited in *Total System Performance Assessment Data Input Package for Requirements Analysis for TAD Canister and Related Waste Package Physical Attributes Basis for Performance Assessment* (SNL 2007 [DIRS 179394], Section 4.1.2.3) indicates that the nondestructive ultrasonic examination employed was comparable to radiographic examination; as the discussion states, both were "capable of detecting volumetric flaws as small as 1 millimeter in size." This was confirmed by the metallographic inspections performed on the specimen rings: the weld imperfections discovered through this process were the same weld imperfections discovered during the ultrasonic testing and radiographic testing inspections. However, three flaws that were indicated by ultrasonic testing and/or radiographic testing were not located upon metallographic examination, as discussed in "Results of Metallographic Study" from the drawing cited in Section 4.1.2.3 of the abovementioned report.

Based on the information provided in the "Results of Metallographic Study" from the drawing cited in *Total System Performance Assessment Data Input Package for Requirements Analysis for TAD Canister and Related Waste Package Physical Attributes Basis for Performance Assessment* (SNL 2007 [DIRS 179394], Section 4.1.2.3), ultrasonic testing inspections revealed seven flaws that were confirmed by metallography. Two of the weld flaws listed in Table 1 from the drawing cited in that report as discovered during the ultrasonic testing and radiographic examination could not be verified by metallographic methods (Rings K2 and S1F) and therefore were not included in this evaluation. (A third flaw not confirmed by metallography was discovered in Ring S3F only by radiographic examination.) The weld flaw volumetric dimensions (here called the X, Y, and Z directions) as evaluated by the ultrasonic testing inspections are presented in Table 4-3. Metallographic examinations confirmed the ultrasonic testing dimensions or showed that ultrasonic testing slightly overestimated the actual flaw dimensions as discussed in "Volumetric Flaws" from the drawing cited in the report.

Table 4-3. Dimensions of the Ultrasonic Indications

Ultrasonic Testing Flaw No.	X-Direction, Length (in)	Y-Direction, Thickness (in)	Z-Direction, Width (in)
Ring K3	1/8 (0.125)	1/16 (0.0625)	1/16 (0.0625)
Ring K4	5/8 (0.625)	1/16 (0.0625)	1/16 (0.0625)
Ring R1F	3/4 (0.75)	1/8 (0.125)	1/16 (0.0625)
Ring R3F	1 3/8 (1.375)	1/8 (0.125)	1/16 (0.0625)
Ring R5F	3/8 (0.375)	1/8 (0.125)	1/16 (0.0625)
Ring W1F	1/2 (0.50)	3/16 (0.188)	1/8 (0.125)
Ring X1F	3/8 (0.375)	9/16 (0.563)	0

Source: Values calculated from dimensions given in Table 1 of the drawing cited in SNL 2007 [DIRS 179394], Section 4.1.2.3.

Based on Figure 3 from the drawing cited in *Total System Performance Assessment Data Input Package for Requirements Analysis for TAD Canister and Related Waste Package Physical Attributes Basis for Performance Assessment* (SNL 2007 [DIRS 179394], Section 4.1.2.3), the X direction gives the azimuthal location of the flaws in the direction of the weld (starting from some fixed point on the ring); the Y direction shows the position of the flaw in the through-wall extent of the weld; and the Z direction shows the radial position of the flaw in the weld. The Y and Z directions are shown in Figure 4-1. The X direction is shown in Figure 6-5, given in Section 6.3.1.5.

The flaws in Ring K are the result of a poor weld preparation, as discussed in "Weld Root Flaws Section" from the drawing cited in *Total System Performance Assessment Data Input Package for Requirements Analysis for TAD Canister and Related Waste Package Physical Attributes Basis for Performance Assessment* (SNL 2007 [DIRS 179394], Section 4.1.2.3), that was performed under conditions that are not representative of the highly controlled environment in which future manufacturing of the waste packages will take place. Nevertheless, following a conservative approach these flaws have been kept in this analysis. The other flaws reported in Table 4-3 are lack of fusion-type defects, as described in the "Weld Flaw Section" from the drawing cited in the abovementioned report.

Table 4-4 summarizes the direct input data for the weld-flaw analyses provided in Section 6.1.

Table 4-4. Weld Flaw Data

Parameter Description	Parameter Value	Source
Lower limit for ultrasonic testing of probability of nondetection (PND)	5×10^{-3}	Bush 1983 [DIRS 107696], p. 13A.5.7
Geometry of specimen welds examined during testing	Various dimensions	SNL 2007 [DIRS 179394], Item 03-17, Figures 1 and 2, Section 4.1.2.3
Number of flaws found and confirmed from ultrasonic testing	7	SNL 2007 [DIRS 179394], Item 03-17, Section "Results of Metallographic Study," Section 4.1.2.3
Detection limit for weld flaws	≥ 1/16th of an inch	SNL 2007 [DIRS 179394], Item 03-13, Section 4.1.2.3
Volumetric information on ultrasonic testing of flaws	Length, thickness, and width of flaws	SNL 2007 [DIRS 179394], Item 03-17, Table 1, Section 4.1.2.3

The parameters given previously are appropriate for use in this analysis because they yield characteristics of flaws of Alloy 22 welds, whose design conforms to that of the closure weld of the waste package.

4.1.3 Miscellaneous Inputs

Table 4-5 summarizes the miscellaneous input data for evaluating the various scenarios leading to defects that have potential for becoming early failure mechanisms for waste packages and drip shields. All of the input data identified in Table 4-5 are from appropriate sources that are qualified for their use in Section 4.1.4.

Table 4-5. Input to Early Failure Mechanisms for Waste Package Outer Corrosion Barrier and Drip Shield

Description	Value	Source
Probability of selecting improper material	65 to 350 lbs of wire out of 1,706,556 lbs	Babcock & Wilcox 1979 [DIRS 108219], pp. 2, I-4, I-6; Part II, Table 1
Probability of inducing defects through handling	4.8×10^{-5} per fuel assembly moved	BSC 2001 [DIRS 157560], Table 5
Drip shield weld filler material	Titanium Grades 7, 28, and 29	SNL 2007 [DIRS 179354], Table 4-2, Item 07-12
Drip shield material	Titanium Grades 7 and 29	SNL 2007 [DIRS 179354], Table 4-2, Item 07-04
Drip shield heat treatment	No maximum time requirement for stress-relief heat treatment, 1,100°F ±50°F for two hours with air cooling	SNL 2007 [DIRS 179354], Table 4-2, Item 07-13
Drip shield emplacement	Requirement for interlock and inspections	SNL 2007 [DIRS 179354], Table 4-2, Item 07-02
Waste package outer corrosion barrier heat treatment	Requirements for heat treatment process; temperature (2,050°F +50°F/−0°F), duration (minimum of 20 min), and quenching (>275°F/min)	SNL 2007 [DIRS 179394], Table 4-1, Item 03-16

Table 4-5. Input to Early Failure Mechanisms for Waste Package Outer Corrosion Barrier and Drip Shield (Continued)

Description	Value	Source
Stress relief of closure welds on waste package outer corrosion barrier lid	Requirements for use of low-plasticity burnishing as stress-relief method	SNL 2007 [DIRS 179394], Table 4-1, Item 03-17
Waste package outer corrosion barrier handling and inspections	Requirements for inspections for surface defects during handling and prior to emplacement	SNL 2007 [DIRS 179394], Table 4-1, Items 03-22, 03-23, and 03-24
Alarm failure for duration heat treatment of waste package outer corrosion barrier	3×10^{-5} per hour Error factor of 10	Blanton and Eide 1993 [DIRS 141700], Table 6f
Failure of makeup water system represented by failure of motor-operated valve to open	Failure rate = 3×10^{-3} Error factor of 5	Blanton and Eide 1993 [DIRS 141700], Table 6a
Pressure failure	Mean value = 1×10^{-6} per hour Error factor of 3	Blanton and Eide 1993 [DIRS 141700], Table 6f
Probability distribution for HEPs	Lognormal	Swain and Guttmann 1983 [DIRS 139383], pp. 2-18 and 2-19
Upper and lower bounds for probability distributions	5% to 95%	Swain and Guttmann 1983 [DIRS 139383], p. 2-19

4.1.4 Qualification of External Source Data

Estimates of HEPs from unqualified external sources were used in this analysis to evaluate operational events. These probability estimates are "data" per SCI-PRO-004. The basis for using this information is that such data are recommended for use by *PRA Procedures Guide, A Guide to the Performance of Probabilistic Risk Assessments for Nuclear Power Plants* (NRC 1983 [DIRS 106591], Sections 4.1 and 4.5.7) and/or are used in evaluations of the probability of occurrence of human errors in the conduct of probabilistic risk assessments for nuclear power plants. This section presents planning and documentation for the data qualification of the unqualified external source data used as direct input only for the intended use in this analysis. Data qualification is performed in accordance with SCI-PRO-005.

4.1.4.1 Data for Qualification

There are five external sources of data used as direct input for this analysis:

1. Data for the probability for humans failing to respond to administrative and engineered controls from Benhardt et al. (1994 [DIRS 157684]) identified in Section 4.1.1 and Table 4-1 of this report

2. Data for the probability for failure of engineered controls from Blanton and Eide (1993 [DIRS 141700]) identified in Section 4.1.3 and Table 4-5 of this report

3. Weld-flaw data revealed through ultrasonic testing from Bush (1983 [DIRS 107696]) identified in Table 4-4 of this report

5. ASSUMPTIONS

5.1 CLOSURE WELD-FLAW SCREENING SIZE

It is assumed that a minimum required size for the detection and screening of closure weld flaws will be 1/16 in (1.5875 mm).

The rationale for selecting 1/16 in as the minimum size for the weld flaw detection and screening limit is that standards for the calibration of ultrasonic testing equipment for detecting a flaw size of 1/16 in are readily available. For example, the calibration block used for the ultrasonic testing examination of the Alloy 22 weld-flaw evaluation contained a reference flaw of 1.0 mm (Smith 2003 [DIRS 163114], Section 3.1). In addition, design requirements specify detection and repair of weld flaws at 1/16th of an inch or greater (SNL 2007 [DIRS 179394], Table 4-1, Items 03-15 and 03-17). Thus, for flaw sizes of 1/16 in and above, the fabrication process equipment is capable of locating closure weld flaws, permitting the operator to either repair the weld section or make a screening determination that it will not adversely affect the postclosure performance of the welded item. The probability of nondetection (PND) of weld flaws (Equation 17) represents that only half of the flaws of this size will actually be detected although actual detection limits are lower, per use of a 1.0-mm reference flaw for tests. Thus, a minimum size of 1/16 in for detection and screening of flaws is conservative since the evaluation of the PND with a parameter of this size overestimates the number of undetected closure weld flaws for postclosure analysis purposes (Section 6.3.1.6).

This assumption, which is used in Sections 6.3.1.6 and 6.3.1.7, is conservative, as stated, and does not require confirmation.

5.2 PROBABILITY DISTRIBUTION FOR IMPROPER MATERIAL SELECTION

It is assumed that the probability distribution for improper selection of fabrication materials can be represented by a lognormal distribution.

The rationale for this assumption is the similarity between the operations of selecting materials for fabrication and the selection of weld filler material. This type of error can be represented by HEPs (Swain and Guttmann 1983 [DIRS 139383], p. 2-17), which are represented by lognormal distributions (Swain and Guttmann 1983 [DIRS 139383], Section 7). For such distributions, Swain and Guttmann (1983 [DIRS 139383], p. 2-19) recommend choosing the 5th and the 95th percentiles of a lognormal distribution when evaluating lower and upper bounds for HEP uncertainty that is characterized as an error factor.

This assumption, which is used in Section 6.3.2, does not require confirmation.

5.3 UNCERTAINTY DISTRIBUTIONS FOR PROBABILITY VALUES

It is assumed that probabilities given as point values represent the mean value of probability distributions and that the uncertainty values for the distributions can be represented by lognormal distributions with a range delimited by an error factor between 3 and 15.

The rationale for this assumption is that there is uncertainty associated with any probability value, whether explicitly specified or not, and the lognormal distribution is one possible representation for distributions that cannot be negative. In addition, assigning a lognormal attribute to nonspecified uncertainty distributions makes them consistent with HEPs, which are represented by lognormal distributions (Swain and Guttmann 1983 [DIRS 139383], pp. 2-18 and 2-19).

The specification of an error factor range between 3 and 15 is a reasonable value that is consistent with the range of HEPs. This spread in error factor values allows the uncertainty distribution for the associated probability a range that is on the order of 10 to 100 (Equation 2).

This assumption is used in Sections 5.7, 6.3.3, 6.3.4, 6.3.5, and 6.4.2 and does not require confirmation.

5.4 CRITICAL PHASE OF THE WASTE PACKAGE OUTER CORROSION BARRIER HEAT TREATMENT

It is assumed that the critical portion of the heat treatment process for the waste package outer corrosion barrier is the final phase of the operation that is the time-sensitive solution annealing of the outer corrosion barrier.

The rationale for this assumption is that strict time constraints are imposed on the solution-annealing phase of the waste package outer corrosion barrier heat treatment to prevent the development of undesirable phases in the outer corrosion barrier material during cool-down (SNL 2007 [DIRS 179394], Table 4-1, Item 03-20). The purpose of the heat treatment is to produce a uniform phase in the outer corrosion barrier material and then avoid an undesirable phase transition during cooling (SNL 2007 [DIRS 179394], Section 4.1.2.2). In addition, the heat treatment will be applied to the outer corrosion barrier as a complete unit with the exception of the closure lid. The overall outer corrosion barrier fabrication is to be performed in a controlled manner (SNL 2007 [DIRS 179394], Table 4-1, Item 03-12). Performance constraints on the operation prior to the solution-annealing phase are less stringent than those pertaining to the solution-annealing phase, permitting potential process faults or failures to be more readily identified and corrected, minimizing the likelihood of nondetection of such events.

This assumption is used in Sections 6.3.3 and 6.3.4 and does not require confirmation since additional phases of the operation can be modeled, if identified as important as a mechanism contributing to early failures.

5.5 MONITORS FOR WASTE PACKAGE OUTER CORROSION BARRIER FABRICATION PROCESSES

It is assumed that the fabrication processes for the waste package outer corrosion barrier will be monitored with appropriate systems (e.g., timers, thermocouples) equipped with recording capability and alarms that serve as surrogates for operational monitoring processes.

The rationale for this assumption is that, firstly, recording capability is a normal part of operations performed under quality assurance procedures to provide the necessary documentation records. This capability applies to all fabrication processes. Secondly, in the event of process malfunctions or failures, it is anticipated that operational monitoring systems will be available to alert the operator to take remedial action. For example, strict time constraints are placed on certain phases of the fabrication process, e.g., the solution annealing phase of the waste package outer corrosion barrier heat treatment, to prevent the development of undesirable phases in the outer corrosion barrier material during cool-down (SNL 2007 [DIRS 179394], Table 4-1, Item 03-16). Imposing limits on the minimum outer corrosion barrier temperature allowable to begin the quench process implies that the outer corrosion barrier must be transferred to the quench facility within a prescribed time period. Exceeding the prescribed transfer period could result in an inadequate heat treatment process. A monitoring system would alert the operator to take remedial action, minimizing the likelihood that a process malfunction is undetected. For this analysis, some type of alarm system serves as a surrogate for such a monitoring system.

This assumption, which is used in Sections 6.3.3 and 6.3.5, requires confirmation that will be accomplished when the fabrication procedures are finalized.

5.6 QUENCHING OF WASTE PACKAGE OUTER CORROSION BARRIER

It is assumed that the waste package outer corrosion barrier quench operation will be performed with the outer corrosion barrier in an inverted axial position.

The rationale for this assumption is that an inverted position with the open end down provides the best arrangement for maintaining a relatively uniform through-wall metal temperature distribution during the rapid cool-down (SNL 2007 [DIRS 179394], Table 4-1, Item 03-16) since both inside and outside surfaces are quenched simultaneously. This arrangement is amenable to pool and/or spray quenching methods. Performing the quenching process with the outer corrosion barrier inverted also prevents any excess water from accumulating in the outer corrosion barrier.

This assumption is used in Section 6.3.3 and requires confirmation that it will be accomplished when the fabrication procedures are finalized.

5.7 PROBABILITY FOR MECHANICAL MALFUNCTIONING OF LIFTING AND MOVING EQUIPMENT

It is assumed that a value of 3×10^{-3} per event is an upper bound for the median probability of having a mechanical malfunction of moving equipment such as cranes and trolleys.

The rationale for this bounding assumption is that equipment malfunctions that could cause a failure of the heat treatment processes are much less severe but more likely than major failures for equipment. Data for major equipment failures (e.g., load drops) that cause damage to the objects being handled were used to develop the probability of damage to fuel assemblies due to equipment failure. This probability was estimated as 1.9×10^{-5} per event (BSC 2001 [DIRS 157560], Table 4). The probability of heavy load drops at reactor power facilities has been estimated as approximately 5.6×10^{-5} per event (Lloyd 2003 [DIRS 174757], Section 3.7.1). The equipment malfunctions that could cause a failure of the heat-treatment processes are much less severe but more likely. These malfunctions could be caused by such

5.10 AUTOMATED SYSTEMS USED FOR FABRICATION PROCESSES ASSOCIATED WITH WASTE PACKAGES AND DRIP SHIELDS

It is assumed that fabrication of waste packages and drip shields will be performed in facilities using equipment operated with self-contained control systems (i.e., generalized systems independent of objects being fabricated).

The rationale for this assumption is that manufacturing activities for waste packages and drip shields are to be performed in accordance with a QA or quality control program (SNL 2007 [DIRS 179394], Table 4-1, Item 03-12). Industrial equipment with self-contained control systems for handling such objects under strict quality assurance requirements are commonly available and routinely used.

This assumption was used in Sections 6.3.3, 6.3.4, and 6.4.2 and does not require confirmation.

Table 6-2. Summary of Defect-Related Failures in Various Welded Metallic Containers (Continued)

Container Type	Information on Failure	Types of Defects Leading to Early Failure
Radioactive cesium capsules	One failure out of 1,600 capsules.	- Administrative error resulting in unanticipated operating environment
Dry-storage casks for spent nuclear fuel	Four out of 19 Sierra Nuclear VSC-24 casks found to have cracked closure welds during postweld inspection (dye-penetrant and helium leak test only).	- Weld flaws - Base metal flaws - Contamination

Source: Summary of results of literature search presented in Sections 6.1.1 through 6.1.5.

A complementary type of defect is added to the previous list: out-of-specification (improper) base metal. This type of defect was not identified in the literature search; only instances of improper weld material were found. However, it is reasonable to consider the possibility that base metal, as well as weld material, might be out of specification. This particular defect mode is combined with those associated with base-metal flaws for the rest of this report. Planned repository design and operations (DOE 2006 [DIRS 176937]) indicate that the generic list should also include defects introduced by stress relief heat treatment of the waste package closure weld with a low-plasticity burnishing process and recognizing that the drip shield or waste packages might be improperly installed. Thus, 13 processes or conditions are evaluated in this analysis. These processes are listed below:

- Weld flaws
- Base metal flaws
- Improper weld filler material
- Improper stress relief for lid (low plasticity burnishing)
- Improper heat treatment
- Improper weld-flux material
- Poor weld-joint design
- Contaminants
- Improperly located welds
- Missing welds
- Handling-induced defects
- Emplacement errors
- Administrative or operational errors.

The 13 types of defects were reviewed for their applicability to waste packages and results discussed in Section 6.2.3. Of these 13 flaws or processes, six processes were screened from further analysis based on either very low likelihood of occurrence or low consequences. A seventh process, administrative or operational errors, was included within the fault tree analyses. The remaining six processes were identified as significant for the waste package outer corrosion barrier, requiring further analysis (Section 6.3). The six processes retained for further analyses with respect to mechanisms for potential early failures of a waste package outer corrosion barrier are as follows:

- Weld flaws
- Improper heat treatment
  - outer corrosion barrier shell
  - outer corrosion barrier closure lid
- Improper stress relief of outer corrosion barrier lid (low plasticity burnishing)
- Waste package mishandling damage
- Improper base metal selection
- Improper weld filler material.

The same 13 processes identified above were reviewed for potentially leading to early failure of a drip shield, and four were identified as significant, requiring further analysis (Section 6.4). The four processes retained for further analyses with respect to mechanisms for potential early failures of a drip shield are as follows:

- Improper heat treatment
- Base metal selection flaws
- Improper weld filler material
- Emplacement errors.

The probability of occurrence and consequences for postclosure performance of the package and drip shield were assessed for the applicable defects.

Weld flaws (e.g., slag inclusions, porosity, lack of fusion, or hydrogen-induced cracking) were a dominant contributor to early failure but usually required an external stimulus (e.g., cyclic fatigue) or environmental conditions to cause the flaw to propagate to failure. In many cases, components with unidentified defects entered service, not because the defect was missed by an inspection, but because no inspection for that type of defect was required at the time they were fabricated. For dry-storage casks, all of the defects were identified by postweld inspection prior to commencement of the storage phase and thus do not represent early failure as it is defined for this analysis.

As indicated previously, many of the defects require an external stimulus or the component was not subjected to inspections that would have identified the defect. There is likewise insufficient information available to defensibly relate the cumulative effect of the environment or stresses to which the component was subjected to that of the waste package or drip shields (e.g., whether the cumulative effects of the stresses and environmental conditions experienced by a pressure vessel in a 40- to 60-year life are relevant to 100, 1,000, or 10,000 years of waste package lifetime). Because the development of early failure modes from material defects is closely connected to the long-term environmental conditions, this analysis addresses the probability that such defects exist, not the likelihood of failures due to defects. Accordingly, the information on the fraction of components that experienced defect-related failure during their intended lifetime is not directly applicable to waste packages or drip shields. In addition, these population-based failure rates do not provide any insight into the time distribution of early failures. However, in some cases, information on the occurrence rate of particular types of defects was obtained from the literature search.

6.2 FABRICATION AND HANDLING PROCESSES RELEVANT TO EARLY FAILURE OF ENGINEERED BARRIER COMPONENTS

6.2.1 Waste Package Fabrication and Handling Processes

The overall dimensions of the TAD canister waste package outer corrosion barrier, a cylinder having a diameter of approximately 1.96 m and a length of approximately 5.85 m, have been developed and documented (SNL 2007 [DIRS 179394], Table 4-3). The processes for the fabrication and handling of the waste package outer corrosion barrier have conceptually been developed. The exact processes will be dependent on the approach of the vendor to meeting the specifications of the YMP. The specifications for the waste package fabrication can be found in *Total System Performance Assessment Data Input Package for Requirements Analysis for TAD Canister and Related Waste Package Physical Attributes Basis for Performance Assessment* (SNL 2007 [DIRS 179394]).

The fabrication process begins with the procurement of the plates that form the right circular cylinders comprising the waste package outer corrosion barrier. There are two primary elements: the inner structural vessel made of Stainless Steel Type 316 (UNS S31600); and the outer corrosion resistant barrier made of Alloy 22 (UNS N06022), a nickel-based chromium/molybdenum alloy (SNL 2007 [DIRS 179394], Table 4-1, Item 03-03). The inner vessel fits within the outer corrosion barrier with a maximum diametral clearance of 10 mm (SNL 2007 [DIRS 179394], Table 4-1, Item 03-04). Each vessel has lower and upper lids. Spacer rings are located within the bottom of the waste package outer corrosion barrier so that the inner lid does not touch the outer lid. The lower lids are welded in place at the fabrication site, while the upper lids are welded in place at the repository after the spent nuclear fuel or defense high-level waste canisters are placed within a waste package. The outer waste package barrier also has external sleeves on either end, 304.8 mm in length (SNL 2007 [DIRS 179394], Table 4-3), that assist in handling operations.

Both vessels are made from rolled and welded plates to form the right circular cylinders. The structural vessel is 50.8 mm thick, while the outer corrosion barrier is 25.4 mm thick (SNL 2007 [DIRS 179394], Table 4-3). The number of segments needed for each right circular cylinder depends directly on the mass of material of a particular heat that can be poured to form an ingot and then worked to form the plate segment. This usually requires the cast material to be, perhaps, forged, then rolled to the required thickness, cut to the required size, and followed by welding and a nondestructive inspection. Ideally, if the smelter could produce an ingot large enough for each vessel, the welding of segments would not be necessary. This is not now the case, and multiple plate segments may be necessary for each vessel. The segments would be welded together by gas tungsten arc welding or another acceptable process, then subjected to intensive NDE to ensure that weld flaws above the acceptable threshold are not present (SNL 2007 [DIRS 179394], Table 4-1, Items 03-12 through 03-15).

After the assembled and welded plates have passed inspection, the edges are machined as needed, then rolled into a cylinder of the required dimension (approximately 1.8 m in diameter) and a longitudinal weld is performed. The likely method would have two or three sections of cylinders fabricated by this method with their longitudinal welds offset, so that cracks in a longitudinal weld could not propagate along the entire length of the vessel. The sections would then be welded circumferentially to complete the vessel, whose overall length is approximately 5.7 m (SNL 2007 [DIRS 179394], Table 4-3). After being inspected and undergoing the threshold flaw testing, the lower lid would be welded in place. The lids, basically large discs, are fabricated separately of the same alloy material as the body of the vessels. The lid thicknesses are 25.4 mm and 50.8 mm, respectively, for the outer corrosion barrier and inner vessel (SNL 2007 [DIRS 179394], Table 4-3). The lower lid welds will also be subjected to detailed NDE (SNL 2007 [DIRS 179394], Table 4-1, Item 03-13). The outer corrosion barrier and its lids are solution-annealed (SNL 2007 [DIRS 179394], Table 4-1, Item 03-16) to preserve their corrosion properties. The inner vessel does not require a heat treatment, since it serves primarily as a support structure. Following heat treatment of the outer corrosion barrier and machining of the weld preparations, the inner vessel is placed within the outer corrosion barrier. The lids are shipped along with the assembled waste package.

The dimensions of the completed vessels will be confirmed to ensure that the inner liner can be inserted into the outer corrosion barrier without interactions. Here, dimensions and ovality are important. The inner liner will then be inserted into the outer corrosion barrier and the completed unit packaged for transport to the repository. The waste package pieces will contain impressed inventory numbers so that each package can be followed through subsequent handling. The empty waste packages will be received and inspected at the repository and placed into temporary storage. When needed, the empty waste packages will be moved to the appropriate building where the TAD or defense high-level waste canister will be inserted in the vertical position. After waste insertion and placement of a Stainless Steel Type 316 spread ring, the inner lid will be welded in place. Following nondestructive inspection, the outer lid will be welded in place. This weld will undergo residual stress mitigation by means of low-plasticity burnishing, followed by detailed NDE (SNL 2007 [DIRS 179394], Table 4-1, Item 03-17). The loaded waste packages will then be rotated vertically and readied for movement by the fuel transporter into the repository position established for that package. The transporter is remotely operated and places the waste package and its pallet in the required position using location sensors.

6.2.2 Drip Shield Fabrication and Handling Processes

Conceptually the drip shield looks like an inverted “U” or mailbox. The overall dimensions of the drip shield, about 2.4 meters across and about 5.8 meters in length including the overlap section, have been developed and documented. These dimensions can be found in *Total System Performance Assessment Data Input Package for Requirements Analysis for Engineered Barrier System In-Drift Configuration* (SNL 2007 [DIRS 179354], Table 4-2, Item 07-01). The processes for the fabrication and handling of the drip shield have conceptually been developed. The exact processes will be dependent on the approach of the vendor to meeting the specifications of the YMP. The requirements and specifications for the drip shield can be found in *Total System Performance Assessment Data Input Package for Requirements Analysis for Engineered Barrier System In-Drift Configuration* (SNL 2007 [DIRS 179354], Table 4-2).

The fabrication process begins with the procurement of the plates and structural support beams that form the drip shield. The body of the drip shield and the connector plate are constructed of Titanium Grade 7 (R52400), an alpha-phase titanium alloy with approximately 0.15 wt % palladium added to increase corrosion resistance (SAE 1993 [DIRS 119579], Reactive and

6.2.3 Disposition of Possible Engineered Barrier Component Fabrication or Handling Processes That Could Lead to Defects

Eleven generic types of defects or processes that could lead to defects were summarized in Section 6.1.6 as potential causes for early failure of metallic containers. Many of these types of defects could also be introduced to a waste package or drip shield during fabrication, transport to the repository, storage, loading, or emplacement. In addition to these 11, two more defect modes have been identified as applicable to waste package and/or drip shield: (1) improper stress relief of waste package closure lid weld, and (2) emplacement error. All 13 possible defects or processes that could lead to defects are discussed below, and some are screened from further evaluation.

- *Weld flaws*: Tensile hoop stresses in the metal will tend to propagate any perpendicular flaws in the welds. Thus, flaws that are oriented approximately perpendicular to the waste package hoop stress and sufficiently near the surface, are recognized and quantified as being capable of propagating. Low-plasticity burnishing is a stress mitigation process in which the metal surface is compressed over a few millimeters depth providing causes plastic deformation in the material beneath the tool. The deformed region is thus constrained by surrounding, undeformed material leaving the treated region in a state of compressive residual stress to counter any residual tensile stresses. Weld flaws in the waste package outer corrosion barrier closure weld are stress-mitigated through a low-plasticity burnishing process. Thus, flaws that are oriented approximately perpendicular to the waste package hoop stress and sufficiently near the surface are recognized and quantified as being capable of causing early failure. All welds in the waste package canister will be inspected with multiple NDEs as described in *Total System Performance Assessment Data Input Package for Requirements Analysis for TAD Canister and Related Waste Package Physical Attributes Basis for Performance Assessment* (SNL 2007 [DIRS 179394], Table 4-1, Items 03-13 and 03-17); thus, any large flaws will be detected and repaired. Because all welds in the waste package outer corrosion barrier and lid, except those created during final closure of the package, are annealed (as was discussed in Section 6.2.1), any residual flaws are not susceptible to propagation and are screened from early-failure analyses. The evaluation of flaws in the closure welds for outer corrosion barrier lid is documented in Section 6.3.1.

  As part of the fabrication process, all drip shield welds will be inspected using a variety of examinations as discussed in *Total System Performance Assessment Data Input Package for Requirements Analysis for EBS In-Drift Configuration* (SNL 2007 [DIRS 179354], Table 4-2, Item 07-10). All welds in the drip shield will be stress-relieved through heat treatment as described in Section 6.2.2, so any flaws remaining after the inspections will not be sources for propagation of cracks. Thus, weld flaws in the drip shield are screened from further evaluation.

- *Base-metal flaws or out-of-specification base metal*: It is conceivable that an out-of-specification base metal could be selected for use in fabricating drip shields or waste packages. The defects could result from having the wrong material alloy or having a base metal delivered to the fabrication operation with undetected flaws that would not be found during subsequent processes. While no documented cases of this type were

- *Missing welds*: Data on the occurrence of this type of defect in fuel rods (presented in Section 6.1.2) indicated that it would occur at a rate much lower than 5×10^{-6} per rod. A missing weld on a waste package or drip shield would be easier to identify than one on a fuel rod and would have a noticeable effect on the configuration of the waste package (e.g., a missing closure weld could cause the lid to fall off when the waste package is tilted to a horizontal position) or drip shield. Therefore, it is expected that the occurrence rate of this defect for a waste package or drip shield would be significantly less than a more-dominant failure mechanism such as improper heat treatment, and this scenario is screened from further evaluation.

- *Contaminants*: The possibility exists that the outer surfaces of a waste package outer corrosion barrier or drip shield could become contaminated with some corrosion-enhancing material. However, fabrication and handling requirements for the waste package outer corrosion barrier (SNL 2007 [DIRS 179394], Table 4-1, Item 03-21) and drip shield (SNL 2007 [DIRS 179354], Table 4-2, Item 07-14) state that operations must be conducted in a manner conducive to minimizing surface contamination. In addition, multiple inspections of the waste package outer corrosion barrier and drip shield are required prior to emplacement (SNL 2007 [DIRS 179394], Table 4-1; 2007 [DIRS 179354], Table 4-2). Therefore, it is expected that the likelihood of this type of defect for a waste package outer corrosion barrier or drip shield being undetected prior to emplacement would be significantly less than the more-dominant failure mechanisms, and, thus, contaminants are screened from further evaluation.

- *Mislocated welds*: This defect is mainly applicable to very small, single-pass welds (e.g., fuel rod end caps). For larger multipass welds, such as those on the waste package or drip shield, any significant mislocation of the electrode would cause the weld arc not to strike. This would be immediately obvious to both the operator and the control system for the automated welder. This is much less likely than a more-dominant failure mechanism such as improper heat treatment and, thus, mislocated welds are screened from further evaluation.

- *Handling or installation damage*: A typical waste package containing a loaded TAD canister will have a mass of approximately 162,000 pounds as shown in *Total System Performance Assessment Data Input Package for Requirements Analysis for TAD Canister and Related Waste Package Physical Attributes Basis for Performance Assessment* (SNL 2007 [DIRS 179394], Table 4-3). The outer corrosion barrier of the waste package will be susceptible to denting or gouging during handling due to its large inertial mass. It is conceivable that dents or gouges could occur and not be detected during subsequent inspections. For this reason, this scenario is considered, and the potential for a defective waste package outer corrosion barrier to result from this scenario is quantified in Section 6.3.6. However, because the strength-to-mass ratio of the drip shield is much higher and the drip shields will be resilient to impacts incurred during handling and emplacement, this mode of defect is not considered further for the drip shields.

- *Emplacement error*: Emplacement of waste packages and drip shields will be performed under a quality control program, and emplacement of drip shields will be monitored remotely by cameras and other mechanical sensory equipment (SNL 2007 [DIRS 179354], Table 4-4, Item 05-01 and Table 4-2, Item 07-14). Minor deviations in the waste package-to-pallet positions or the improper location of waste packages relative to other waste packages is conceivable; however, the consequences of this would be negligible, as long as the packages are protected by the drip shield from rockfall and seepage. Major deviations in these components are considered sufficiently unlikely that they are not considered further because inspections will detect the deviations, which will be fixed. It is conceivable, however, that drip shields could be improperly joined to adjacent drip shields, rather than correctly as described in *Total System Performance Assessment Data Input Package for Requirements Analysis for Engineered Barrier System In-Drift Configuration* (SNL 2007 [DIRS 179354], Table 4-2, Items 07-02 and 07-02B), and that subsequent inspections would fail to identify the problem. For this reason, this mode of introducing defects to the repository configuration is recognized, and the potential for an improper drip shield emplacement to result from this scenario is quantified in Section 6.4.4.

- *Administrative or operational error*: Administrative and operational errors are expected, and provisions in drip shield and waste package fabrication and handling procedures and equipment will be made to reduce these errors to acceptable levels. Even after taking the planned precautions, these types of errors are still recognized as likely, and the associated rates and consequences are included in the evaluations documented in Sections 6.3 and 6.4. Therefore, these types of errors are not considered to be separate defect modes.

6.3 WASTE PACKAGE POTENTIAL DEFECTS

Of the 13 defect modes or processes identified in Section 6.2.3, six were screened from further analysis on the basis of either very low likelihood of occurrence or low consequences. The seven remaining processes were identified as applicable to fabrication and handling of waste packages. One of these, administrative or operational errors, is to be included within the fault tree analyses. The remaining six processes retained for detailed analyses with respect to mechanisms for early waste package failure are as follows:

- Weld flaws
- Improper heat treatment
  - outer corrosion barrier shell
  - outer corrosion barrier closure lid
- Improper stress relief of outer corrosion barrier lid (low plasticity burnishing)
- Waste package mishandling damage
- Improper base metal selection
- Improper weld filler material.

reliability of various inspection methods, but this software was developed for stainless steel and not Alloy 22.

Work has been performed directly on the welding of Alloy 22 specimen rings (Smith 2003 [DIRS 163114]; SNL 2007 [DIRS 179394]) that duplicate closely the actual outer lid weld of a waste package. Although the design of the outer lid has been modified since that work was performed, the modifications do not impact the validity of the results obtained here. Only the closure weld configuration was modeled in the specimen ring testing and, although diameters are different, the general form and size of the weld remains the same, as shown in "Detail D" of the drawing cited in *Total System Performance Assessment Data Input Package for Requirements Analysis for TAD Canister and Related Waste Package Physical Attributes Basis for Performance Assessment* (SNL 2007 [DIRS 179394], Section 4.1.2.3). Therefore, the weld flaw inspection results are used as a surrogate to represent the expected weld flaws in the closure lid of the waste package outer corrosion barrier.

Sixteen specimen rings were welded employing procedures, processes, and equipment similar to that expected to be used for the closure of the waste package (Smith 2003 [DIRS 163114], Section 2.3). Nondestructive examinations were performed to accumulate significant information on the weld flaws and included ultrasonic and radiographic testing, which was followed by metallographic examination. This information consists of weld flaw location, size and shape. Based on this information, summarized in Section 4.1.2.2, several distributions are developed here to characterize the size of the flaws in the through-wall extent of the weld (Y direction on Figure 4-1), their density (mean number of flaws per volume of weld) and their depth (distance between the outer surface of the weld and the onset of the flaw in the Y direction).

Metallographic inspections were performed on the specimen rings at the sites where imperfections were indicated by ultrasonic testing and/or radiographic testing as discussed in Section 4.1.2.2. Three flaws were not observed in the follow-up metallographic inspection and are not included in this analysis. Based on all the testing results, it was determined that, "UT [ultrasonic testing] and RT [radiographic testing] are capable of detecting volumetric flaws as small as 1 millimeter in size…" from "Study Summary" in the drawing cited in *Total System Performance Assessment Data Input Package for Requirements Analysis for TAD Canister and Related Waste Package Physical Attributes Basis for Performance Assessment* (SNL 2007 [DIRS 179394], Section 4.1.2.3). Of course, it was not possible to perform metallographic examination on the entire specimen rings since it is a very time-consuming process; instead, metallographic inspections (up to six per ring) were performed at randomly selected locations in the areas where no flaw had been detected through ultrasonic testing inspection. None of these metallographic inspections revealed a flaw of size larger than the estimated ultrasonic testing detection threshold of 1 mm. This strongly suggests that the majority, if not all, of the flaws greater than 1 mm were detected, as noted in "Study Summary" from the drawing cited in *Total System Performance Assessment Data Input Package for Requirements Analysis for TAD Canister and Related Waste Package Physical Attributes Basis for Performance Assessment* (SNL 2007 [DIRS 179394], Section 4.1.2.3).

The imperfections found through metallographic examinations that were not detected by the ultrasonic/radiographic testing inspections were gas pores, and the majority of them were less than 3×10^{-3} inch (around 8×10^{-2} mm) in diameter. Gas pores are spherical in shape when the gas is in thermal equilibrium with its surrounding liquid (Holman 1997 [DIRS 101978], Section 9-5), in this case metal, and have no orientation. Therefore, they are not part of those flaws that are radially oriented. Gas pores are treated the same as spherical porosity in *Stress Corrosion Cracking of the Drip Shield and the Waste Package Outer Barrier* (SNL 2007 [DIRS 181953], Section 6.3.4.1). In other words, they will not induce propagation of cracks via SCC. Thus, they are unlikely to affect the performance of the waste package and are discarded from further consideration.

The same type of ultrasonic testing inspections will be performed on the welds of the waste package (SNL 2007 [DIRS 179394], Table 4-1, Item 03-17) to identify those flaws that may jeopardize its performance so that these flaws can be removed. Based on the design requirement that specifies the detection criterion of weld flaws to be equal to or greater than 1/16 in (SNL 2007 [DIRS 179394], Section 4.1.2.3) and on the improved ultrasonic testing detection results, the characteristic flaw size is set at 1/16 in (1.5875 mm). This value reasonably represents that only half of the flaws of this size will actually be detected. Thus, while the ultrasonic testing detection limit appears better than this size, the 1/16-in flaw size is deemed the appropriate size at which weld repair should be performed and where ultrasonic detection capability is more reliable.

The characteristics of the flaws that may remain in the waste package closure welds can be calculated from the distributions by knowing the per waste package closure weld volume and weld thickness. The TSPA can utilize these results, with the critical flaw orientation probability and an applicable depth factor, to model where undetected flaws remain and might result in SCC that can penetrate the waste package closure weld. The following subsections will each describe a portion of the analysis that is then usable, either in part or entirely, by TSPA to determine the potentially adverse weld-flaw population that survives to repository service. The computations were carried out in Appendix A using MathCAD® (output DTN: MO0701PASHIELD.000). The results of the analysis are shown with rounded values. If it is necessary to redo the analysis, the computations should be carried out from the input values given in Section 4.1.2; the intermediate values should not be used, unless otherwise stated.

6.3.1.1 Analysis Input Descriptions

The direct inputs described in Section 4.1.2 are used in the MathCAD® evaluation of weld flaw distributions. The following briefly describes those preliminary input operations as contained in Appendix A, Section A.1.

For purposes of calculating the volume of the 16 specimen-ring welds used in Section 6.3.1.3, the diameter of the weld centerline is needed. Table 4-2 yields a weld length of around 4.85 m for a specimen ring. This is multiplied by the cross-sectional area, which is calculated in Appendix A, Section A.1 (variable cross section) based upon the weld geometry descriptions in Table 4–2. The 16 rings therefore contain an estimated total weld volume of, $V_f = 1.656 \cdot 10^{-2}$ m^3.

The volume of weld in a waste package is determined by using the same cross-sectional geometry as the specimen rings; therefore, the number of flaws to be expected will be governed by λ_d. The Bayesian approach with a noninformative prior is used for the PDF determination for the same reasons as those presented in Section 6.3.1.2.

Based on previous parameters, the number of flaws in the weld follows a Poisson distribution $P_n(n,\lambda_d, V_f)$ (Equation 12), with λ_d having the PDF given in Equation 11.

In conclusion, the probability on the number of flaws n in a volume of weld V_f can be evaluated using the Poisson distribution $P_n(n,\lambda_d, V_\mathrm{f})$ given in Equation 12. The flaw-density parameter λ_d has the PDF defined in Equation 11. Applying these equations to the current waste package design results in the flaw-expectation probabilities shown in Table 6-3.

Table 6-3. Expected Distribution of As-Welded Waste Package Weld Flaws (informational only)

Number of Weld Flaws	Probability
0	0.585
1	0.303
2	0.089
3	0.019
4	0.004

Source: Computation, Appendix A, Section A.3.

6.3.1.4 Flaw Depth

The flaw depth is the distance between the outer surface of the weld and the onset of the flaw in the Y direction (see Figure 4-1 for orientation of the Y direction). A uniform distribution is chosen to represent the flaw depth. Ultrasonic testing indications shown in Table 4-3 seem to indicate that flaws are scattered over the entire extent of the Y direction (0.97 in), but, with only seven data points, it is difficult to demonstrate this statistically. The welding process itself is comprised of multiple welding passes; this provides a mechanistic reason for a uniform distribution of flaws, since any particular layer of welding may contain a flaw.

6.3.1.5 Flaw Orientation

The orientation of the flaws is investigated in the plane of the specimen rings. The objective is to investigate the angle θ that the flaws make with the direction of the weld (see Figure 6-5 for a schematic representation). This is important in trying to determine an estimate of the flaws that have mostly a radial orientation (a broad definition of radially orientated flaws is those flaws that have an angle θ greater than 45°). These radially oriented flaws are able to propagate through-weld, being driven by the hoop stress. However, the more abundant circumferential flaws are less impacted by this driving hoop stress and are also unlikely to reorient (SNL 2007 [DIRS 181953], Section 6.3.4.3).

Table 6-5. Parameter Summary for Evaluating Flaw Characteristics

Flaw Characteristic	Before Ultrasonic Inspection	After Ultrasonic Inspection and Weld Repair
Flaw size (s, in mm)	CDF P_{sg} given in Equation 7 Secondary equation: Equation 2 Parameters: λ_s, t, n_f, s_t	CDF P_{sgut} given in Equation 21 Secondary equations: Equations 6, 8, 17, 19 Parameters: λ_s, t, n_f, s_t , ε_1, s_0, ν
Flaw number (n)	Poisson distribution: Equation 12 Secondary equation: Equation 11 Parameters: λ_d, V, n_f, V_f	Poisson distribution: Equation 24 Secondary equations: Equations 6, 8, 11, 17, 19, 23 Parameters: λ_d, V, n_f, V_f, λ_s, t, ε_1, s_0, ν, s_t
Flaw orientation[a]	Of the flaws, 0.8% are radially oriented	Of the flaws, 0.8% are radially oriented
Flaw depth[b]	Uniform distribution on weld thickness	Uniform distribution on weld thickness

[a] Calculated in Section 6.3.1.5.
[b] Discussed in Section 6.3.1.4.

Table 6-6 shows the mean, the 5th, and the 95th percentiles of the predicted flaw sizes, before ultrasonic inspection (Equation 10) and after ultrasonic inspection and weld repair (Equation 21). These values are calculated based on the distribution of the flaw size, weighted with the probability values assumed by λ_s.

Table 6-6 also shows the probability of having zero, one, and two or more flaws in the welds of the waste package before ultrasonic inspection, and after ultrasonic inspection and weld repair. The results in this table are only an example, and TSPA will need to re-determine the values for its use. Note that these results are not combined with other defect probabilities (see Section 7.2).

Table 6-6. Main Characteristics of Flaws in Welds of Waste Package (informational only)

	Weld Flaw Size[a] (mm)			Probability of Number of Flaws[b]		
	Mean	**5th percentile**	**95th percentile**	**0**	**1**	**2 or more**
Before ultrasonic inspection	4.8	0.23	15.2	0.585	0.303	0.112
After ultrasonic inspection and weld repair	1.0	0.072	2.6	0.844	0.140	0.015

[a] Flaw sizes are given with two significant figures. MathCAD® results in Appendix A, Sections A.2 and A.6.
[b] Probability values on number of flaws are the rounded MathCAD® results in Appendix A, Sections A.3 and A.7.

6.3.2 Improper Base-Metal Selection for Waste Package Outer Corrosion Barrier

In the absence of data on the likelihood of making improper material selections, the basis for the probability distribution associated with this type of event is the similarity between the operations of selecting materials for fabrication and selecting weld filler material. The improper selection of weld material affecting a significant weld population is documented in response to NRC Bulletin 78-12 (NRC 1978 [DIRS 165403]), which was prompted by the discovery that the weld chemistry of a portion of the Crystal River 3 surveillance-block weld did not meet the specification requirements. In the preparation of a response to the bulletin, Babcock & Wilcox (1979 [DIRS 108219]) investigated their records to determine the extent to which out-of-specification weld wire may have been used in the fabrication of reactor vessels. Their findings showed that, out of 1,706,556 pounds of weld wire (Babcock & Wilcox 1979 [DIRS 108219],

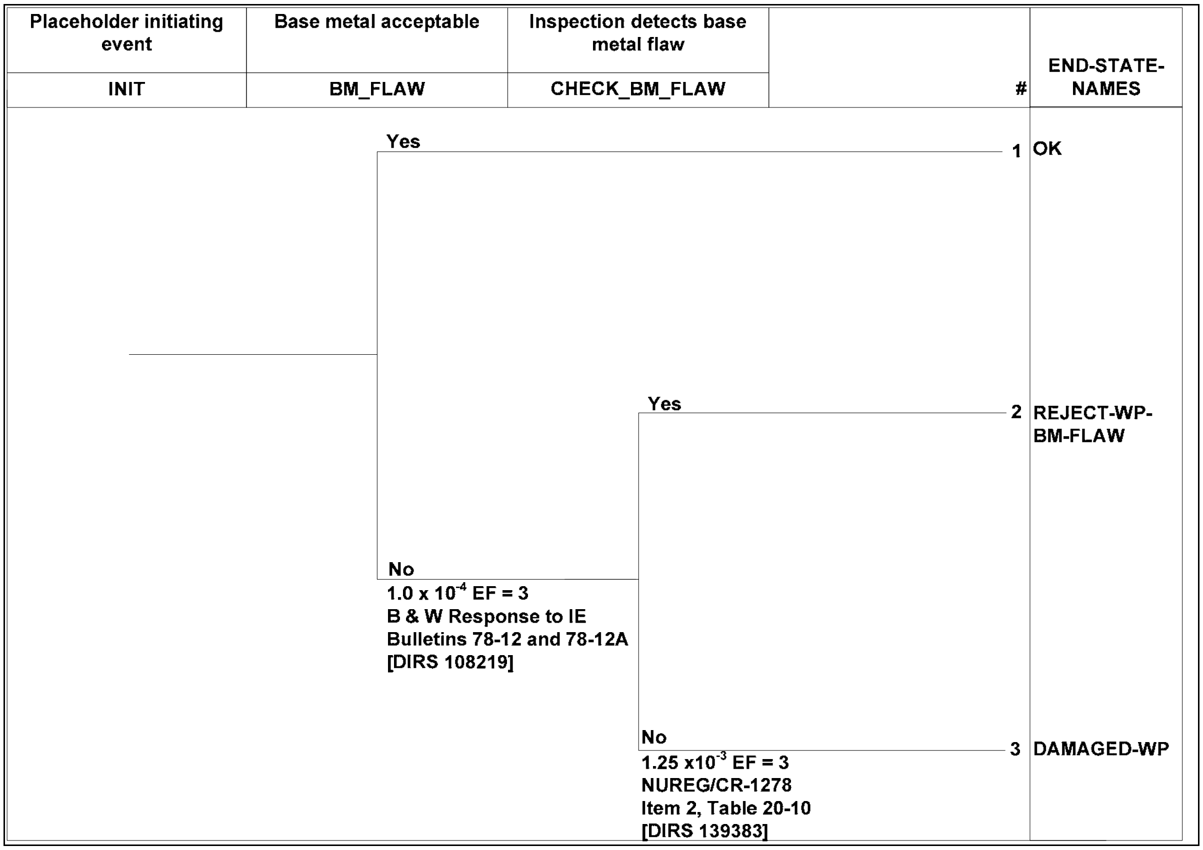


Figure 6-9. Event Tree for Evaluating Improper Base Metal Selection for Waste Package Outer Corrosion Barrier

6.3.3 Improper Heat-Treatment Implementation for Waste Package Outer Corrosion Barrier

Heat treatment of the outer corrosion barrier of the waste package can be controlled by any suitable method of heating and cooling, provided the required heating and cooling rates, metal temperature uniformity, and temperature control are maintained (SNL 2007 [DIRS 179394], Table 4-1, Item 03-16). Such controls are assumed to be integrated into the heat treatment facility independent of the objects being processed (Assumption 5.10, Section 5). The heat treatment, however, must provide for heating of the entire outer corrosion barrier with the exception of the closure lid as a single application. Quenching in a water bath to achieve the minimum quenching rate for the outer corrosion barrier (SNL 2007 [DIRS 179394], Table 4-1, Item 03-16) is evaluated in this report. Auxiliary instrumentation associated with the heat treatment of the outer corrosion barrier uses calibrated thermocouples in contact with the material while protecting them from direct contact with water. These thermocouples monitor the operation and provide a record of the heat treatment and solution annealing process. Such records are maintained for the quality assurance documentation and can be inspected as a check that the annealing process followed the procedures correctly. The solution-annealing operation following the heat treatment is a time-sensitive operation, and particular attention must be paid to this part of the process in order to achieve proper annealing. The final machining of the inner diameter of the outer corrosion barrier, if required, and of the final closure weld area will be performed after the solution-annealing process is complete.

The outer corrosion barrier is to be furnace-heated at a temperature of 2,050°F + 50°F/–0°F for a minimum of 20 minutes (no maximum specified) and then quenched. Cooling will be achieved by immersion in water or spray quenching with water. The cooling rate for the entire outer corrosion barrier will be greater than 275°F/min from soak temperature to less than 700°F (SNL 2007 [DIRS 179394], Table 4-1, Item 03-16 and Section 4.1.2.2) to avoid a phase transition during cooling. The quench delay (time from removal from furnace to start of quench) needs to be sufficiently limited to assure that the quench initiation starts at 2,050°F or higher. Since it is expected that the outer corrosion barrier will be quenched in an inverted position (Assumption 5.6, Section 5), a snorkel must be installed on the interior of the outer corrosion barrier to permit the interior to fill rapidly if immersion quenching is selected. The quench rate is specified to be greater than 275°F/min, and, based on a rate that is on the order of 300°F/min, the quenching operation will require approximately four minutes to complete. Thus, it is reasonable that the makeup water system must operate for at least six minutes to be at capacity when needed. It is assumed that this last phase of the heat treatment of the waste package outer corrosion barrier (i.e., removal from the furnace and quenching) is the critical part of the process (Assumption 5.4, Section 5), and the analysis of the heat treatment process focuses on this phase. It is expected that the outer corrosion barrier will be moved into the heat treatment facility and then to the quench chamber by a crane, since this type of handling equipment is the most suitable for such large and non-compact objects as the outer corrosion barrier.

While fabrication processes for the waste package outer corrosion barrier have not been finalized (Section 5), prototypes have been fabricated that provide collaborative support for the assumptions concerning fabrication processes. In particular, a full-sized Alloy 22 prototype outer corrosion barrier was furnace-heated in an inverted position and subsequently tank-quenched on both sides using two pipes for purging internal gases. Figure C-1 in Appendix C shows the outer corrosion barrier being lowered by a crane into the quench tank. Figure C-2 in Appendix C shows the postannealed outer corrosion barrier with the purge piping still attached.

The probability that the waste package outer corrosion barrier will be subjected to an improper heat treatment, without the error being detected prior to emplacement in the repository, is a combination of human error and process failure probabilities where the HEPs follow lognormal distributions, and the process failure probabilities are point values. It is assumed that process failure probabilities, usually given as point or rate values, can be represented as the mean value of a distribution assumed to be lognormal (Assumption 5.3, Section 5). Error factors were thus assigned to point values to provide a range for uncertainty in the values. Heat treatment of the waste package inner vessel is not evaluated, since no special heat-treatment process is specified for the inner vessel, except that maximum temperatures associated with welding have been specified (BSC 2006 [DIRS 180190], Section 5.5.1.3A); these maximum temperatures are cited in *Total System Performance Assessment Data Input Package for Requirements Analysis for TAD Canister and Related Waste Package Physical Attributes Basis for Performance Assessment* (SNL 2007 [DIRS 179394], Section 4.1.2.2).

The event tree for evaluating an improper heat treatment for the waste package outer corrosion barrier is shown in Figure 6-10. Five events in the heat treatment process that could lead to an improper heat treatment combined into event sequences are considered in this evaluation. These events are as follows:

- The first top event (Figure 6-10, HT_SHELL_MOVE_WP) tests whether or not the outer corrosion barrier is moved from the heat treatment facility to the quench facility within the time constraint necessary to maintain the outer corrosion barrier temperature ≥ the 2,050°F quench initiation temperature. The top branch represents success and the lower branch failure. This event is evaluated through a fault tree containing two basic events, CRANE_MALFUNCTION and CRANE_OPERATOR_ERROR as shown in Figure B-4 in Appendix B.

  Complete failure of the crane system (e.g., stops for some extended period) would be readily apparent and the heat treatment operation repeated. Thus, a crane malfunction is identified as an undetected equipment-operating problem where the crane fails to move the outer corrosion barrier from the heat treatment facility to the quench tank within the required time limit such that the outer corrosion barrier temperature drops below the specified quench initiation temperature. This could be caused by degradation of the supply power, cable entanglement, etc. that slows, but does not halt the operation. The crane malfunctioning probability is represented by a median value of 3×10^{-3} (Assumption 5.7, Section 5) with an error factor of 3 that is assumed to provide an upper bound on the probability of mechanical malfunctions of moving equipment. Using Equation 4 results in a mean value for the probability distribution of 3.75×10^{-3} per event.

  The crane operator error is identified as the failure to recognize or respond to the crane malfunction while the operation is in progress. This error would result in delay in moving the outer corrosion barrier from the heat treatment facility to the quench tank and allowing the process to continue. This event is represented by the HEP "failure to complete a change of state…" (Item 7 of Table 4-1) that has a median value of 3×10^{-3}, a mean value of 3.75×10^{-3}, and an error factor of 3.

- As stated in the description of the top event (HT_SHELL_MOVE_WP), it is expected that travel time between the furnace and the quench facility must be sufficiently short to maintain the temperature above the minimum quench initiation temperature (set at 2,050°F). It is expected that the maximum time allowable for the move, adjusted for local conditions, will be monitored with a timer system equipped with recording capability and an alarm. The top event (Figure 6-10, HT_SHELL_MOVE_CHECK_WP) tests whether or not the outer corrosion barrier movement from the heat treatment facility to the quench facility within the specified time constraint is successful and properly monitored. The top branch represents success and the lower branch failure. While this check is normally operative for all moves, a failure of the check process only has consequences for outer corrosion barrier move failures. This event is evaluated through a fault tree containing two basic events, TIMER_FAILURE and HT_OPERATOR_ERROR, as shown in Figure B-5 in Appendix B.

6.3.4 Improper Heat-Treatment Implementation for Waste Package Outer Corrosion Barrier Lid

Heat treatment of the outer corrosion barrier lid of the waste package can be accomplished by any suitable method of heating and cooling, provided the required heating and cooling rates, metal temperature uniformity, and temperature control are maintained (SNL 2007 [DIRS 179394], Table 4-1, Item 03-16). Such controls are assumed to be integrated into the heat treatment facility independently of the objects being processed (Assumption 5.10, Section 5). Quenching in a water bath to achieve the minimum quenching rate for the lid (SNL 2007 [DIRS 179394], Table 4-1, Item 03-16) is evaluated in this report. Auxiliary instrumentation associated with the heat treatment of the outer corrosion barrier lid utilizes calibrated thermocouples in contact with the material while protecting them from direct contact with water. These thermocouples monitor the operation and provide a record of the heat-treatment/solution-annealing process as it evolves. Such records are important for the quality assurance documentation and as a check that the annealing process followed the procedures correctly. The solution-annealing operation following the heat treatment is a critical operation, and particular attention must be paid to this part of the process in order to achieve proper annealing.

The outer corrosion barrier lid is to be furnace heated at a temperature of 2,050°F + 50°F/–0°F for 20 minutes minimum (no maximum specified) and then quenched. Cooling will be achieved by immersion in water or spray quenching with water. The cooling rate for the outer corrosion barrier lid shall be greater than 275°F/min from soak temperature to less than 700°F (SNL 2007 [DIRS 179394], Section 4.1.2.2) to avoid a phase transition during cooling. The quench delay (time from removal from furnace to start of quench) needs to be sufficiently limited to assure that the quench initiation starts at 2,050°F or higher. The quench rate is specified to be greater than 275°F/min, and, assuming the rate is on the order of 300°F/min, the quenching operation requires approximately four minutes. Thus, it is reasonable that the makeup water system must operate for at least six minutes to be at capacity when needed. It is assumed that this last phase of the heat treatment of the waste package outer corrosion barrier lid, removal from the furnace and quenching, is the critical part of the process (Assumption 5.4, Section 5), and the analysis of the heat treatment process focuses on this phase. It is expected that the outer corrosion barrier lid will be moved into the heat treatment facility and then to the quench chamber by either a trolley or a crane as these types of handling equipment are common for large objects, where a trolley is analyzed as the preferred method, since the lid is a regular plate.

The probability that the waste package outer corrosion barrier lid will be subjected to an improper heat treatment, without the error being detected prior to emplacement in the repository, is a combination of human error and process failure probabilities, where the HEPs follow lognormal distributions and the process failure probabilities are point values. It is assumed that process failure probabilities, usually given as point or rate values, can be represented as the mean value of a distribution assumed to be lognormal (Assumption 5.3, Section 5). Error factors were thus assigned to point values to provide a range for uncertainty in the values.

The event tree for evaluating an improper heat treatment for the waste package outer corrosion barrier lid is shown in Figure 6-11. Five events in the heat treatment process for the lid that could lead to an improper heat treatment combined into event sequences are considered in this evaluation. These events are as follows:

- The first top event (Figure 6-11, HT_LID_MOVE_WP) tests whether the outer corrosion barrier lid is moved from the heat treatment facility to the quench facility within the time constraint necessary to maintain the lid temperature ≥ the 2,050°F quench initiation temperature or not where the top branch represents success and the lower branch failure. This event is evaluated through a fault tree containing two basic events, TROLLEY_MALFUNCTION and TROLLEY_OPERATOR_ERROR as shown in Appendix B, Figure B-9.

  Complete failure of the trolley system (e.g., stops for some extended period) would be readily apparent and the heat treatment operation repeated. Thus, a trolley malfunction is identified as an equipment-operating problem where the trolley fails to move the lid from the heat treatment facility to the quench tank or spray system within the required time limit such that the lid temperature drops below the specified quench initiation temperature. This could be caused by events such as the degradation of the supply power or cable entanglement, which slow but do not halt the operation. However, this type of malfunction causes the transfer operation to exceed the time specified for the operation. The trolley-malfunctioning probability is represented by a median value of 3×10^{-3} (Assumption 5.7, Section 5) with an error factor of 3 that is assumed to provide an upper bound on the probability of mechanical malfunctions of moving equipment. Using Equation 4 results in a mean value for the probability distribution of 3.75×10^{-3} per event.

  The trolley operator error is identified as the failure to recognize or respond to the trolley malfunction while the operation was in progress. This error would result in a delay in moving the corrosion barrier lid from the heat treatment facility to the quench tank and allowing the process to continue. This event is represented by the HEP “failure to complete a change of state…” (Item 7 of Table 4-1) that has a median value of 3×10^{-3}, a mean value of 3.75×10^{-3}, and an error factor of 3.

- As stated in the description of the top event (HT_LID_MOVE_WP), it is expected that travel time between the furnace and the quench facility must be sufficiently short to maintain the temperature above the minimum quench initiation temperature (set at 2,050°F). It is expected that the maximum time allowable for the move, adjusted for local conditions, will be monitored with a timer system equipped with recording capability and an alarm. The top event (Figure 6-11, HT_LID_MOVE_CHECK_WP) tests whether the outer corrosion barrier movement from the heat treatment facility to the quench facility within the specified time constraint is successful and properly monitored or not where the top branch represents success and the lower branch failure. While this check is normally operative for all moves, a failure of the check process only has consequences for outer corrosion barrier lid move failures. This event is evaluated through a fault tree containing two basic events, TIMER_FAILURE and HT_OPERATOR_ERROR as shown in Appendix B, Figure B-10.

6.3.5 Low-Plasticity Burnishing Treatment Implementation

The low-plasticity burnishing process has been selected as the method to be used for the stress mitigation technique on the closure weld of the outer lid to waste package, since it is the method of choice from a value-engineering evaluation (SNL 2007 [DIRS 179394], Table 4-1, Item 03-17) and is also identified as the method of choice in *Yucca Mountain Project Conceptual Design Report* (BSC 2006 [DIRS 176937], Section 4.5.3.6).

The equipment that would likely be employed in the low-plasticity burnishing process for stress mitigation of the outer lid weld of the waste package is relatively simple mechanically and the process relatively fast. Therefore, in order to evaluate the probability that the outer lid weld of a given waste package will be subjected to an improper low-plasticity burnishing process, without being detected prior to emplacement in the repository, it is necessary to identify expected general elements of the process.

The low-plasticity burnishing hardware is expected to be a dedicated system with no requirements for an operator selection to be made from (possibly) a set of multiple operating modes; process malfunctions will be signaled to the operator via alarms (Assumption 5.5, Section 5). This expectation follows from the specification that the low-plasticity burnishing operation is designated only for stress mitigation of the final waste package lid welding operation. In proof of concept tests, the low-plasticity burnishing operation has been successfully performed with the tool attached to a commercial computer controlled machine. Thus, it is expected that only one operating setup would be necessary for this process. Such a system would likewise be expected to be amenable for continuous monitoring during the operation.

It is likewise expected that a record of the results of the post-operation inspection (e.g., visual, ultrasonic) parameters following the low-plasticity burnishing process will be maintained and that this record will be reviewed as a QA check performed by an individual other than the operator. This expectation is consistent with QA requirements that results of inspections must be preserved and thus are expected to be available for checking. It is conservative to combine inspections into one review (since it is expected that multiple inspection methods will be utilized), and thus the probability of a failure to observe from the record that a malfunction of the low-plasticity burnishing process occurred can be approximated by the human error probability of misreading a digital readout device (Item 2 of Table 4-1).

In addition to HEP failure modes, there exists the possibility of a process failure. It is assumed that process failure probabilities, usually given as point or rate values, represent the mean value of a distribution assumed to be lognormal (Assumption 5.3, Section 5). Error factors were thus assigned to point values to provide a range for uncertainty in the values. This failure mode is evaluated through a fault tree approach by assigning probability values to the mechanisms that lead to the occurrence of undetected process malfunctions during the low-plasticity burnishing of a waste package.

failure to detect errors made by others" (Item 6 of Table 4-1), with a median of 0.1 providing a mean value of 1.6×10^{-1}, with an error factor of 5.

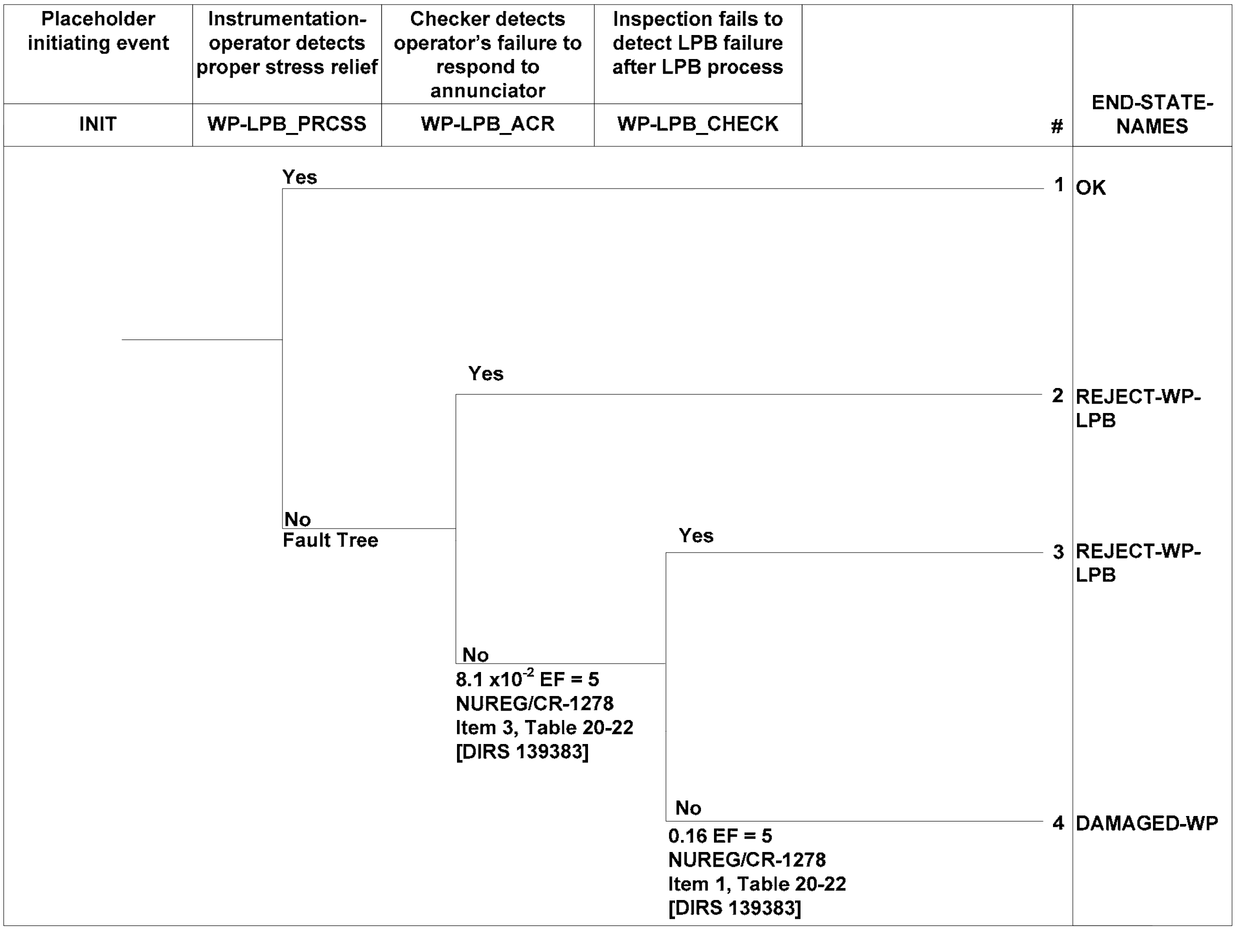


Figure 6-12. Event Tree for Evaluating Low-Plasticity Burnishing Treatment of the Waste Package Outer Corrosion Barrier Lid

6.3.6 Improper Handling of Waste Package

Handling damage is defined as any visible gouging or denting of the waste package surface that may jeopardize the performance of the Alloy 22 barrier. It is expected that inspections will be performed on the waste package outer corrosion barrier prior to emplacement to detect traces of damage to the waste package (SNL 2007 [DIRS 179394], Table 4-1, Items 03-22, 03-23, and 03-24). These inspections are expected to include a visual inspection of the waste package while in the surface facilities of the repository following receipt of the waste package and remote inspections (via camera) at various times prior to repository closure. The more difficult inspections are those requiring remote camera devices; this is the process focused upon for this analysis of the probability of undetected flaws. Since actual operating experience has yet not been accrued on the handling of the waste packages, information on reported instances of damage to nuclear fuel assemblies during their handling has been used as a surrogate to estimate that probability. These data were selected as fuel assembly-handling activities and are performed in a nuclear environment representative of the highly controlled conditions under which handling of the waste package is expected to occur. Therefore, it is deemed appropriate to use this information for estimating the probability of damaging a waste package by mishandling.

The probability of fuel assembly damage was evaluated in *Waste Package Misload Probability* (BSC 2001 [DIRS 157560], Table 5) as a point value of 4.8×10^{-5} per moved fuel assembly. As was noted in *Waste Package Misload Probability* (BSC 2001 [DIRS 157560], Table 4), the sources of fuel assembly damage events included human errors, procedural errors, and equipment failure. Thus, associating this probability with an HEP and applying an error factor derived for HEPs for the uncertainty range is inappropriate.

There are multiple opportunities identified for mishandling and potentially damaging a waste package outer surface between the inspection of the waste package outer corrosion barrier at reception and the final inspection at the time of emplacement. The waste package might be mishandled and damaged by typical operations (e.g., being tilted in an upward position, being down-ended, being placed onto the waste package pallet, or being moved from the transporter vehicle to the emplacement vehicle). These operations involve a waste package directly, i.e., maneuvers to reposition a waste package, either empty or loaded, into a different position or orientation. Another potential source of damage prior to drip shield emplacement is from drift collapse. Although inspections of waste packages for damage will be required following observations of drift collapse (SNL 2007 [DIRS 179394], Table 4-1, Item 03-24), the possibility exists for nondetection of damage. Since these inspections will be performed remotely, the same probability of nondetection of damage by remote sensors is assigned to drift collapse damage. Other potential sources of minor surface defects, although they are outside the maximum size specified (SNL 2007 [DIRS 179394], Table 4-1, Item 03-23), include loading and closure operations. As stated above, these inspections will be performed remotely; therefore, the same probability of non-detection of damage by remote sensors is assigned to damage from these sources. The various types of operations that have been identified are the principal ones for which it is anticipated that the waste package surface will not be shielded by protective equipment but rather will be exposed. Mishandlings that could occur when loading the fuel assemblies into TAD canisters (or the waste package basket) are not considered because such mishandling will affect only the assembly basket or, at most, the inner surface of the stainless steel cylinder, which are not of concern for the performance of the Alloy 22 barrier and potential early failure mechanisms.

This information is developed in an event tree for the mishandling of the waste package, as shown in Figure 6-13. Since processing steps for the waste package (outer corrosion barrier and TAD canister) have not been finalized, the various operations that could lead to waste package surface damage were not analyzed in detail for each operation.

The top event (Figure 6-13, MISH-WP) is evaluated with a fault tree composed of eight generic basic events, as shown in Figure B-15, which act as surrogates for operations that could lead to potential waste package surface damage. Each of the basic events was assigned a probability value of 4.8×10^{-5} (BSC 2001 [DIRS 157560], Table 5) and an error factor of 10 to provide an uncertainty range.

However, if a simplifying assumption is made (in the TSPA model) that units with defects fail immediately, then the distributions for occurrence of defects become distributions for failed units.

The output DTN: MO0701PASHIELD.000 includes the combined uncertainty distributions for undetected defects in the waste package outer corrosion barrier and drip shield with the individual end-state uncertainty distributions provided in output DTN: MO0705EARLYEND.000.

7.2 TSPA WELD-FLAW IMPLEMENTATION

Flaws in the closure-lid welds are potential sites for stress corrosion crack initiation. The characteristics of weld flaws in the closure welds are important to consider in regards to the waste package SCC mechanism and as such are treated separately from the other processes whose early failure probabilities were combined (Section 6.5.1). 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 SCC initiation. In addition, while size plays a role in the potential severity of a flaw, no minimum size is defined, and all remaining weld flaws are considered for potential propagation; however, the flaw-density distribution is based only upon the (non-spherical) detected flaws and may therefore underestimate the number of small (sub-millimeter) flaws.

To quantitatively estimate the number of remaining flaws in the waste package outer barrier closure weld, several steps are needed. This analysis is presented in Section 6.3.1. The size distribution (Section 6.3.1.2, Equation 7 and gamma distribution parameter λ_s), based upon ultrasonic testing-detected flaws in Alloy 22 specimen rings, is screened by the detection capability of ultrasonic testing (Section 6.3.1.6, Equation 17). This results in a determination of the fraction of weld flaws that are not detected (Section 6.3.1.7). That fraction is multiplied by the initial weld-flaw density (Section 6.3.1.3, Equation 12 and gamma distribution parameter λ_d, from Equation 11) to provide a distribution for the remaining weld flaws of potential concern (Section 6.3.1.8). Only a small fraction (0.8%, Section 6.3.1.5) of those flaws may be oriented sufficiently normal (perpendicular) to the plane tangent to the hoop stress direction such that they might propagate through the weld by SCC action. The depth of these flaws is considered to be uniformly distributed through the weld thickness (Section 6.3.1.4).

7.3 EVALUATION OF YUCCA MOUNTAIN REVIEW PLAN CRITERIA

Because this report serves, in part, as the basis for the repository license application, the information contained herein conforms to applicable acceptance criteria. The YMRP (NRC 2003 [DIRS 163274]) contains acceptance criteria intended to establish the basis for the review of the material contained in the license application and, in particular, material applicable to the barrier system. This analysis addresses the degradation of two features of the engineered barrier system—the waste package outer corrosion barrier and the drip shield. Thus, based on the processes involved with the degradation of the waste package outer corrosion barrier and drip shield and the potential impact of such degradation, the acceptance criteria that are applicable to this analysis are evaluated below.

177092 DOE 2006. *Quality Assurance Requirements and Description.* DOE/RW-0333P, Rev. 18. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: DOC.20060602.0001.

178849 SNL 2007. *Technical Work Plan for Postclosure Engineered Barrier Degradation Modeling.* TWP-EBS-MD-000020 REV 00. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20070216.0001.

178871 SNL 2007. *Total System Performance Assessment Model /Analysis for the License Application.* MDL-WIS-PA-000005 REV 00. Las Vegas, Nevada: Sandia National Laboratories.

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

179394 SNL 2007. *Total System Performance Assessment Data Input Package for Requirements Analysis for TAD Canister and Related Waste Package Physical Attributes Basis for Performance Assessment*. TDR-TDIP-ES-000006 REV 00. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20070918.0005.

179567 SNL 2007. *Total System Performance Assessment Data Input Package for Requirements Analysis for DOE SNF/HLW and Navy SNF Waste Package Physical Attributes Basis for Performance Assessment*. TDR-TDIP-ES-000009 REV 00. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20070921.0009.

180190 BSC 2007. *Waste Package Fabrication.* 000-3SS-DSC0-00100-000-001. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20070315.0001.

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

8.2 CODES, STANDARDS, REGULATIONS, AND PROCEDURES

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

LS-PRO-0203. *Q-List and Classification of Structures, Systems, Components and Barriers.*

SCI-PRO-001. *Qualification of Unqualified Data.*

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

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

APPENDIX A – EVALUATION OF WELD-FLAW TEST DATA

The weld-flaw data from *Analysis of Mechanisms for Early Waste Package/Drip Shield Failure* (BSC 2004 [DIRS 170024]) have been re-analyzed with the Mathcad® computational file *Early Fail-Weld Flaw-rlj.xmcd* in the output DTN: MO0701PASHIELD.000 as depicted in this appendix. The weld-flaw data are derived from the drawing cited in *Total System Performance Assessment Data Input Package for Requirements Analysis for TAD Canister and Related Waste Package Physical Attributes Basis for Performance Assessment* (SNL 2007 [DIRS 179394], Section 4.1.2.3). The waste package outer corrosion barrier data are derived from *Total System Performance Assessment Data Input Package for Requirements Analysis for TAD Canister and Related Waste Package Physical Attributes Basis for Performance Assessment* (SNL 2007 [DIRS 179394], Table 4-3).

Set Mathcad sheet preferences

$\mathrm{ORIGIN} := 1 \qquad \mathrm{sd1} := \mathrm{Seed}(1381285117)$

A.1 Inputs from Specimen Rings

The source references and justifications for the values presented here are from Section 4.1 of the associated report (*Analysis of Mechanisms for Early Waste Package/Drip Shield Failure*). Note that Section numbers refer to the associated report. Briefly, there were 16 specimen rings that were extensively examined for flaws. The breakdown of the number of confirmed flaws by specimen ring is as follows: specimen K two flaws, specimen R three flaws, specimen W one flaw, specimen X one flaw.

Total of seven flaws. Flaw size components, units entered in 1/16th of an inch.

Actual flaw distribution used in A.3 for comparison only.

$$X := \begin{pmatrix} 2 \\ 10 \\ 12 \\ 22 \\ 6 \\ 8 \\ 6 \end{pmatrix} \qquad Y := \begin{pmatrix} 1 \\ 1 \\ 2 \\ 2 \\ 2 \\ 3 \\ 9 \end{pmatrix} \qquad Z := \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 2 \\ 0 \end{pmatrix}$$

$$\mathrm{FlawDistribution} := \begin{array}{cl} \begin{pmatrix} 12 \\ 2 \\ 1 \\ 1 \\ 0 \\ 0 \end{pmatrix} & \begin{array}{l} \text{Zero flaws in specimen} \\ \text{one flaw} \\ \text{two flaws} \\ \text{three flaws} \\ \\ \\ \end{array} \end{array}$$

$$\mathrm{Normal\_FlawDistribution} := \frac{\mathrm{FlawDistribution}}{16}$$

Sum of flaw sizes in Y-direction in units of mm

$s_t := \left(\frac{25.4}{16}\right) \cdot \sum Y \qquad s_t = 31.750 \qquad$ s_t = Length of weld flaws

Number of flaws detected

$n_f := \mathrm{length}(Y) \qquad n_f = 7.000$