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| 00A | Initial Issue<br>This design report supercedes the previous document ANL-DDC-ME-000001 REV 00 to report the results of the finite element analyses and evaluations for the latest HLW/DOE SNF Codisposal waste package designs. The changes are extensive and all pages are affected. | 97 | 97 | T.A. Schmitt | A.K. Scheider | D.J. Tunney | M.J. Anderson | 3/2/04 |
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**FIGURES**

## TABLES

## 1. PURPOSE

A design methodology for the waste packages and ancillary components (i.e., the emplacement pallets and drip shields) has been developed to provide designs that satisfy the safety and operational requirements of the Yucca Mountain Project. This methodology is described in the *Waste Package Component Design Methodology Report* (Mecham 2004 [DIRS 169790]). To demonstrate the practicability of this design methodology, four waste package configurations have been selected to illustrate the application of the methodology. These four configurations are the 21-pressurized water reactor (PWR) absorber plate waste package, the 44-boiling water reactor (BWR) waste package, the 5 defense high-level radioactive waste (DHLW)/U.S. Department of Energy (DOE) spent nuclear fuel (SNF) Codisposal Short waste package, and the naval canistered SNF long waste package. Also included in this demonstration is the emplacement pallet and continuous drip shield.

The purpose of this report is to document how that design methodology has been applied to the waste package configurations intended to accommodate the DOE SNF and high-level radioactive waste (HLW). This demonstrates that the design methodology can be applied successfully to these waste package configurations and support the License Application for construction of the repository. In this document, the results of design calculations are summarized and used to show that the designs are in compliance with the applicable criteria in *DOE and Commercial Waste Package System Description Document* (BSC 2004 [DIRS 167273]) and *Project Design Criteria Document* (Doraswamy 2004 [DIRS 169548]).

## 2. QUALITY ASSURANCE

The HLW/DOE SNF Codisposal waste packages are classified as safety category items (BSC 2003 [DIRS 165179], Table A-2, p. A-3). Therefore, this document is subject to the requirements of *Quality Assurance Requirements and Description* (DOE 2004 [DIRS 168669]). This document was developed in accordance with AP-3.12Q, *Design Calculations and Analyses*.

## 3. USE OF SOFTWARE

No computer software is used in the generation of this report. Contributory calculations provide descriptions of software used.

## 4. DESIGN INPUTS AND ASSUMPTIONS

Generic design inputs and assumptions that are used in contributory calculations to this report may be found in *Waste Package Component Design Methodology Report* (Mecham 2004 [DIRS 169790], Sections 4 and 5). Specific design inputs and assumptions may be found in the supporting calculations.

# 5. GENERAL DESCRIPTION

## 5.1 GENERAL CONFIGURATION

Section 114(a)(1)(B) of the Nuclear Waste Policy Act of 1982 (NWPA), as amended (42 U.S.C. 10134(a)(1)(B)) [DIRS 101681], requires "a description of the waste form or packaging proposed for use at such repository, and an explanation of the relationship between such waste form or packaging and the geologic medium of the site." This section describes the waste forms to be disposed, along with their packaging. An explanation of the important parameters considered in the design of the waste package is included in this section, as is a summary of the expected performance of the waste package design. This section:

- Presents an overview of the waste forms and the waste package design
- Describes the waste package, its design bases, and its functions
- Discusses in detail the waste forms, the parameters considered in designing the waste package (and its variations), and the evaluations performed on the design
- Describes the material selection of the waste package
- Presents the results of design evaluations of the waste package.

**Waste Form Overview**—Waste forms to be received and packaged for disposal include SNF from commercial power reactors, SNF owned by the DOE (including naval fuel), and canisters of solidified HLW from prior commercial and defense fuel reprocessing operations.

Section 114(d) of the NWPA (42 U.S.C. 10134(d) [DIRS 101681]) limits the first repository's capacity to no more than 70,000 metric tons of heavy metal (MTHM) "...until such time as a second repository is in operation." The types of waste that would be accepted at the repository have been allocated as follows (DOE 2002 [DIRS 155970], Chapter 2):

- 63,000 MTHM of commercial SNF
- 7,000 MTHM of DOE HLW, commercial HLW, and DOE SNF.

The waste forms received at a repository are in solid form. Materials that can ignite or react chemically at a level that compromises containment or isolation are not accepted by the repository. Neither the waste forms nor the waste packages contain free liquids that can compromise waste containment. Materials that are regulated as hazardous waste under the Resource Conservation and Recovery Act of 1976 (42 U.S.C. 6901 et seq. [DIRS 103936]) are not disposed in the repository (DOE 1999 [DIRS 105164], Section 4.2.3).

**Waste Package Overview**—The design of a waste package configuration is based on the characteristics of the waste forms that it would hold. Because commercial and DOE HLW forms have similar characteristics, both may be placed into a waste package of the same design. This has allowed the DOE to design waste packages capable of accommodating all the types of SNF and HLW currently generated or anticipated in the United States, whether commercial or governmental.

The waste package has been designed, in conjunction with the natural and other engineered barriers, to ensure compliance with applicable U.S. Nuclear Regulatory Commission (NRC) regulations, to contribute to safe operations during the preclosure phase, to make efficient use of the repository area, and to preserve the option of retrieving the waste. To perform its containment and isolation functions, the waste package described in this report has been designed to take advantage of a location in the unsaturated zone.

The waste package design consists of two concentric cylinders in which the waste forms are placed. The inner cylinder is composed of stainless steel type 316. The outer cylinder would be made of a corrosion-resistant nickel-based alloy (Alloy 22 [UNS N06022]). The waste package design configurations for DOE SNF and HLW are larger in diameter and thicker than those for commercial SNF. The corrosion-resistant material of the outer layer protects the underlying layer of structural material from corrosion, and the structural material supports the thinner material of the outer layer.

The waste package design has outer and inner lids. The outer (closure) lids are made of Alloy 22 (UNS N06022). The inner lids are made of stainless steel type 316, and their thickness varies, depending on the waste package design configuration. The final closure weld of the Alloy 22 (UNS N06022) outer lid, undergoes stress-mitigation to prevent against stress corrosion cracking. Since this mitigation cannot easily be performed through the entire thickness of the outer lid, an Alloy 22 (UNS N06022) lid on the closure end of the waste package (middle lid) provides additional protection against stress corrosion cracking in the closure weld area.

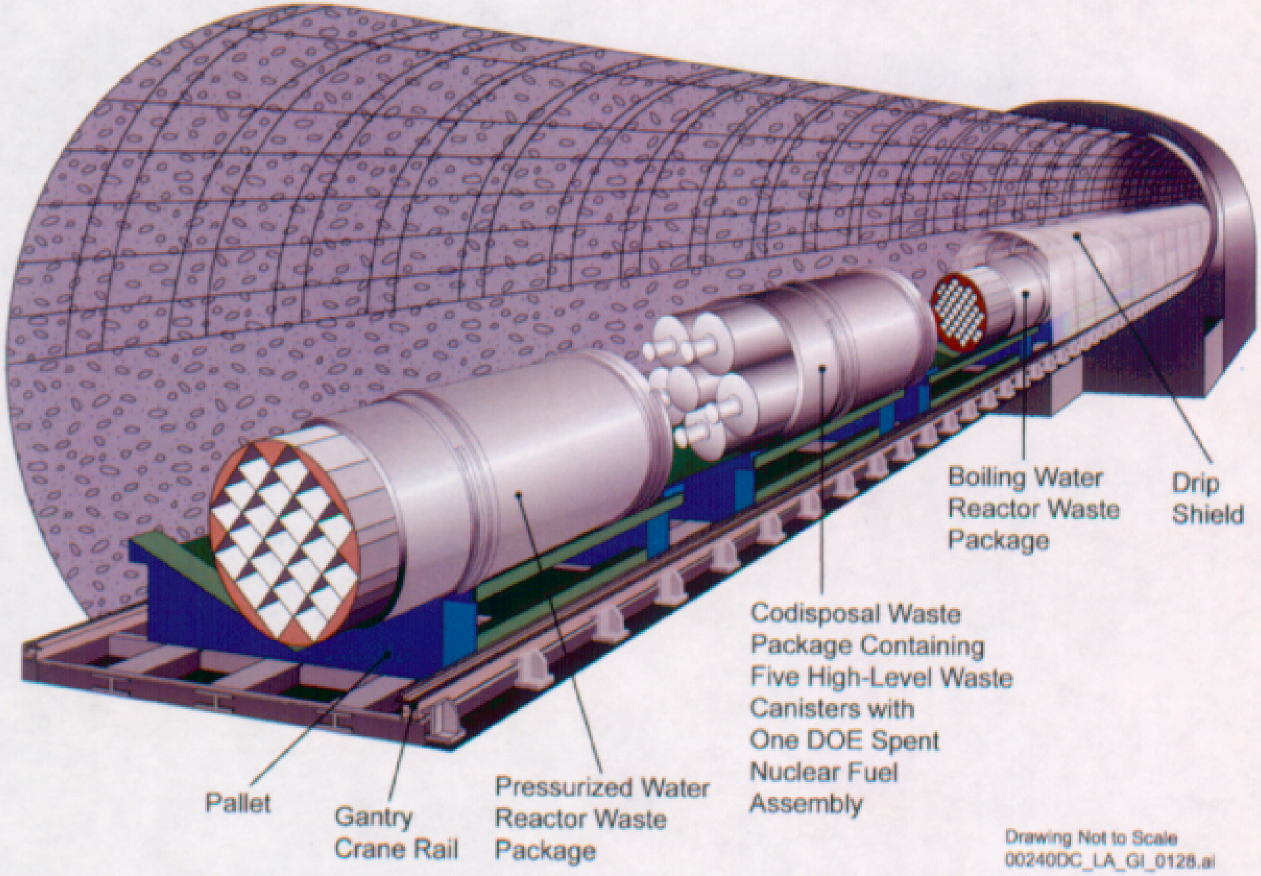
Before the double-walled waste package is sealed, helium is added as a fill gas. The helium prevents oxidation of the waste form and helps transfer heat from the waste form to the wall of the inner vessel of the waste package. Transferring heat away from the waste form is an important means of controlling waste form temperatures. This helps preserve the integrity of the metal cladding on the fuel rods, thus extending the life of an existing barrier to water infiltration.

All waste package design configurations use a remote lifting-and-handling mechanism. The collar-sleeve-and-trunnion joint apparatus allows the necessary handling of the waste package before it is placed on an emplacement pallet and transferred to the designated drift. Each waste package also has a unique permanent identifying label (BSC 2003 [DIRS 166653], Section 6.4.2).

Although they share the features described previously, the waste package designs configurations have different internal components to accommodate the different waste forms. For example, the waste package for uncanistered commercial SNF has an internal basket assembly to support fuel assemblies. In other waste packages (e.g., the HLW and DOE SNF waste packages), the internal basket has a different design, or, as is the case with naval SNF, the basket is contained inside the canister.

### 5.1.1 General Design Basis for the Waste Package

The waste isolation system is an important element of a repository. The primary component of the system would be the waste package. As defined in 10 CFR 63.2 [DIRS 158535], a waste package includes the waste form and any containers, shielding, packing, and other absorbent materials immediately surrounding it. The invert material does not immediately surround the waste package, so it is not considered part of the waste package. Figure 1 illustrates the waste package within the emplacement drift of the waste isolation system.




Source: Mecham 2004 [DIRS 169790], Figure 2.

Figure 1. Schematic Illustration of the Emplacement Drift with Cutaway Views of Different Waste Packages

The waste package has been designed to use materials that perform well under the anticipated conditions at Yucca Mountain. The design analyses performed on the waste package include evaluations of structural integrity, thermal performance, criticality safety, and shielding properties.

### 5.1.2 Preclosure Design Performance Specifications

The performance specifications for the functionality of the waste package during the repository's preclosure phase are consistent with 10 CFR 63.112(b) [DIRS 158535]. This regulation provides for the DOE's analysis of the ability of the waste package's structures, systems, and components to perform their intended safety functions during an accident or event sequences. For the waste package, event sequences are determined by identifying the functions of the waste package and evaluating the effects on its performance of given events that could occur during normal handling of the waste package or during a credible accident scenario (i.e., events that have at least 1 chance in 10,000 of occurring before permanent closure of the repository) 10 CFR 63.2 [DIRS 156671].

These event sequences and their effects on performance were defined by reviewing the results of BSC 2003 [DIRS 164128], Section 6 constituting a bounding list of preclosure event sequences that could affect the waste packages. Using this list, engineers performed structural, thermal, and criticality analyses of the impacts such events could have on waste package performance.

### 5.1.3 Postclosure Performance Specification

10 CFR 63.113(b) (10 CFR 63 [DIRS 158535]) requires the entire repository system to meet specific dose limits for 10,000 years. The waste package is one of many barriers relied upon to meet this limit. The objective is to design a waste package that works in concert with the natural environment to meet performance standards while reducing the uncertainty associated with the current understanding of natural processes at the site.

### 5.1.4 Design Descriptions

An analysis was undertaken to determine the number of design configurations needed to handle the different waste forms that would constitute the anticipated waste stream in the most economical manner (CRWMS M&O 1997 [DIRS 100224]). The objective of the evaluation was to determine:

- The number of different waste package design configurations needed
- The capacity of each waste package design configuration (i.e., the amount of waste it would hold)
- The limits on SNF properties (e.g., age, thermal characteristics) that might apply to each waste package design configuration.

The complete system of waste package design configurations is intended to allow reliable disposal of those waste forms that a repository would accept while still enhancing overall efficiencies.

To determine the most efficient set of waste package design configurations for commercial SNF, the DOE designed waste package configurations of various assembly-holding capacities and incorporated into the design methods for removing decay heat and preventing criticality. This resulted in the selection of a set of five waste package design configurations as the most efficient means of accommodating the anticipated waste stream of commercial SNF. A similar process led to three design configurations for DOE SNF and DOE and commercial HLW. Two other design configurations are specific to naval SNF, which arrive presealed in canisters (Macheret [DIRS 154624], Sections 4.2 and 4.3). Some DOE naval SNF is loaded into waste packages with HLW; this DOE SNF and HLW also arrive in presealed canisters.

Nine types of canisters of DOE SNF and HLW may be received at the repository (Macheret [DIRS 154624], Sections 4.2 and 4.3):

1. Naval SNF canisters, short
2. Naval SNF canisters, long
3. DOE Standardized SNF canisters, short
4. DOE Standardized SNF canisters, long
5. Larger-diameter DOE Standardized SNF canisters, short
6. Larger-diameter DOE Standardized SNF canisters, long
7. Solidified HLW canisters, short
8. Solidified HLW canisters, long
9. Multicanister overpacks containing SNF from the Hanford N Reactor.

The focus of the remaining sections of this report is DOE SNF and DOE and commercial HLW.

The number of canisters of solidified HLW greatly exceeds the number of canisters of DOE SNF. Therefore, the DOE has developed an efficient arrangement for packing them together (Macheret [DIRS 154624], Section 4.2). This mixing of DOE SNF and HLW is called "codisposal." Codisposal also helps maintain criticality control for DOE SNF that contains highly enriched uranium. Naval SNF canisters, which are larger in diameter, are not placed in codisposal waste packages; they are placed one canister per waste package. Because the waste package design configurations being considered contain both DOE SNF and HLW, the following section describes both waste forms, as well as the appropriate waste package design configurations.

DOE SNF has a wide variety of physical, chemical, and nuclear characteristics and represents an inventory of approximately 2,500 MTHM; 2,333 MTHM of this is included in the waste allocation for disposal in the repository (DOE 2002 [DIRS 158405], Section 8.1). The waste packages designed for DOE SNF accept fuel irradiated at DOE facilities, and certain types of material irradiated at commercial nuclear reactors, including debris from the Three Mile Island-2 reactor and fuel from the Fort Saint Vrain reactor. All DOE waste canisters are sealed before they are transported to the repository.

The largest single component of the DOE SNF inventory by weight is uranium metal fuel, at approximately 2,130 MTHM (DOE 2002 [DIRS 158405], Appendix C, Section 5.1, Table 1). Fuel from the N Reactor at Hanford, Washington, accounts for 2,100 MTHM of this inventory. During its 20-year life, the N Reactor produced nuclear isotopes for defense purposes. N Reactor fuel has an initial enrichment of less than 2 percent $^{235}U$. It is placed in multicanister overpacks that both store the waste onsite and transport it to the repository. The multicanister overpack is a stainless steel container that is slightly wider at the top than at the bottom (DOE 2002 [DIRS 158405], Appendix C, Section 5.1, Table 1). Although N Reactor fuel is the largest portion of the DOE SNF inventory by weight, it is emplaced in the repository in only one percent of the waste packages.

Approximately 184 MTHM of the DOE inventory is low-enriched uranium oxide, some of which is standard commercial SNF used for testing. Some is the fuel debris from the damaged reactor core at Three Mile Island-2, which is already stored in small canisters that can be placed inside a DOE standardized SNF canister. The DOE standardized SNF canister can then be inserted into a transportation cask and transported to the repository (DOE 2002 [DIRS 158405], Appendix C, Section 5.1, Table 1).

Approximately 125 MTHM of the DOE inventory includes uranium enriched initially to more than 20 percent uranium-235, uranium enriched initially to between 5 and 20 percent uranium-235, and thorium- and plutonium-based fuels (DOE 2002 [DIRS 158405], Appendix C, Section 5.1, Table 1).

The canisters for DOE SNF are standardized to efficiently utilize the waste package design configuration (BSC 2004 [DIRS 167273], Table 5). Table 12 gives the preliminary canister dimensions.

About 22,000 canisters of HLW are generated by 2035 (DOE 1997 [DIRS 101816], Section 1.5.4). Approximately 1.5 percent comes from reprocessed commercial nuclear fuel; the rest comes from treatment of materials from the defense nuclear program. The estimated number of HLW canisters to be emplaced in the first repository is approximately 8,300, based on the total inventory limit in the NWPA.

Liquid HLW undergoes a process at its current site that yields a solid leach-resistant material, typically a borosilicate glass. While still liquid, the glass is poured into stainless steel canisters. After the glass cools and solidifies, the canisters are sealed. The repository would accept solid HLW generated from activities at DOE's Savannah River, South Carolina, and Hanford, Washington, sites, as well as from the Idaho National Environmental and Engineering Laboratory. The waste arrives in presealed canisters. The repository also receives, subject to the execution of a disposal contract between the DOE and the state of New York, commercial HLW from the West Valley Demonstration Project in New York.

The canisters containing HLW are standardized to accommodate the waste package design configuration and to reduce manufacturing costs. Table 9 gives the canister dimensions.

## 5.2 HLW/DOE SNF CO-DISPOSAL GENERAL CONFIGURATION

Three waste package design configurations have been developed for codisposal of DOE SNF and HLW (BSC 2004 [DIRS 167273], Section 4.1.2.1). They are:

**5 DHLW/DOE SNF Co-disposal Short**—This design configuration holds five vitrified waste canisters from the Savannah River Site (SRS), diameter of 0.61 m (24.0 in.) and length of 3.0 m (118.1 in.), or canisters of the same size from the other sites, and a canister of DOE-owned SNF in the center. This waste package design configuration can be seen in:

*Design & Engineering, 5 DHLW/DOE SNF - Short Waste Package Configuration*, 000-MW0-DS00-00101-000-00A (BSC 2004 [DIRS 166860])

*Design & Engineering, 5 DHLW/DOE SNF - Short Waste Package Configuration*, 000-MW0-DS00-00102-000-00A (BSC 2004 [DIRS 166946])

*Design and Engineering Organization, 5 DHLW/DOE SNF - Short Waste Package Configuration*, 000-MW0-DS00-00103-000-00A (BSC 2004 [DIRS 166947]).

**5 DHLW/DOE SNF Co-disposal Long**—This design configuration holds five vitrified waste canisters from the Hanford Site, diameter of 0.61 m (24.0 in.) and length of 4.57 m (180.0 in.), or canisters of the same size from the other sites, and a canister of DOE-owned SNF in the center. This waste package design configuration can be seen in:

*Design & Engineering, 5 DHLW/DOE SNF - Long Waste Package Configuration*, 000-MW0-DS00-00201-000-00A (BSC 2004 [DIRS 166861])

*Design and Engineering Organization, 5 DHLW/DOE SNF - Long Waste Package Configuration*, 000-MW0-DS00-00202-000-00A (BSC 2004 [DIRS 166949])

*Design and Engineering Organization, 5 DHLW/DOE SNF - Long Waste Package Configuration*, 000-MW0-DS00-00203-000-00A (BSC 2004 [DIRS 166950]).

There are many forms of DOE-owned SNF. These waste forms arrive at the repository in canisters suitable for long-term disposal. Most of this fuel is placed in standard canisters suitable for the two codisposal waste package types described previously.

However, N-reactor fuels are placed in a larger multi-canister overpack (MCO). Consequently a unique waste package type is required for this fuel type. The internals of this waste package type allow placement of two N-reactor fuel canisters along with two HLW glass canisters. The DOE standardized SNF canisters include a basket to provide structural support, criticality control, and heat transfer, as needed. One waste package design configuration has been developed at the conceptual stage, with the rest being grouped in a category of miscellaneous.

**2-MCO/2-DHLW Codisposal**—The MCO is a canister for Hanford Site N-Reactor fuel. This design configuration holds two MCOs with a diameter of 0.643 m (25.31 in.) and a length of 4.202 m (165.43 in.) and two Hanford HLW glass canisters. This waste package design configuration can be seen in:

*Design & Engineering, 2-MCO/2-DHLW Waste Package Configuration*, 000-MW0-DS00-00301-000-00A (BSC 2004 [DIRS 166862])

*Design & Engineering, 2-MCO/2-DHLW Waste Package Configuration*, 000-MW0-DS00-00302-000-00A (BSC 2004 [DIRS 166919])

*Design & Engineering, 2-MCO/2-DLHW Waste Package Configuration*, 000-MW0-DS00-00303-000-00A (BSC 2004 [DIRS 166951])

*Design & Engineering, 2-MCO/2-DHLW Waste Package Configuration*, 000-MW0-DS00-00304-000-00A (BSC 2004 [DIRS 166952]).

There are a number of major components that comprise the waste package. A standard nomenclature has been established for referring to these components. This nomenclature is shown in Table 1.

Table 1. Standard Nomenclature for Waste Package Components

| Preferred Terminology | Acceptable for Clarity or Brevity | Description |
|---|---|---|
| Trunnion Sleeve | Trunnion Collar Sleeve | The welded attachment that accepts the trunnion collar |
| Trunnion Collar | | The removable ring that mates with the trunnion sleeve |
| Outer Corrosion Barrier | Outer Barrier<br>Alloy 22 Shell | The Alloy 22 (UNS N06022) shell (sides and the outer barrier bottom lid) |
| Outer Lid | Final Alloy 22 Lid | The outermost lid, Alloy 22 (UNS N06022) |
| Middle Lid | | The first Alloy 22 (UNS N06022) lid, the middle of three lids |
| Spread Rings | | The four-part ring that, when spread into position, mechanically holds the inner vessel lid in place |
| Inner Vessel Lid | Inner Lid | The stainless steel lid that seals the Inner Vessel |
| Inner Vessel | Stainless Steel Vessel | The inner vessel that is the ASME B&PV code-stamped pressure vessel |
| Shell Interface Ring | | The stainless steel ring that sits between the support ring and the inner vessel |
| Inner Vessel Support Ring | | The Alloy 22 (UNS N06022) ring that keeps the inner vessel off of the bottom of the outer corrosion barrier |

Source: BSC 2003 [DIRS 167167], Appendix D.

The major internal differences between the 5 DHLW/DOE SNF Short, 5 DHLW/DOE SNF Long, and 2-MCO/2-DHLW waste packages and the fuels they accommodate are summarized in Table 2.

Table 2. HLW/DOE SNF Codisposal Waste Package Internal Components

| Fuels | Waste Package | Internal Placement | Internal Configuration Notes |
|---|---|---|---|
| Vitrified High-Level Waste (SRS, INEEL and West Valley) | 5 DHLW/DOE SNF Short, 5 DHLW/DOE SNF Long, or 2-MCO/2-DHLW | Five peripheral locations | The 5 DHLW/DOE SNF Long or 2-MCO/2-DHLW are acceptable, however not economical. |

| Fuels | Waste Package | Internal Placement | Internal Configuration Notes |
|---|---|---|---|
| Vitrified High-Level Waste (Hanford) | 5 DHLW/DOE SNF Long or 2-MCO/2-DHLW | Five peripheral locations | The 2-MCO/2-DHLW is acceptable, provided no cylinders contain plutonium "can-in-can" waste.[a] |
| Vitrified High-Level Waste with "Can-in-Can" Pu (SRS)[a] | 5 DHLW/DOE SNF-Short or 5 DHLW/DOE SNF-Long | One only in peripheral locations | Remaining peripheral locations must be loaded with HLW cylinders. Central location must be left empty.<br><br>The 5 DHLW/DOE SNF Long is acceptable, however not economical. |
| 18" DOE Long Standardized SNF Canister | 5 DHLW/DOE SNF Long | Center location | Peripheral locations must not be loaded with cylinders that contain plutonium "can-in-can" waste.[a] |
| 18" DOE Short Standardized SNF Canister | 5 DHLW/DOE SNF Short or 5 DHLW/DOE SNF Long | Center location | Peripheral locations must not be loaded with cylinders that contain plutonium "can-in-can" waste.[a]<br><br>The 5 DHLW/DOE SNF Long is acceptable, however not economical. |
| 24" DOE Short Standardized SNF Canister | 5 DHLW/DOE SNF Short or 5 DHLW/DOE SNF Long | One only in peripheral locations | Remaining peripheral locations must be loaded with HLW cylinders. Central location must be left empty.<br><br>Peripheral locations must not be loaded with cylinders that contain plutonium "can-in-can" waste.[a]<br><br>The 5 DHLW/DOE SNF Long is acceptable, however not economical. |
| 24" DOE Long Standardized SNF Canister | 5 DHLW/DOE SNF Long | One only in peripheral locations | Remaining peripheral locations must be loaded with HLW cylinders. Central location must be left empty.<br><br>Peripheral locations must not be loaded with cylinders that contain plutonium "can-in-can" waste.[a] |
| Multi-canister Overpack (Hanford N-reactor Fuel) | 2-MCO/2-DHLW | On MCO support plate assemblies | No cylinders can contain plutonium "can-in-can" waste.[a] |

NOTES: INEEL = Idaho National Engineering and Environmental Laboratory.

[a]Plutonium waste forms are not part of the current baseline of the License Application, however it is important to understand the loading requirements of the HLW/DOE SNF codisposal waste packages.

### 5.3 JUSTIFICATION OF DESIGN FEATURES

The outer lid is designed with a flat top. This is a result of the value engineering study in *Value Study Report—Waste Package Reevaluation* (BSC 2003 [DIRS 163185], Attachment III). With the middle lid present, it is unnecessary to use induction annealing on the final weld. Therefore, the final lid is laser peened or burnished to reduce residual stresses (BSC 2004 [DIRS 167278], Section 4.1.1.6).

The bottom trunnion sleeve is extended past the outer barrier to act as an energy absorber in case of an accident. The part that extends has a tapered surface to allow runoff when the waste package is horizontal.

For ease of assembly, the inner vessel and outer barrier have a gap in between, both radially and axially. The axial gap is at least 10 mm (0.39 in.)(BSC 2003 [DIRS 161691], Section 7), and the radial gap is at least 1 mm (0.04 in.) (BSC 2001 [DIRS 152655], Section 6.1, Table 4). These distances account for differences in thermal expansion values for Alloy 22 (UNS N06022) and stainless steel type 316.

The shell interface ring is added as a measure to absorb energy during the corner drop load case. Its placement alleviates high stresses from occurring in the inner vessel bottom corner (CRWMS M&O 2000 [DIRS 157822], Section 6).

The support ring is added to prevent the weight of the fuel from creating a force in the middle of the bottom lid of the outer barrier when the waste package is in the vertical position. The support ring elevates the inner vessel and prevents it from contacting the outer barrier.

The waste package internals for the DOE SNF and HLW waste packages are listed in *DOE and Commercial Waste Package System Description Document* (BSC 2004 [DIRS 167273], Tables 1 and 5). The cavity length for the waste packages is determined from the length of the HLW canisters. Since there are two lengths of HLW canisters (3.00 m (118.1 in.) and 4.57 m (179.9 in.)) there are two waste package configurations to accommodate them. For the 5 DHLW/DOE SNF-Short waste package, the cavity height is 3.013 m (118.625 in.) and for the 5 DHLW/DOE SNF-Long and the 2-MCO/2-DHLW waste packages the cavity length is 4.620 m (181.875 in.). For the 5 DHLW/DOE SNF waste packages a basket structure is designed to allow five HLW canisters placed radially with a single DOE standardized SNF canister in the center. The 2-MCO/2-DHLW waste package holds two MCO and two HLW canisters diagonally from each other. There is a difference in length between the MCO and HLW canister that a small pedestal placed in the bottom of the waste package accounts for (BSC 2004 [DIRS 166862]; BSC 2004 [DIRS 166952]). This pedestal also has the option of being designed to absorb energy in the event of the MCO being dropped into the waste package while being loaded.

There are many different waste forms to be loaded into the three waste package configurations presented in this document. Some of these waste forms are placed in canisters having two different lengths (referred to as "Short" and "Long"). The 5 DHLW/DOE SNF Codisposal Long waste package and 2-MCO/2-DHLW waste package are designed for those fuels that are a maximum length of 4.57 m (179.9 in.). These many different waste forms and sizes lead to different loading configurations within the three waste packages. It is possible to load the short fuels into either of the long waste packages; however, this is to be avoided as it is not economical to do so. The waste form loading is as follows:

**Vitrified High-Level Waste (SRS, Idaho National Engineering and Environmental Laboratory (INEEL) and West Valley)**—These are to be placed in either a 5 DHLW/DOE SNF Codisposal Short waste package or in a 5 DHLW/DOE SNF Codisposal Long waste package, in the five peripheral locations. In addition, two may be placed in a 2-MCO/2-DHLW waste package.

**Vitrified High-Level Waste (Hanford)**—These are to be placed in a 5 DHLW/DOE SNF Codisposal Long waste package in the five peripheral locations. Alternatively, two may be placed in a 2-MCO/2-DHLW waste package, provided the pour cylinders do not contain plutonium "can-in-can" waste form.

**Vitrified High-Level Waste with "Can-in-Can" Pu (SRS)**—This waste form is not in the baseline for License Application, however it is important to note that this form can be placed in the codisposal waste packages with strict restrictions. Only one of these vitrified HLW pour cylinders may be placed in one of the peripheral locations of either a 5 DHLW/DOE SNF Codisposal Short waste package or in a 5 DHLW/DOE SNF Codisposal Long waste package. The four other peripheral locations must be loaded with HLW pour cylinders that do not incorporate "Can-in-Can" Pu disposal. The central location in this waste package must be left empty.

**18" DOE Long Standardized SNF Canister**—These must be placed in the center location of a 5 DHLW/DOE SNF Codisposal Long waste package. If any of the HLW pour cylinder contain plutonium "can-in-can" waste forms, then the center location must remain empty.

**18" DOE Short Standardized SNF Canister**—These may be placed in the center location of either a 5 DHLW/DOE SNF Codisposal Short waste package or a 5 DHLW/DOE SNF Codisposal Long waste package. If any of the HLW pour cylinders contain plutonium "can-in-can" waste forms, then the center location must remain empty.

**24" DOE Short Standardized SNF Canister**—Only one of these may be placed in one of the peripheral locations of a 5 DHLW/DOE SNF Codisposal Long waste package or a 5 DHLW/DOE SNF Codisposal Short waste package, with the remaining peripheral locations filled with HLW. Further, the center location must be left empty. If any of the HLW pour cylinders contain plutonium "can-in-can" waste forms, then the 24" canister may not be loaded into the waste package.

**24" DOE Long Standardized SNF Canister**—Only one of these may be placed in one of the peripheral locations of a 5 DHLW/DOE SNF Codisposal Long waste package, with the balance filled with HLW. Further, the center location must be left empty. If any of the HLW pour cylinders contain plutonium "can-in-can" waste forms, then the 24" canister may not be loaded into the waste package.

**Multi-canister Overpack (Hanford N-reactor Fuel)**—Two MCOs may be placed in the 2-MCO/2-DHLW Waste Package. As noted above, HLW pour cylinders containing plutonium "can-in-can" waste forms may not be placed in this waste package.

Note that positions for vitrified HLW pour cylinders may be left empty in any of the waste packages, but this would be uneconomical. Also, plutonium waste forms are outside of the current baseline for License Application, but is important to note the restrictions for the different loading combinations.

### 5.3.1 Dimensions

Dimensions should be taken from the configuration drawings cited in Section 5.2.

### 5.3.2 Material Selection

The selection of materials from which reliable waste packages could be fabricated followed a multistep analysis and design process. It began by analyzing the critical functions of a particular waste package and its various components. In selecting a material for a component of the waste package, the designers considered both the material's availability and the critical functions the component would serve as part of the waste package. Eight major components and eight performance criteria were identified for selecting materials (CRWMS M&O 1997 [DIRS 100259], Section 3). The eight major components are:

- Structural vessel
- Corrosion-resistant barrier
- Fill gas
- Interlocking plates for commercial design configurations
- Fuel tubes for commercial design configurations
- Structural guides for commercial design configurations
- Guide tube for codisposal design configurations
- Thermal shunts for commercial design configurations.

Not every waste package design configuration requires all of these components; it varies according to the waste form each holds. However, all eight of these components cover the major requirements of all ten waste package design configurations.

The eight criteria that contribute to performance are:

- Mechanical performance (strength)
- Chemical performance (resistance to corrosion and microbial attack)
- Predictability of performance (understanding the behavior of materials)
- Compatibility with materials of the waste package and waste form
- Ease of fabrication using the material
- Previous experience (proven performance record)
- Thermal performance (heat distribution characteristics)

- Neutronic performance (criticality and shielding).

Reasonableness of cost was considered as a discriminator.

**Corrosion-Resistant Materials**—Corrosion performance has been determined to be the most important criterion for a long waste package lifetime. Essential performance qualities therefore include a material's resistance to general and localized corrosion, stress corrosion cracking, and hydrogen-assisted cracking and embrittlement. The effects of long-term thermal aging are also important. To address the performance requirements for the waste package, the DOE has initiated studies to gain a better understanding of the processes involved in predicting the rate of waste package material corrosion over the 10,000-year regulatory period.

Combinations and arrangements of materials as containment barriers were carefully considered from several perspectives. In the process, analysts considered such criteria as (1) material compatibility (e.g., galvanic/crevice corrosion effects); (2) the material's ability to contribute to defense in depth (e.g., because it has a different failure mode from other barriers); (3) the material's ease of fabrication; and (4) the potential impact of thin, corrosion-resistant materials used as containment barriers on a repository's essential operations, such as waste package loading, handling, and emplacement.

The major objectives centered on understanding the temperature and humidity conditions that would exist at different times for a range of thermal operating modes in a particular unsaturated zone, then designing the waste packages accordingly. Since the properties of any material selected for a corrosion barrier would inevitably be influenced by the temperature and humidity conditions in a repository of a particular design at a particular site, selecting the right corrosion-resistant material became one of the most important priorities.

After assessing potential materials available for waste package corrosion barriers, analysts selected nickel- and titanium-based alloys as the most promising candidate materials for corrosion resistance in an oxidizing environment such as Yucca Mountain. Using a corrosion-resistant material as the outer barrier of the waste package significantly lowers the risk of waste package failure from corrosion. Alloy 22 (UNS N06022) was selected as the preferred material for the outer barrier because it has excellent resistance to corrosion in the environment expected at Yucca Mountain; it is easier to weld than titanium; and it has a better thermal expansion coefficient match to stainless steel type 316 than titanium. A structurally strong material (stainless steel) was chosen for the inner layer of the waste package (CRWMS M&O 2000 [DIRS 138173], Section 7.6).

Alloy 22 (UNS N06022) also offers benefits in the areas of program and operating flexibility. It is extremely corrosion-resistant under conditions of high temperature and low humidity, such as those that would prevail for hundreds to thousands of years in a repository designed to allow a relatively high thermal output from the waste packages.

**Structural Materials**—The major functional requirement of the structural material for the inner layer of the waste package is to support the corrosion-resistant outer material. Stainless steel type 316 was selected for the structural layer (CRWMS M&O 2000 [DIRS 138173], Section 7.6).

This material provides the required strength; has a better compatibility with Alloy 22 (UNS N06022) than carbon steel; and provides an economical solution to functional requirements. Table 3 presents the yield and tensile strengths of Alloy 22 (UNS N06022) and stainless steel type 316.

Table 3. Yield and Tensile Strengths of Alloy 22 (UNS N06022) and Stainless Steel Type 316

| | | Alloy 22 (UNS N06022) (MPa) | Stainless Steel Type 316 (MPa) |
|---|---|---|---|
| Yield Strength ($\sigma_y$) | RT[a] | 310 | 207 |
| | 100°C[b] | 273 | 177 |
| | 300°C[b] | 214 | 132 |
| Engineering Tensile Strength | RT[a] | 689 | 517 |
| | 100°C[b] | 688 | 515 |
| | 300°C[b] | 632 | 495 |
| True Tensile Strength ($\sigma_u$) | RT[b] | 971 | 703 |
| | 100°C[b] | 977 | 664 |
| | 300°C[b] | 910 | 619 |

NOTE: RT = room temperature.
Sources:
[a]ASME 2001 [DIRS 158115], Section II, Part D, Tables Y-1 and U.
[b]BSC 2003 [DIRS 166184], Section 5.

The design configurations for commercial SNF and DOE codisposal waste packages include internal components (i.e., structural guides, interlocking plates, fuel tubes, and thermal shunts) that must be able to sustain the mechanical loads created by handling, emplacement, and, if necessary, retrieval. Thus, mechanical performance was a major selection criterion. Thermal performance was also an important selection criterion because these components provide an additional path for conducting heat from the waste form to the walls of the waste package. The fuel tubes contact both the waste form and the basket plates. If the material selected for the tubes causes the waste form to degrade, release rates could be increased; if it causes the plates to degrade, criticality control could be compromised. Therefore, compatibility with other materials was an important criterion. The waste package design does not rely on these components for postclosure performance, so corrosion-resistant materials are not needed. Two grades of carbon steel (SA 516 Grades 55 and 70) were found to be the best choices for these internal components, based on the criteria; the designers chose to use Grade 70 (CRWMS M&O 2000 [DIRS 138189], Section 4).

The fill gas can be a significant conductor of heat from the waste form to the internal basket, so thermal performance was deemed one of the most important criteria in choosing a gas. The fill gas should not degrade other components of the waste package, so compatibility with other materials was another important criterion. Helium is inert and is routinely used as the fill gas for fuel rods, which indicates that helium would have an excellent compatibility with SNF. Based on a review of data on thermal conductivity, it was chosen over other candidate gases, such as nitrogen, argon, and krypton (CRWMS M&O 2000 [DIRS 138192], Sections 3.3.1 through 3.3.3).

### 5.3.3 ASME Code Position

The basis for the selection and application of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PV) Code to the waste package is documented in the document entitled, *BSC Position on the Use of the ASME Boiler and Pressure Vessel Code for the Yucca Mountain Waste Packages* (BSC 2003 [DIRS 165058]). This section summarizes the salient points of that document with regard to the design of the waste package.

*Yucca Mountain Review Plan, Final Report* (NRC 2003 [DIRS 163274]) provides specific guidance on the appropriateness of using the ASME B&PV Code (ASME 2001 [DIRS 158115]) in the design of the waste package (e.g., Section 2.1.1.7.2.3 (1)); however, it does not prescribe the exact implementation of the code.

In any discussion of the ASME B&PV Code, it is important to first note that it is a pressure vessel safety code and that its primary mission is to assure structural adequacy for pressure loading. Any other use of the ASME B&PV Code, such as the use of the conservative material properties contained in it or failure limits for non-pressure loading, must be justified on insight into the structural phenomena that are postulated to occur. For the waste packages, component sizing and thickness are not determined by pressure loads but rather by dynamic events that the waste package might experience. Therefore, the application of the ASME B&PV Code design rules for dynamic loading of the waste packages must be carefully scrutinized to ensure that the rules are properly applied. The preparation of that document is described in *BSC Position on the Use of the ASME Boiler and Pressure Vessel Code for the Yucca Mountain Waste Packages* (BSC 2003 [DIRS 165058]).

For the application of the ASME B&PV code, Section III, Division I, Subsection NC (ASME 2001 [DIRS 158115]), has been selected by Bechtel SAIC Company (BSC) for the code-compliant design and fabrication of the waste packages. It is important to differentiate the parts of the waste package to which the code apply. There are four major assembled components of the waste package. These are (1) the stainless steel type 316 inner vessel, (2) the Alloy 22 (UNS N06022) outer corrosion barrier, (3) the internal basket assemblies, and (4) the removable trunnion collar that is used for lifting and handling purposes. With regard to the code design, the only one of these parts that is considered a pressure vessel is the stainless steel type 316 inner vessel.

With regard to the hermeticity of the inner vessel and integrity of the same against pressure loads, no currently postulated dynamic structural event involves simultaneous over-pressurization of the inner vessel. For over-pressurization, the capability of the spread ring and seal weld combination to retain the design pressure is assured by a helium leak check. While the seal welds are anticipated to be sound welds, no credit for resistance against dynamic events is taken as these are partial-penetration welds. Therefore, for dynamic structural events where the inner vessel in the vicinity of the seal welds may be reasonably anticipated to experience significant loads, these welds are not credited to maintain the hermeticity of the inner vessel. In such cases, it must be shown that the outer corrosion barrier does not breach to maintain containment of the waste form.

For the other components of the waste package, the ASME B&PV code (ASME 2001 [DIRS 158115]) is only used as guidance, either through the use of conservative material properties or conservative stress limits. For credible preclosure event sequences and the assessment of those event sequences, the code and supporting code interpretations are used to formulate layered defensible material failure criteria. The basis for these failure criteria is discussed in Section 7.1.2.3.

It should be noted that if a waste package suffers a nontrivial dynamic event (i.e., drop, tip over, etc.), the waste form would be repackaged in a new waste package and the original waste package permanently removed from service.

# 6. SUMMARY OF DESIGN REQUIREMENTS

Preclosure and postclosure requirements are discussed in this section. Functional requirements are taken from BSC 2004 [DIRS 167273].

## 6.1 PRECLOSURE

### 6.1.1 Normal Operations

Functional Requirement Number: 3.1.3.1

Functional Requirement Title: Waste Package Handling Limits

Functional Requirement Text: Waste package handling shall not introduce any surface defect in the corrosion barrier exceeding those identified by performance assessment and on interface exchange drawings. Surface defects include, but are not limited to, scratches, nicks, dents, and permanent changes to the surface stress condition (Table 4).

Table 4. Waste Package Handling Limits Performance Requirements

| Performance Requirement Number | Performance Requirement Text | Applicability |
|---|---|---|
| 1 | This issue is under investigation and will be resolved prior to construction authorization. A closure weld defect is the area of most concern and shall be limited to 1.6 mm (1/16 inch) (BSC 2004 [DIRS 164475], pp. 59-60). | Yes |

Functional Requirement Number: 3.1.3.2

Functional Requirement Title: Waste Package Closure

Functional Requirement Text: Sealing operations shall be performed on the waste package (Table 5).

Table 5. Waste Package Closure Performance Requirements

| Performance Requirement Number | Performance Requirement Text | Applicability |
|---|---|---|
| 1 | Waste package sealing operations shall meet the requirements for the waste package as specified in the SDD for the waste package closure system. | Yes |

#### 6.1.1.1 Thermal

Thermal design requirements for normal operations include:

Maximum cladding temperature for DOE spent fuel is taken as the same for commercial SNF, i.e., 350°C (Doraswamy 2004, Section 5.1.3.2 [DIRS 169548]) (this requirement is for both preclosure and postclosure).

Maximum temperature for DHLW is taken as 400°C (DOE 1995 [DIRS 129122], Appendix A, Section 1.4, p.23). The 400°C temperature limit, which is 50-100°C below the glass transition temperature (Canori and Leitner 2003 [DIRS 166275], Appendix A), was chosen to provide a conservative, discrete control target. No changes have been detected in phase structure when glass is maintained at or below the glass transition temperature for reasonable time periods.

Maximum waste package heat output of 11.8 kW at emplacement (BSC 2004, Section 3.1.1.5 [DIRS 167273]).

#### 6.1.1.2 Structural

Functional Requirement Number: 3.1.1.1

Functional Requirement Title: Preclosure Containment

Functional Requirement Text: The waste package contains the waste form within its boundary for the preclosure period (Table 6).

Table 6. Preclosure Containment Performance Requirements

| Performance Requirement Number | Performance Requirement Text | Applicability |
|---|---|---|
| 1 | The sealed waste package shall not breach during normal operations or during credible preclosure event sequences. | Yes |
| 2 | The waste package shall be designed and constructed to the codes and standards specified in Doraswamy 2004 [DIRS 169548], Section 5.1.1. | Yes |
| 3 | Normal operations and credible event sequence load combinations are defined in Mecham 2004 [DIRS 169790], Section 6.2.2.<br><br>Note: The normal operations and credible event sequence load combinations are in Mecham 2004 [DIRS 169790], Section 6.2.2 and are not present in Doraswamy 2004 [DIRS 169548]. | Yes |
| 4 | The waste package shall be designed to permit retrieval during the preclosure period until the completion of a performance confirmation program and Commission review of the information obtained from such a program. | Yes |
| 5 | The waste package shall be designed to permit retrieval during the preclosure period so that any or all of the emplaced waste could be retrieved on a reasonable schedule starting at any time up to 50 years after waste emplacement operations are initiated, unless a different time period is approved or specified by the Commission. | Yes |
| 6 | The waste package shall be designed to meet the full range of preclosure operating conditions for up to 300 years after the final waste emplacement. | Yes |

The waste package shall be designed to account for residual and differential thermal expansion stresses (Mecham 2004 [DIRS 169790], Section 6.2.2.2).

The waste package shall be designed to account for internal pressure resulting thermally (i.e., differential thermal expansion) and due to fuel cladding rupture (Mecham 2004 [DIRS 169790], Section 6.2.2.3).

### 6.1.1.3 Shielding

Shielding analyses evaluate the effects of ionizing radiation on personnel, equipment, and materials. The primary sources for waste package radiation are gamma rays and neutrons emitted from SNF and HLW. Loading, handling, and transporting of waste packages would be carried out remotely to keep personnel exposure as low as reasonably achievable (e.g., having the human operators behind radiation shield walls, using remote manipulators, viewing operations with video cameras). The general shielding requirements are stated in Section 4.9.1 of Doraswamy (2004 [DIRS 169548]). Table 4.9.1-2 of Doraswamy (2004 [DIRS 169548]) does not list any shielding requirements on the waste package. The transporter and fuel and canister handling buildings provide shielding.

### 6.1.1.4 Waste Form Accommodation

Functional Requirement Number: 3.1.1.4

Functional Requirement Title: Defense High-Level Waste Quantities and Characteristics

Functional Requirement Text: The sealed waste package shall provide conditions necessary to maintain the physical and chemical stability of the waste form. [Note: Time/temperature limits for Commercial SNF in air are currently being established in order to maintain the waste form before the waste package is sealed] (Table 7).

Table 7. Waste Form Maintenance Performance Requirements

| Performance Requirement Number | Performance Requirement Text | Applicability |
|---|---|---|
| 1 | The sealed waste package environment shall provide conditions that maintain waste form characteristics that restrict transport of radionuclides. | Yes |
| 2 | The waste package shall maintain all commercial SNF waste forms containing zirconium-based cladding during preclosure and postclosure periods at temperatures that will not accelerate the degradation of the cladding to the point that it affects the performance of the system. | Yes |
| 3 | The waste package shall meet the temperature criteria in the Doraswamy 2004 [DIRS 169548], Section 5.1.3.2, for all Zirconium clad commercial fuel. | Yes |
| 4 | The waste form region of the sealed waste package shall have an inert atmosphere with limited oxidizing agents. | Yes |

Functional Requirement Number: 3.1.2.1

Functional Requirement Title: Defense High-Level Waste Quantities and Characteristics

Functional Requirement Text: The waste package shall accommodate defense HLW canisters (Tables 8 and 9).

Table 8. Defense High-Level Waste Quantities and Characteristics Performance Requirements

| Performance Requirement Number | Performance Requirement Text | Applicability |
|---|---|---|
| 1 | Table 9 identifies nominal parameters (size, maximum weight, and materials) of the shipping canisters that may be used in design. | Yes |

Table 9. High-Level Radioactive Waste Canisters

| Canister Producer | Nominal Outside Diameter | Nominal Overall Height | Maximum Individual Canister Weight | Canister Material | Expected Canisters |
|---|---|---|---|---|---|
| Savannah River Site | 24 in. (61 cm) | 118 in. (3.00 m) | 5,512 lb (2,500 kg) | 304L Stainless Steel | 7,347[a, d] |
| Hanford Site (Long) | 24 in. (61 cm) | 180 in. (4.57 m) | 9,260 lb (4,200 kg) | 304L Stainless Steel | 14,500 |
| Idaho National Engineering and Environmental Laboratory (INEEL)[b] | 24 in. (61 cm) | 118 in. (3.00 m) | 5,512 lb (2,500 kg) | 304L Stainless Steel | (d) |
| West Valley Demonstration Project[c] | 24 in. (61 cm) | 118 in. (3.00 m) | 5,512 lb (2,500 kg) | 304L Stainless Steel | 300 |

NOTES: [a]635 canisters contain immobilized plutonium waste form.
[b]Specification not issued; characteristics assumed to be same as Savannah River canister.
[c]Contract to send/receive waste has not been issued; characteristics assumed to be same as Savannah River canister.
[d]Some of the 7347 canisters come from INEEL.
Source: BSC 2004 [DIRS 167273], Table 1.

Functional Requirement Number: 3.1.2.3

Functional Requirement Title: DOE SNF Quantities and Characteristics

Functional Requirement Text: The waste package shall accommodate DOE SNF (Tables 10 to 12).

Table 10. DOE SNF Quantities and Characteristics Performance Requirements

| Performance Requirement Number | Performance Requirement Text | Applicability |
|---|---|---|
| 1 | Table 11 identifies the SNF groups that make up DOE SNF. The DOE SNF will arrive at the MGR in disposable canisters of the sizes and weights identified in Table 12. | Yes |

Table 11. DOE Spent Nuclear Fuel Groups for Total System Performance Assessment

| | |
|---|---|
| 1. U Metal, Zr Clad, Disrupted | 18. U-Si, Al Clad |
| 2. U Metal, Al Clad, Single Pass Reactor | 19. U/Th Carbide, Graphite, Hi-Integrity, Ft. St. Vrain |
| 3. U-Zr | 20. U/Th Carbide, Graphite, Low-Integrity, Peach Bottom |
| 4. U-Mo, Zr Clad, Fermi | 21. U or U/Pu Carbide, Non Graphite |
| 5. U Oxide, Zr Clad, Intact, Shippingport PWR | 22. MOX, Zr Clad |
| 6. U Oxide, Zr Clad, Intact, Saxton | 23. MOX, SST |
| 7. U Oxide, Zr Clad, Intact, Commercial | 24. MOX, Misc. Clad |
| 8. U Oxide, SST Clad, Intact | 25. U/Th Oxide, Zr Clad |
| 9. U Oxide, SST Clad, Intact | 26. U/Th Oxide, Dresden |
| 10. U Oxide, SST Clad, Intact | 27. U-Zr-Hx |
| 11. U Oxide Failed, or Declad | 28. U-Zr-Hx |
| 12. U Oxide, Fail or Declad | 29. U-Zr-Hx, Al Clad, TRIGA Alum |
| 13. U Oxide, Fail or Declad, TMI-2 | 30. U-Zr-Hx, DeClad |
| 14. U Oxide, Al Clad | 31. Na-Bonded, SST/Misc. FERMI I Blanket |
| 15. U Oxide, Al Clad | 32. Canyon Stab., SRS Target |
| 16. U-Al or U-Alx, Al Clad | 33. Misc. SNF |
| 17. U-Al or U-Alx, Al Clad | |

NOTE: U-Al and U-Alx refer to the same fuel. MOX = mixed oxide fuel; U-Zr-Hx = U-Zr Hydride fuel where x is the ratio of Hydrogen to Zr; SRS = Savannah River Site; SST = stainless steel, TMI = Three Mile Island, PWR = Pressurized Water Reactor.
Source; BSC 2004 [DIRS 167273], Table 4.

Table 12. DOE SNF Canisters

| Canister Type | MAX Diameter | MAX Length | MAX Weight[a] | Material |
|---|---|---|---|---|
| NSNFP 18 in. x 10 ft. | 18.68 in. (474.2 mm) | 118.11 in. (3,000 mm) | 5,005 lb (2,270 kg) | Type 316L Stainless Steel |
| NSNFP 18 in. x 15 ft. | 18.74 in. (476.0 mm) | 179.92 in. (4,570 mm) | 6,000 lb (2,721 kg) | Type 316L Stainless Steel |
| NSNFP 24 in. x 10 ft. | 24.80 in. (629.9 mm) | 118.11 in. (3,000 mm) | 8,996 lb (4,080 kg) | Type 316L Stainless Steel |
| NSNFP 24 in. x 15 ft. | 24.87 in. (631.7 mm) | 179.92 in. (4,570 mm) | 10,000 lb (4,535 kg) | Type 316L Stainless Steel |
| MCO 25 in. x 14 ft. | 25.31 in. (642.87 mm) | 166.435 in. (4,227.5 mm) | 19,642 lb (8,909.6 kg) | Type 304L Stainless Steel |

NOTES: [a]Canister plus contents.
NSNFP = National Spent Nuclear Fuel Project.
Source: BSC 2004 [DIRS 167273], Table 5.

The DOE SNF and HLW waste packages shall have physical dimensions to accommodate the fuel listed in Tables 1 and 5 of BSC (2004 [DIRS 167273]).

#### 6.1.1.5 Criticality

The preclosure safety analysis must include consideration of means to prevent and control criticality (10 CFR 63.112(e)(6) [DIRS 158535]). In addition to any criticality countermeasures that might be included with a DOE SNF waste form in the standardized canister, and the inherent sub-critical neutron multiplication of the vitrified high-level waste, avoidance of criticality is ensured by moderator exclusion from the waste package during preclosure (Doraswamy 2004 [DIRS 169548], Sections 4.9.2.2.3 and 4.9.2.2.6).

Section 5.1.27 of BSC 2003 [DIRS 164128] states that a design requirement will ensure that dropping a DOE SNF canister (standardized or MCO) into a waste package intended for DOE SNF, with moderator exclusion in effect, will not lead to a preclosure nuclear criticality. Criticality must be precluded whether the waste package is initially empty or loaded with the most reactive configuration of DHLW canisters or another MCO, as appropriate.

### 6.1.2 Event Sequence Evaluation

#### 6.1.2.1 Thermal

The thermal incident that is included in this section is the fire accident. During a fire, maximum cladding temperature for DOE spent fuel is taken to be the same as for commercial SNF, 570°C (Doraswamy 2004, [DIRS 169548], Section 5.1.3.2). Maximum glass temperature is taken to be the glass transition temperature, 450-500°C (Canori and Leitner 2003 [DIRS 166275], Appendix A).

#### 6.1.2.2 Structural

The waste package shall not breach during normal operation or during credible preclosure sequence events (BSC 2004, [DIRS 167273], Section 3.1.1.1). These include the following:

**Rock Fall on Waste Package**–The waste package is at rest on the emplacement pallet in the drift without a drip shield, when rock(s) fall and impact the waste package surface (Mecham 2004 [DIRS 169790], Section 6.2.2.4).

**Object Drop on Waste Package**–The waste package is at rest in a vertical position and a equipment failure (i.e., gantry crane) falls and impacts the top of the waste package (Mecham 2004 [DIRS 169790], Section 6.2.2.4).

**Missile Impact on Waste Package**–The waste package is at rest and a small object at high velocity impacts the waste package surface (Mecham 2004 [DIRS 169790], Section 6.2.2.4).

**Waste Package Vertical Drop**–The waste package is being lifted in a vertical orientation at a height of 2.0 m (6.6 ft) when the lifting device inadvertently drops it. The waste package impacts the ground squarely on its base (Mecham 2004 [DIRS 169790], Section 6.2.2.5).

**Waste Package Tip-Over**–The waste package is at rest on the ground in a vertical position and an external force (such as a seismic event) causes the waste package to tip over and impact the ground. A tip-over from an elevated surface is also considered (Mecham 2004 [DIRS 169790], Section 6.2.2.5).

**Waste Package Horizontal Drop**–The waste package is being lifted in a horizontal orientation at a height of 2.4 m (7.9 ft) when the lifting device inadvertently drops it. The waste package impacts the ground squarely on its side (Mecham 2004 [DIRS 169790], Section 6.2.2.5).

**Horizontal Drop with Emplacement Pallet**–The emplacement pallet with waste package is being lifted in a horizontal orientation when the lifting device inadvertently drops it. The emplacement pallet with waste package impacts the ground along its horizontal axis. This is also done as a horizontal drop onto the emplacement pallet. The emplacement pallet is the object considered that may puncture the waste package (Mecham 2004 [DIRS 169790], Section 6.2.2.5).

**Waste Package Corner Drop**–The waste package is being lifted in a vertical orientation at a height of 2.0 m (6.6 ft) when the lifting device inadvertently drops it. A corner of the waste package impacts the ground first (Mecham 2004 [DIRS 169790], Section 6.2.2.5).

**Waste Package 10-Degree Oblique Drop with Slap Down**–The waste package is being lifted in a horizontal orientation at a height of 2.4 m (7.9 ft) when the lifting device inadvertently releases one end. After the bottom end has rotated 10 degrees, the lifting device holding the top of the waste package fails and the entire waste package falls due to gravity and impacts the ground.

**Waste Package Swing Down**–The waste package is being lifted in a horizontal orientation at a height of 2.4 m when the lifting device inadvertently releases one end. One end of the waste package remains held by the lifting device while the other end swings down and impacts the ground (Mecham 2004 [DIRS 169790], Section 6.2.2.5).

**Waste Package Exposed to Vibratory Ground Motion**–The waste package is subjected to vibratory ground motion in the underground for a seismic evaluation for an annual frequency of exceedance of $5\times10^{-4}$ per year (Mecham 2004 [DIRS 169790], Section 6.2.2.6).

## 6.2 POSTCLOSURE

### 6.2.1 Structural

Functional Requirement Number: 3.1.1.2

Functional Requirement Title: Postclosure Confinement

Functional Requirement Text: The sealed waste package shall restrict the transport of radionuclides to the outside of the waste package boundary after repository closure (Table 13).

Table 13. Postclosure Confinement Performance Requirements

| Performance Requirement Number | Performance Requirement Text | Applicability |
|---|---|---|
| 1 | In conjunction with natural barriers and other engineered barriers, the sealed waste package shall limit transport of radionuclides in a manner sufficient to meet long-term repository performance requirements. | Yes |
| 2 | The waste package shall be designed and constructed to the codes and standards specified in Doraswamy 2004, [DIRS 169548], Section 5.1.1. | Yes |
| 3 | Normal operations and event load combinations are defined in Mecham 2004, [DIRS 169790], Section 6.2.2.<br><br>Note: The normal operations and credible event sequence load combinations are in Mecham 2004 [DIRS 169790], Section 6.2.2 and are not present in Doraswamy 2004 [DIRS 169548]. | Yes |

The accident condition from Section 6.2.2 of Mecham (2004 [DIRS 169790]) is the postclosure seismic event.

### 6.2.2 Thermal

Functional Requirement Number: 3.1.1.5

Functional Requirement Title: Postclosure Primary Performance

Functional Requirement Text: The waste package shall be designed so that, working in combination with natural barriers and other engineered barriers, the radiological exposures to the reasonably maximally exposed individuals are within the limits established through 10 CFR 63.113(b) [DIRS 158535], and the release of radionuclides into the accessible environments are within the limits established through 10 CFR 63.113(c) [DIRS 158535] (Table 14).

Table 14. Postclosure Primary Performance Requirements

| Performance Requirement Number | Performance Requirement Text | Applicability |
|---|---|---|
| 1 | The maximum waste package power at emplacement is 11.8 kW. | Yes |

Thermal requirements are the same for postclosure as for preclosure.

### 6.2.3 Criticality

Functional Requirement Number: 3.1.1.3

Functional Requirement Title: Criticality Control

Functional Requirement Text: The sealed waste package shall provide criticality control (Table 15).

Table 15. Criticality Control Performance Requirements

| Performance Requirement Number | Performance Requirement Text | Applicability |
|---|---|---|
| 1 | The methodology defined in the *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505]) shall be used to demonstrate acceptable criticality control for waste packages. | Yes |
| 2 | The waste package shall meet criteria 4.9.2.2.2 from Doraswamy 2004 [DIRS 169548], Section 4.9.2. | Yes |

*Project Requirements Document* (Canori and Leitner 2003 [DIRS 166275]) gives the requirements and rationale for waste package criticality. These are given in Section 3 of the document, PRD-013/T-016 and PRD-013/T-038. The methodology for waste package criticality analyses is provided in YMP 2003 [DIRS 165505].

# 7. SATISFACTION OF DESIGN REQUIREMENTS

## 7.1 PRECLOSURE

The waste package must satisfy defined performance specifications to protect the public and workers and to meet the performance objectives of a repository. An example of a performance specification is the ability of a waste package to withstand a tip-over event without breaching. Performance specifications are discussed in the following sections, where they are categorized by relevant engineering discipline (i.e., thermal, criticality, structural, and shielding). Detailed discussions of performance specifications are available in System Description Documents (e.g., BSC 2004 [DIRS 167273]).

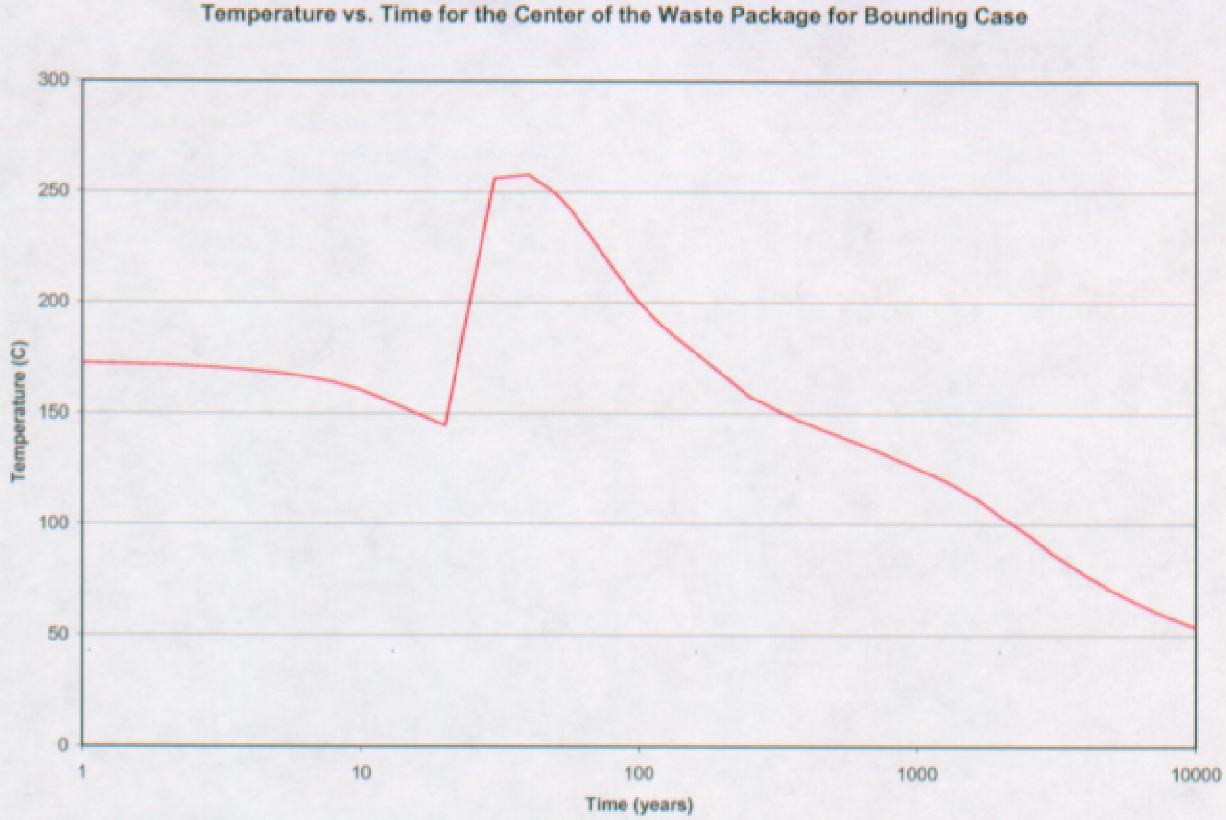
### 7.1.1 Normal Operations

#### 7.1.1.1 Thermal

The thermal calculations for normal operations are performed continuously through preclosure and postclosure times. During preclosure, peak temperatures are far below the limit due to the significant heat removal by the ventilation system. Highest temperatures occur a few decades after closure.

Two-dimensional, thermal calculations for a 5 DHLW/DOE SNF-Short waste package are reported in BSC (2003 [DIRS 166937], Section 6). A Fort Saint Vrain fuel assembly and five SRS short canisters are used as a reasonably bounding case due to the large number of possible canisters that may reside in the center of the waste package. The heat generation at emplacement for each canister is 699 watts and for the Fort Saint Vrain fuel is 776 watts giving a total heat for the waste package of 4270 watts. Fort Saint Vrain fuel has the highest heat for DOE fuel forms, and SRS canisters have the highest average canister heat load.

The temperature boundary conditions applied to the waste package outer surface for the two-dimensional calculations are taken from a three-dimensional (pillar) calculation of a representative drift segment (BSC 2003 [DIRS 164726], Section 6). Figure 2 shows the temperature at the center of the 5 DHLW/DOE SNF-Short waste package under nominal conditions.




Source: BSC 2003 [DIRS 166937], Figure 3.

Figure 2. Temperature vs. Time for the Center of the 5 DHLW/DOE SNF Waste Package

Temperatures were highest in the center but did not vary by more than about 20°C from the center to the outer surface of the waste package. The margin is about 100°C below the lower limit of 350°C. The margin below the glass transition temperature of 450-500°C is over 200°C. The breaching of a 21-PWR waste package producing 11.8 kW initial heat output, thereby replacing the helium fill gas with air, will result in about a 50°C difference in the pre-closure, and about a 20°C difference in the post-closure (see BSC 2004 [DIRS 166695], Figure 5).

Several conservative assumptions are used in the calculations, the peak waste package surface temperature using conduction only for a 21-PWR waste package (see BSC 2004 [DIRS 166695], Section 6) is about 230°C.

**Two-Dimensional Repository Calculations**

Numerous calculations have been performed with a two dimensional representation of the repository (see BSC 2004 [DIRS 166695]). These calculations use line heat loads and waste packages are considered as a continuous infinite cylindrical heat source. Such calculations can be performed rapidly and the numerous results are used to generate response surfaces, that is surfaces of constant peak waste package surface temperature as a function of waste package spacing, ventilation efficiency, and ventilation time. Different sets of response surfaces are generated for varied line heat loads. By holding all but one variable constant on a given response surface, operating curves can be generated which show the variation of waste package temperature due to variation in the remaining variable. The repository two-dimensional temperatures cannot be strictly applied to waste packages, but the change in temperature in a small locus of points provides the designer with a good method to determine the impact that changes in design has on waste package temperatures. Hence, the results of bounding calculations presented in this report can be used with the operating curves from BSC 2004 [DIRS 166695], Section 6 to estimate thermal margins resulting from design variations.

No thermal conditions for this waste package (in the transporter) sitting in the surface facility weld cell have been calculated, but they were calculated for the 21-PWR waste package, a more limiting case (BSC 2003 [DIRS 164075], Section 6). Most of the cases in this calculation were for a waste package in a shielded transporter, but one case had no transporter. These calculations show that without shielding, waste form temperatures near the center of the waste package remain below 350°C at all times, even if steady thermal conditions are achieved. If shielding is used, temperatures remain below 350°C for several days, but will eventually exceed this temperature. For this reason the duration waste packages with high heat loads can remain in a shielded transporter must be limited.

#### 7.1.1.2 Structural

##### 7.1.1.2.1 Lifting

The waste package must be able to be lifted using the twist-on trunnion collars for normal operations. The waste package is lifted by the top trunnion collar when in the vertical orientation and by both the top and bottom trunnion collars when in the horizontal orientation. Since the top trunnion collar lifts the entire waste package in the vertical orientation and the Naval SNF Long waste package has the greatest mass, this scenario was analyzed. The results of various waste package components at room temperature and 300°C are presented in Tables 16 and 17.

Table 16. Maximum Stress Intensities at Room Temperature

| | $\sigma_{int}$ (MPa) | $\sigma_y$ (MPa) | $\sigma_u$ (MPa) | $\sigma_{int}/\sigma_y$ | $\sigma_{int}/\sigma_u$ | 1/3 $\sigma_y$ | 1/5 $\sigma_u$ |
|---|---|---|---|---|---|---|---|
| Outer Corrosion Barrier | 56 | 310 | 689 | 0.18 | 0.08 | 103 | 138 |
| Trunnion Sleeve | 280 | 310 | 689 | 0.90 | 0.41 | 103 | 138 |
| Trunnion Sleeve Bottom Weld | 44 | 310 | 689 | 0.14 | 0.06 | 103 | 138 |
| Trunnion Collar | 320 | 1170 | 1310 | 0.27 | 0.24 | 390 | 262 |
| Trunnion | 158 | 1170 | 1310 | 0.14 | 0.12 | 390 | 262 |

Source: BSC 2003 [DIRS 166827], Table 6-3.

Table 17. Maximum Stress Intensities at 300°C

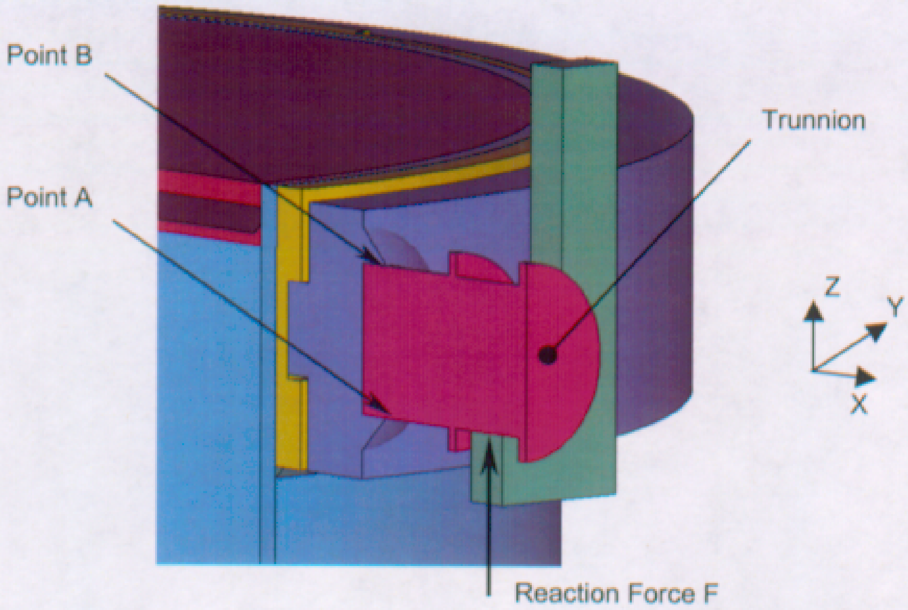
| | $\sigma_{Int}$ (MPa) | $\sigma_y$ (MPa) | $\sigma_u$ (MPa) | $\sigma_{Int}/\sigma_y$ | $\sigma_{Int}/\sigma_u$ | 1/3 $\sigma_y$ | 1/5 $\sigma_u$ |
|---|---|---|---|---|---|---|---|
| Outer Corrosion Barrier | 54 | 214 | 688 | 0.25 | 0.08 | 71 | 138 |
| Trunnion Sleeve | 360 | 214 | 688 | 1.68 | 0.52 | 71 | 138 |
| Trunnion Sleeve Bottom Weld | 44 | 214 | 688 | 0.21 | 0.06 | 71 | 138 |
| Trunnion Collar | 320 | 965 | 1100 | 0.33 | 0.29 | 322 | 220 |
| Trunnion | 156 | 965 | 1100 | 0.16 | 0.14 | 322 | 220 |

Source: BSC 2003 [DIRS 166827], Table 6-4.

Tables 16 and 17 show that the maximum stresses in the components of the waste package are less than 1/3 the yield strength and 1/5 the tensile strength (ANSI N 14.6-1993 [DIRS 102016], Section 4.2.1.1). However, the trunnion sleeve and the trunnion collar have maximum stress intensities above those limits. BSC (2003 [DIRS 166827], Section 6) shows the maximum stress in the trunnion sleeve is a localized contact stress between the trunnion sleeve and the trunnion collar. Furthermore, BSC (2003 [DIRS 166827], Section 6) shows that the stresses are far below the requirements in the surrounding areas and through the thickness of the engagement. In addition the trunnion collars and trunnion sleeve have rounded corners and chamfered corners that would alleviate stresses in the corners and edges.

The trunnion undergoes repeated bending stress from the engagement of the hooks. From Tables 15 and 16, the tensile stress at Point A cycles from zero to approximately 160 MPa. Since the trunnion collars are reusable and can be used either on the top end of the waste package or the bottom end of the waste package, Point A may cycle from zero to 160 MPa in tension or zero to 160 MPa in compression. Point B lies on the exact opposite surface of the direction of bending, the stress is the same, only it is in compression when Point A is in tension and in tension when Point A is in compression. Since fatigue failure occurs faster in tension-compression than in tension-tension (see Figure 10, ASM 1980 [DIRS 104317]), this is the most conservative application for this type of loading.

Therefore, Points A and B undergo cycles from 0 to 160 MPa. Meaning the mean stress is 80 MPa and the alternating stress is also 80 MPa.




Source: BSC 2003 [DIRS 166827], Figure 6-1.

Figure 3. Location of Stress on the Trunnion

From ASM (1980 [DIRS 104317], Figure 10) it is seen that the stress is approximately 7 times less than the fatigue limit for $10^7$ cycles. Although the yield and tensile strength of the material for this Constant-life diagram is slightly higher, considering the trunnion collar never undergoes $10^7$ cycles and its cycling is not constant, the design of the trunnion collar is adequately designed for any possible fatigue. Therefore the trunnion collars are appropriately designed for normal handling operations.

#### 7.1.1.2.2 Radial Thermal Expansion

The necessary radial gap due to elevated temperatures is explored in BSC (2001 [DIRS 152655]). The objective of this activity is to determine the tangential stresses of the outer corrosion barrier, due to uneven thermal expansion of the inner vessel and outer corrosion barriers of the current waste package design. The tangential stresses are significantly larger than the radial stresses associated with thermal expansion, and at the waste package outer surface the radial stresses are equal to zero. The scope of this activity is limited to determining the tangential stresses the waste package outer corrosion barrier is subject to due to the interference fit, produced by having two different shell coefficients of thermal expansions. The inner vessel has a greater coefficient of thermal expansion than the outer corrosion barrier, producing a pressure between the two shells. The temperature range for this calculation is 20°C to 239°C. Closed form solutions are used to obtain the results.

The outer corrosion barrier maximum tangential stresses at the outer and inner surfaces for a corresponding gap size are shown in Table 18 and Table 19.

Table 18. Outer Corrosion Barrier Maximum Tangential Stress at the Outer Surface

| | Maximum Tangential Stress at the Outer Surface, $\sigma_{os}$ (MPa) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Waste Package Type | Gap Size (mm) | | | | | | | | | | |
| | 0.0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 |
| 21-PWR | 140.9 | 122.1 | 103.2 | 84.4 | 65.6 | 46.8 | 27.9 | 9.1 | 0.0 | 0.0 | 0.0 |
| 44-BWR | 140.9 | 122.4 | 103.9 | 85.5 | 67.0 | 48.5 | 30.1 | 11.6 | 0.0 | 0.0 | 0.0 |
| 24-BWR | 141.3 | 117.4 | 93.5 | 69.6 | 45.8 | 21.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 12-PWR Long | 140.8 | 117.2 | 93.6 | 69.9 | 46.3 | 22.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 5 DHLW/DOE SNF Short | 131.4 | 117.9 | 104.4 | 90.9 | 77.4 | 63.9 | 50.4 | 36.9 | 23.4 | 9.9 | 0.0 |
| 2-MCO/2-DHLW | 130.9 | 115.0 | 99.2 | 83.4 | 67.5 | 51.7 | 35.8 | 20.0 | 4.2 | 0.0 | 0.0 |
| Naval SNF Long | 130.4 | 115.7 | 101.1 | 86.4 | 71.7 | 57.0 | 42.4 | 27.7 | 13.0 | 0.0 | 0.0 |

Source: BSC 2001 [DIRS 152655], Table 4.

Table 19. Outer Corrosion Barrier Maximum Tangential Stress at the Inner Surface

| | Maximum Tangential Stress at the Inner Surface, $\sigma_{is}$ (MPa) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Waste Package Type | Gap Size (mm) | | | | | | | | | | |
| | 0.0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 |
| 21-PWR | 144.6 | 125.3 | 106.0 | 86.6 | 67.3 | 48.0 | 28.7 | 9.4 | 0.0 | 0.0 | 0.0 |
| 44-BWR | 144.5 | 125.6 | 106.6 | 87.7 | 68.7 | 49.8 | 30.8 | 11.9 | 0.0 | 0.0 | 0.0 |
| 24-BWR | 146.1 | 121.4 | 96.7 | 72.0 | 47.3 | 22.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 12-PWR Long | 145.6 | 121.1 | 96.7 | 72.3 | 47.8 | 23.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 5 DHLW/DOE SNF - Short | 134.8 | 120.9 | 107.1 | 93.2 | 79.4 | 65.5 | 51.7 | 37.9 | 24.0 | 10.2 | 0.0 |
| 2-MCO/2-DHLW | 134.8 | 118.5 | 102.2 | 85.9 | 69.5 | 53.2 | 36.9 | 20.6 | 4.3 | 0.0 | 0.0 |
| Naval SNF Long | 134.1 | 119.0 | 103.9 | 88.8 | 73.7 | 58.6 | 43.5 | 28.5 | 13.4 | 0.0 | 0.0 |

Source: BSC 2003 [DIRS 152655], Table 5.

As a result of this calculation the minimum radial gap is determined to be 1.0 mm (0.04 in.).

#### 7.1.1.2.3 Axial Thermal Expansion

Four different potential waste package design configurations are evaluated in this document (BSC 2003 [DIRS 161691], Section 7): the 21-PWR, Naval SNF Long, 44-BWR, and 5 DHLW/DOE SNF Long. For each one of these potential waste package design configurations, a parametric study is performed to calculate the interference produced by the thermal expansion of the inner vessel and outer corrosion barrier to determine the required axial gap. Because the inner vessel undergoes a greater change in temperature and has a larger coefficient of thermal expansion as compared to those of the outer corrosion barrier, this interference is calculated as the inner vessel length minus the outer corrosion barrier cavity length subsequent to thermal expansion. The length of this interference is equal to the required axial gap created during fabrication (i.e., at room temperature and prior to fuel loading) to avoid contact between the inner vessel and outer corrosion barrier during thermal expansion. The maximum interference between the inner vessel and outer corrosion barrier produced from thermal expansion is equal to the minimum required waste package axial gap. These minimum axial gaps are presented in Table 20.

Table 20. Minimum Required Axial Gap Between the Inner Vessel and Outer Corrosion Barrier

| Waste Package Type | Maximum Interference (mm) | (in.) |
|---|---|---|
| 21-PWR | 8.1 | 0.32 |
| Naval SNF – Long | 7.6 | 0.30 |
| 44-BWR | 8.0 | 0.32 |
| 5 DHLW/DOE SNF- Long | 6.8 | 0.27 |

Source: BSC 2003 [DIRS 161691], Table 4.

Table 20 shows that the maximum interference occurs in the 21-PWR waste package and is 8.1 mm. For consistency amongst the waste package design configurations the minimum axial gap is determined to be 10.0 mm (0.39 in.).

#### 7.1.1.2.4 Internal Pressurization Due to Thermal Expansion

*Waste Package Outer Barrier Stress Due to Thermal Expansion with Various Barrier Gap Sizes* (BSC 2001 [DIRS 152655]) determines the resulting tangential (hoop) and longitudinal stresses in the outer corrosion barrier produced by an internal pressure increase due to elevated temperatures and a decreasing volume from thermal expansion. From BSC 2001 ([DIRS 152655], Tables 4 and 5) the required radial gap between the waste package inner vessel and outer corrosion barrier to avoid contact is 1 mm (0.04 in.). This calculation assumes that the waste package inner vessel and outer corrosion barrier have a 1-mm (0.04 in.) gap between them, and this gap collapses completely; consequently, the gas volume between the inner vessel and outer corrosion barrier decreases, increasing the internal pressure.

Table 21 provides the resulting gage pressure with respect to ambient pressure for each waste package. The results are summarized in Table 22 and the non-dimensional results in Table 23, comparing the tangential (hoop) and longitudinal stress to the yield stress (BSC 2003 [DIRS 167005], Section 6).

Table 21. Resulting Gage Pressure with Respect to Ambient Pressure

| Waste Package | Gage Pressure with Respect to Ambient, $p_{gage}$ (atm) | (KPa) | (psi) |
|---|---|---|---|
| 21-PWR | 2.65 | 268 | 38.9 |
| Naval SNF - Long | 2.24 | 227 | 32.9 |
| 44-BWR | 2.59 | 263 | 38.1 |
| 5 DHLW/DOE SNF - Long | 2.09 | 212 | 30.7 |

Source: BSC 2003 [DIRS 167005], Table 2.

Table 22. Calculation Results

| Waste Package | Tangential Stress, $\sigma_h$ | | Longitudinal Stress, $\sigma_l$ | |
|---|---|---|---|---|
| | (MPa) | (ksi) | (MPa) | (ksi) |
| 21-PWR | 10.2 | 1.48 | 5.12 | 0.742 |
| Naval SNF - Long | 10.3 | 1.50 | 5.17 | 0.750 |
| 44-BWR | 10.2 | 1.48 | 5.12 | 0.742 |
| 5 DHLW/DOE SNF - Long | 10.5 | 1.52 | 5.26 | 0.762 |

Source: BSC 2003 [DIRS 167005], Table 3.

Table 23. Non-Dimensional Results

| Waste Package | $\sigma_h/\sigma_y$ (%) | $\sigma_l/\sigma_y$ (%) |
|---|---|---|
| 21-PWR | 4.51 | 2.26 |
| Naval SNF - Long | 4.55 | 2.28 |
| 44-BWR | 4.51 | 2.25 |
| 5 DHLW/DOE SNF - Long | 4.63 | 2.32 |

Source: BSC 2003 [DIRS 167005], Table 4.

Based on the results of Table 23, the outer corrosion barrier is subjected to a stress that is less than 5 percent of its yield strength in the hoop direction and less than 3 percent in the axial direction.

#### 7.1.1.2.5 Static Weight on the Emplacement Pallet

*Static Waste Packages on Emplacement Pallet* (BSC 2002 [DIRS 165492]) reports static stresses for four waste packages resting on the emplacement pallet with three different variations in radial gap between the inner vessel and outer corrosion barrier, producing parametric results. This was done to create a solution that can be used for later modifications to the design. The radial gap sizes evaluated were 4 mm (0.16 in.), 10 mm (0.39 in.), and 15 mm (0.59 in.). The outer corrosion barrier thickness was reduced to conservatively show 10,000 years of corrosion degradation. Table 24 from BSC (2002 [DIRS 165492], Section 6) shows that the 5 DHLW/DOE SNF-Short is capable of sustaining its own weight when on the emplacement pallet.

Table 24. Maximum Stresses Intensities in Outer Corrosion Barrier

| Waste Package | 4 mm Radial Gap (MPa) | 10 mm Radial Gap (MPa) | 15 mm Radial Gap (MPa) |
|---|---|---|---|
| 21-PWR | 90 | 80 | 90 |
| 44-BWR | 86 | 80 | 116 |
| Naval Long | 74 | 84 | 76 |
| 5 DHLW/DOE SNF-Short | 20 | 42 | 52 |

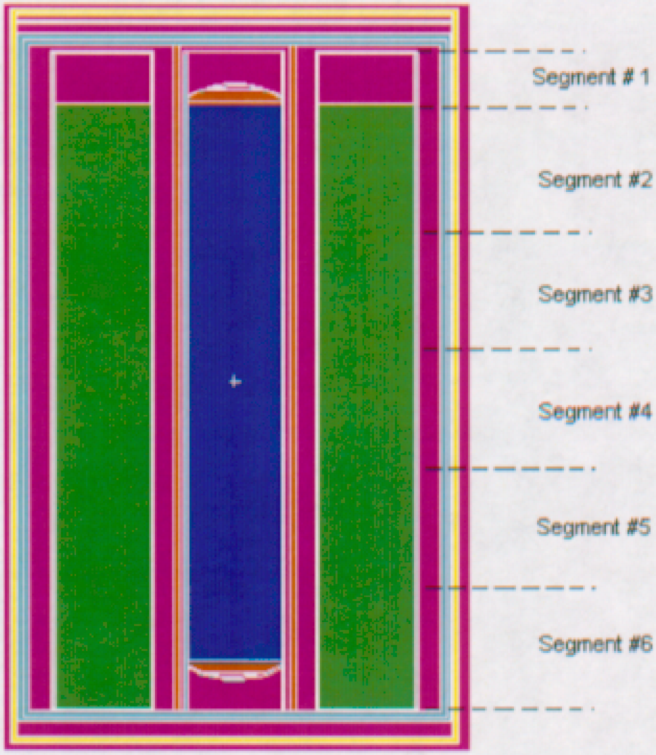
Source: BSC 2003 [DIRS 165492], Table 6-2.

The stresses reported are less than the yield stress of Alloy 22 (UNS N06022). The results indicate significant margin to failure for a range of gap sizes. The yield stress of Alloy 22 (UNS N06022) may be found in Table 3 of this document. Therefore, the waste package is able to withstand the stresses of its own weight even after 10,000 years of degradation. Since this is a bounding case, the results show that the non-degraded waste package is also capable of withstanding the stresses of its own weight.

### 7.1.1.3 Shielding

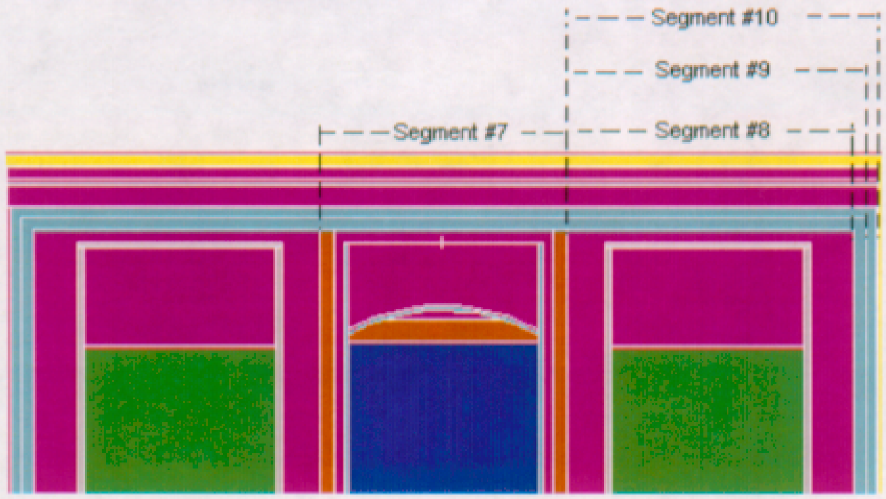
Shielding analyses evaluate the effects of ionizing radiation on personnel, equipment, and materials. The primary sources for waste package radiation are gamma rays and neutrons emitted from SNF and HLW. Loading, handling, and transporting of waste packages would be carried out remotely to keep personnel exposure as low as reasonably achievable (e.g., having the human operators behind radiation shield walls, using remote manipulators, viewing operations with video cameras). The general shielding requirements are stated in Section 4.9.1 of Doraswamy (2004 [DIRS 169548]).

In *Dose Rate Calculation for 5 DHLW/DOE SNF Short Waste Package* (BSC 2003 [DIRS 166210], Section 6), MCNP is used to estimate particle crossings over the surfaces of interest to determine the particle flux. Therefore, the external radial and axial surfaces of the waste package are divided into surface segments. The average dose rate over each segment area is tabulated to examine the spatial distribution of the dose rate. Figures 4, 5, and 6 illustrate the radial, axial, and angular segments, respectively, used in this dose rate calculation.




NOTE: Figure not to scale.
Source: BSC 2003 [DIRS 166210], Figure 4

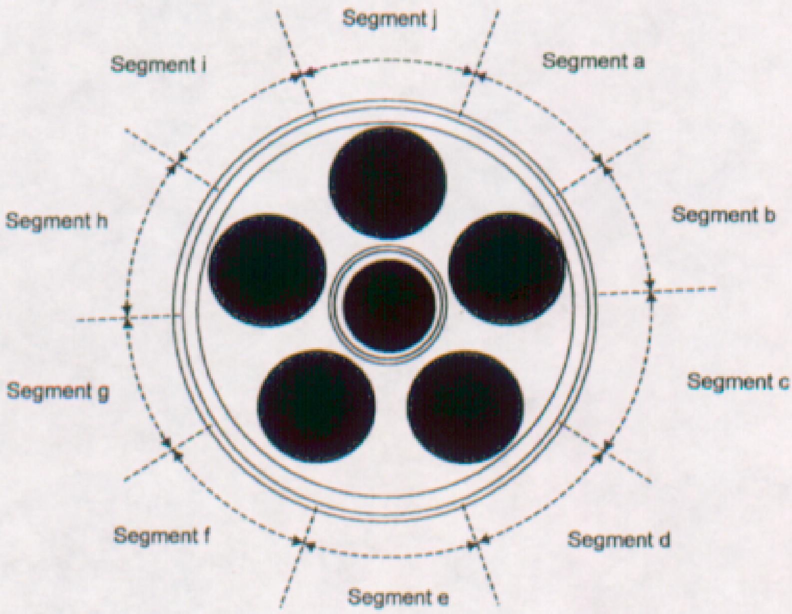
Figure 4. Waste Package Radial Surfaces Segments used in Dose Rate Calculation




NOTE: Figure not to scale.

Source: BSC 2003 [DIRS 166210], Figure 5.

Figure 5. Waste Package Axial Surfaces Segments used in Dose Rate Calculation




Source: BSC 2003 [DIRS 166210], Figure 6.

Figure 6. Angular Segments of Waste Package Outer Radial Surface used in Dose Rate Calculations

The results of the dose rate calculations from BSC (2003 [DIRS 166210]) are presented in Appendix A and lead to the following conclusions:

Dose rates, including gamma and neutron contributions, have been calculated inside the waste package, on the external surface of the waste package, and at various distances away from the waste package.

A maximum of 74.91 rem/hr (Table 52) at the external radial surface of the waste package occurs at the shadowed axial segment # 4. The dose rates on the waste package bottom and top surfaces, seen in Table 56, are 43.86 rem/hr (Segment 10) and 22.93 rem/hr (Segment 7), respectively.

The waste package radial surface dose rates features a slight angular variation, with a value of 77.10 rem/hr (Table 58) on segments next to the DHLW canisters and a value of 74.09 rem/hr (Table 57) on segments next to the gaps between canisters. The waste package radial dose rates are also characterized by a small variation along the axial direction. Thus, the average waste package exterior surface dose rates vary from a maximum of 74.91 rem/hr (Segment 4) to a minimum of 64.17 rem/hr (Segment 6) across the height of the DHLW glass canisters, as seen in Table 52. At the location of the maximum and minimum surface dose rate, the DHLW glass canisters fractional dose is 66.23 rem/hr and 59.30 rem/hr, respectively (Table 53).

The waste package radial shells reduce the maximum dose rate values from 7521.97 to 74.91 rem/hr, the top shells reduce the dose rate values from 1358.87 to 22.93 rem/hr, and the bottom shells reduce the dose rate values from 6162.58 to 41.97 rem/hr.

The neutron component is negligible as compared with the photon component of the total dose rates.

#### 7.1.1.4 Waste Form Accommodation

Sections 10 through 13 of DOE (2002 [DIRS 158398]) give the minimum dimensions of the waste package cavity that are to be used to accommodate the SNF fuels. The dimensions of the fuels from BSC (2004 [DIRS 167273], Table 1 and Table 5) are provided in Table 9 and Table 12. Accommodation of these dimensions may be verified against Table 25 and the configuration drawings listed in Section 5.2.

Table 25. HLW/DOE Waste Package Dimensions

| Waste Package | Nominal Diameter | Nominal Length | Loaded Weight |
|---|---|---|---|
| 5 DHLW/DOE SNF-Short | 83.70 in.<br>(2126.0 mm) | 135.94 in.<br>(3,452.8 mm) | 79,600 lb<br>(36,100 kg) |
| 5 DHLW/DOE SNF-Long | 83.70 in.<br>(2126.0 mm) | 199.19 in.<br>(5,059.4 mm) | 117,000 lb<br>(53,100 kg) |
| 2-MCO/2-DHLW | 72.08 in.<br>(1830.7 mm) | 199.19 in.<br>(5,059.4 mm) | 104,00 lb<br>(47,200 kg) |

#### 7.1.1.5 Criticality

In general, the amount of DOE SNF allowed per canister is a function of the physical size and weight limitations of the canister. The limitation on the amount of fissile material per canister provides criticality control. However, insoluble neutron absorbers (gadolinium compounds and alloys) are required for criticality control within the canister for some DOE SNF groups. To date, several items have been identified as important to criticality (DOE 2002 [DIRS 158405], Section 5.2). The performance and distribution of the neutron absorber material is important in preventing criticality.

The canister shell is also important in preventing criticality because it initially confines the fissile elements and neutron absorber material so they cannot be separated. The canister baskets developed for the representative fuel types are particularly important in cases where they provide the distribution mechanism for neutron absorber material.

Preclosure safety assessments for waste package criticality event sequences are not completed at this time. These evaluations are expected to demonstrate compliance with the preclosure requirements listed in Section 6.1.1.5.

### 7.1.2 Event Sequences

#### 7.1.2.1 Thermal

Conditions used in fire calculations *Thermal Response of the 5-DHLW/DOE SNF Short Waste Package to Hypothetical Fire Accident* (BSC 2003 [DIRS 164998], Section 5) represented a parametric range up to and including the full transportation fire (800°C for 30 minutes), even though this fire is expected to be much more severe than the event sequence fire. A very conservative heat rate for DOE SNF is used based on 111 Triga fuel elements only one year after reactor discharge and using a peaking factor of 1.25 for a total of 2077 watts in the center waste package position. The heat generation at emplacement for each of the five glass canisters is 699 watts, for a total waste package heat of 5570 watts. The total heat generation used for the fire calculations is 30 percent higher than that used in reasonably bounding calculation for normal operations.

Fire calculations for the 5 DHLW/DOE SNF waste package include seventeen cases (BSC 2003 [DIRS 164998], Section 6). The distinguishing features of these cases are shown in Table 26. The emissivity of the surroundings was 1.0. A nominal heat transfer coefficient, h, was used for natural convection around a horizontal cylinder during the fire but no convection was allowed during the initial and post-fire conditions. Table 27 summarizes the calculated peak temperature of the waste package components for each case. The effect of gaps, higher heat rates, increased convection were investigated along with fire temperature and duration.

The results of the fire calculations show that for all cases, even for the full transportation fire, all waste form temperatures are below the glass transition temperature of 450-500°C (Canori and Leitner 2003 [DIRS 166275], Appendix A). The lowest margin is 5°C and the margin for 10 minute fires is at least 25°C. Including a gap either at the stainless steel inner vessel or at the canister interface lowers peak temperatures by about 100°C.

Table 26. Case Description for Fire Calculations

| Case No. | Model Type | Fire Temp (°C) | Fire Duration (min) | DOE/DHLW Canisters Thermal Load (Watts) | Solar Energy Absorption Rate (cal/cm$^2$) | Natural Convection During Fire | Emissivity of Waste Package Outer Surface (normal conditions) |
|---|---|---|---|---|---|---|---|
| Base | No Gap | 800 | 30 | 2077 / 699.39 | 400 | h | 0.87 |
| GapMax | SRS Can to Inner Waste Package Gap | 800 | 30 | 2077 / 699.39 | 400 | h | 0.87 |
| RadGap | Radial Gap Between Shells | 800 | 30 | 2077 / 699.39 | 400 | h | 0.87 |
| 1 | No Gap | 800 | 30 | 2492.4 / 699.39 | 400 | | 0.87 |
| 2 | No Gap | 800 | 30 | 2077 / 1049.085 | 400 | h | 0.87 |
| 3 | No Gap | 800 | 30 | 2077 / 699.39 | 400 | h | 0.783 |
| 4 | No Gap | 800 | 30 | 2077 / 699.39 | 640 | h | 0.87 |
| 5 | No Gap | 800 | 30 | 2077 / 699.39 | 400 | 1.2 h | 0.87 |
| 6 | No Gap | 800 | 35 | 2077 / 699.39 | 400 | h | 0.87 |
| 7 | No Gap | 700 | 30 | 2077 / 699.39 | 400 | h | 0.87 |
| 8 | No Gap | 600 | 30 | 2077 / 699.39 | 400 | h | 0.87 |
| 9 | No Gap | 800 | 20 | 2077 / 699.39 | 400 | h | 0.87 |
| 10 | No Gap | 700 | 20 | 2077 / 699.39 | 400 | h | 0.87 |
| 11 | No Gap | 600 | 20 | 2077 / 699.39 | 400 | h | 0.87 |
| 12 | No Gap | 800 | 10 | 2077 / 699.39 | 400 | h | 0.87 |
| 13 | No Gap | 700 | 10 | 2077 / 699.39 | 400 | h | 0.87 |
| 14 | No Gap | 600 | 10 | 2077 / 699.39 | 400 | h | 0.87 |

Source: BSC 2003 [DIRS 164998], Table 6-1.

Table 27. Calculated Peak Temperatures for Fire Calculations

| Case No. | Peak Temperature of Component (°C) | | | | | |
|---|---|---|---|---|---|---|
| | SRS Glass | SRS Canister | Support Tube | Waste Package Angles and Divider Plates | Inner Vessel | Outer Corrosion barrier |
| Base | 401.8 | 408.5 | 245.5 | 374.4 | 502.0 | 558.1 |
| GapMax | 302.8 | 304.1 | 254.8 | 382.4 | 502.5 | 558.5 |
| RadGap | 289.5 | 292.1 | 257.0 | 283.0 | 330.6 | 688.1 |
| 1 | 403.3 | 410.0 | 256.9 | 376.5 | 503.1 | 559.0 |
| 2 | 410.1 | 416.7 | 269.0 | 383.4 | 507.1 | 562.3 |
| 3 | 407.0 | 413.5 | 252.2 | 379.7 | 505.7 | 561.2 |
| 4 | 414.6 | 421.2 | 258.8 | 386.8 | 512.9 | 567.3 |
| 5 | 403.9 | 410.7 | 245.7 | 376.3 | 504.7 | 560.7 |
| 6 | 437.4 | 444.2 | 249.1 | 405.9 | 541.4 | 590.7 |
| 7 | 323.9 | 328.9 | 238.1 | 306.8 | 397.7 | 445.0 |
| 8 | 261.2 | 264.6 | 231.8 | 252.1 | 312.1 | 349.0 |
| 9 | 321.7 | 327.1 | 237.7 | 304.1 | 406.8 | 479.7 |
| 10 | 264.8 | 268.7 | 232.0 | 254.8 | 325.3 | 383.3 |
| 11 | 222.4 | 222.1 | 227.3 | 226.2 | 260.3 | 303.6 |
| 12 | 223.6 | 223.2 | 228.4 | 227.3 | 289.1 | 382.8 |
| 13 | 219.9 | 219.7 | 225.0 | 223.9 | 239.5 | 310.2 |
| 14 | 217.0 | 216.9 | 222.4 | 221.3 | 201.4 | 251.7 |

Source: BSC 2003 [DIRS 164998], Table 6-2.

Table 27 shows that the maximum temperature during the fire accident is below 570°C. Therefore, the applicable criterion is met.

### 7.1.2.2 Structural

The preclosure safety analysis considers the probability of potential hazards, taking into account the range of uncertainty associated with the data that support probability calculations. Event sequences are defined (Mecham 2004 [DIRS 169790]) (Section 5.2.8 and Section 6.1.2.2) and these sequences of human-induced and natural events are used as inputs to calculate the consequences of potential failures of structures, systems, and components in terms of worker safety and dose to workers and the public during the preclosure period of a repository at Yucca Mountain.

The waste package is a component identified as important to safety (BSC 2003 [DIRS 165179], Table A-2, p. A-3) since it provides containment for the waste forms. The waste package is credited to prevent a release, in terms of dose to workers and the public during the preclosure period. Therefore, the waste package is designed to a set of criteria to ensure that the waste package does not breach as a result of credible event sequences.

The waste package design is evaluated using a finite element analysis based on numerical simulations of waste package dynamic events including, but not limited to, vertical and horizontal drops, slap downs, drops onto objects, collisions, and equipment drops onto the waste package.

The failure criterion used is explained in detail in Section 7.1.2.3.1.2 and is broken into a tiered screening criteria shown below. The easiest to apply and most conservative criteria are applied initially. If these can not be met, less conservative screening criteria are imposed that require more calculations. These screening criteria in decreasing order of conservatism are (an element's total stress intensity is equal to twice the element's maximum shear stress (ASME 2001 [DIRS 158115], Section III, Division 1, NB-3000)):

| | |
|---|---|
| Maximum $\sigma_{int} < 0.7\sigma_u$? | Yes: Meets $P_m$ and $P_L$ limits without the need for wall averaging. |
| No:<br>Maximum $\sigma_{int} < 0.77\sigma_u$? | Yes: Meets $P_L$ limit without the need for wall averaging but the stress field must not be uniform around the entire circumference (only a concern for vertical drop events). |
| No:<br>Maximum wall-averaged $\sigma_{int} < 0.7\ \sigma_u$ ? | Yes: Meets $P_m$ and $P_L$ limits. |
| No:<br>Maximum wall-averaged $\sigma_{int} < 0.77\sigma_u$ ? | Yes: Meets $P_L$ limit if the stress fields are not uniform around the entire circumference (only a concern for vertical drop events). |
| No:<br>Maximum wall-averaged $\sigma_{int} < 0.84\ \sigma_u$<br><u>and</u><br>wall-averaged $\sigma_{int} < 0.77\ \sigma_u$ at $\sqrt{R \cdot t}$<br>surrounding maximum location? | Yes: Meets $P_L$ and average primary shear limit |
| No:<br>Maximum wall-averaged $\sigma_{int} < 0.9\ \sigma_u$<br><u>and</u><br>wall-averaged $\sigma_{int} < 0.77\ \sigma_u$ at $\sqrt{R \cdot t}$<br>surrounding maximum location?<br><u>and</u><br>wall-average of each shear stress on the stress classification line<br>($\tau_{xy}$, $\tau_{yz}$ and $\tau_{xz}$) $< 0.42\sigma_u$ ?<br>(x,y,z are element (not global) directions orthogonal to the SCL) | Yes: Meets $P_L$ and average primary shear limit |

No: Fails simplified screening criterion.

If the wall-averaged $\sigma_{int}$ limits can not be met, perform a less conservative rigorous Code evaluation using all six stress components (and solve a cubic equation for principle stress direction values) and/or use multiple stress classification lines to extrapolate to governing wall locations when they have significant non-membrane primary stress intensity contributions.

If the average primary shear limit can not be met, then review appropriateness of using a stress classification plane rather than an stress classification line.

#### 7.1.2.2.1 Preclosure Rock Fall Evaluations

Rock falls may occur both in the preclosure and postclosure periods. For the preclosure period, the drip shields have not yet been emplaced, so rocks may fall onto the emplaced waste packages. Four waste package configurations, including the 5 DHLW/DOE SNF-Short waste package, are investigated to determine their structural response to rock fall dynamic loads (Mecham 2004 [DIRS 169790], Section 6.2.2.4).

*Rock Fall on Waste Packages* (BSC 2004 [DIRS 167182]) determined the response of the waste package components to multiple rock falls onto the same location. For this purpose, a representative 21-PWR waste package configuration is selected and the bottom end of the waste package is impacted by two identical rocks (3.0 MT, 5.9 m/s). Since the geometry of all waste packages are essentially the same except for their diameters and lengths, the results of this case are applicable to other waste package configurations.

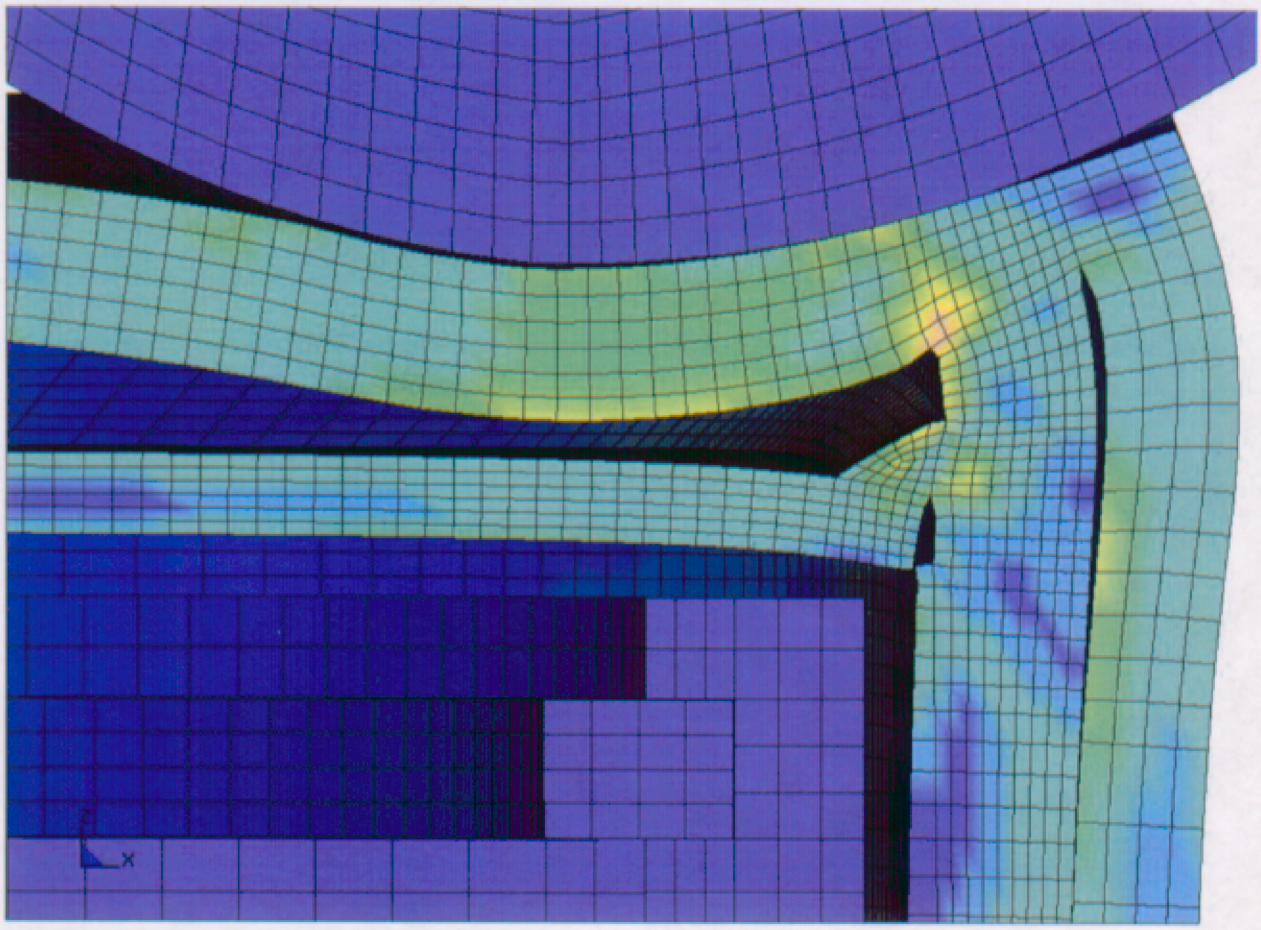
Postclosure rock fall without a Drip Shield is more critical since the waste package may corrode over time. Therefore the rock fall on the waste package is simulated using a reduced thickness of the outer corrosion barrier and the results are bounding for preclosure rock fall (see Section 7.2.1.2). For the simulation of the rock fall onto a corroded waste package, the thickness of each Alloy 22 (UNS N06022) component is appropriately reduced based on the calculation of the depth of the corroded layer (BSC 2004 [DIRS 167182], Section 6).

The results of the rock fall evaluations indicate that for all rock impact simulations, the maximum stress intensity in the outer corrosion barrier and outer lids is less than 70 percent of the tensile strength of Alloy 22 (UNS N06022) at maximum temperatures, during their presence in the repository (BSC 2004 [DIRS 167182], Section 6). Therefore, no breach of the waste package is expected from preclosure rock fall (see Section 7.1.2.2).

#### 7.1.2.2.2 Object Drop on 5 DHLW/DOE SNF Short Waste Package

The Object Drop (Section 6.1.2.2) consists of raising a hook that is used to lift the waste package directly above a vertically standing waste package. The hook is raised to a maximum height of 9.1 m (30 ft), after which the lifting device, with the hook attached, fails and the hook falls due to gravity. The hook then impacts the waste package top surface. The simulation is performed using LS-DYNA finite element software. The simulation is performed at room temperature and 300°C to bound potential waste package operational temperatures. The results (BSC 2003 [DIRS 166829], Section 6) presented in this subsection are obtained by using the maximum hook elevation of 9.1 m (30 ft) and a hook mass of 907 kg (2,000 lb.) (BSC 2003 [DIRS 164128], Assumption 5.3.41):

Figure 7 outlines the shape of the impact region at the end of simulation at room temperature. It is also important to notice that the middle lid remains to be directly supported by the outer corrosion barrier. Consequently, there is no contact between the middle lid and the inner vessel.




Source: BSC 2003 [DIRS 166829], Figure 9.

Figure 7. Detail of End of Simulation at 300°C

It is important to emphasize that there are no contacts between the Alloy 22 (UNS N06022) and stainless steel type 316 waste package components. (It can be verified by examination of the contact force time history that there is no contact between the middle lid and the inner lid lifting feature, or the middle lid and the inner lid.) The negligibly small maximum stresses recorded in the inner vessel and the inner lid are numerical side effects coming from the mutual contact among the components of the inner vessel assembly (i.e., the inner vessel, the inner lid, and the spread ring) due to gravity. These contacts are non-physical and should be disregarded as such. It can be concluded, therefore, that the inner vessel remains exactly as it was prior to the impact.

#### 7.1.2.2.3 Pressurized System Missile Impact on Waste Package

Four different waste package design configurations are evaluated in *Pressurized System Missile Impact on Waste Packages* (CRWMS M&O 2000 [DIRS 149351], Section 6): 21-PWR, 44-

BWR, 5 DHLW/DOE SNF-Short, and Naval SNF Long waste packages. For each one of these waste package design configurations, a parametric study is performed by reporting the results for different missile diameter, mass, and velocities. These parameters are given in Table 28.

Table 28. Missile Impact Parameters for Three Different Case Studies

| | Case 1 | Case 2 | Case 3 |
|---|---|---|---|
| Missile diameter | 10 mm | 20 mm | 30 mm |
| Missile mass | 0.5 kg | 1.0 kg | 1.5 kg |
| Missile velocity | 5.7 m/s | 6.0 m/s | 6.3 m/s |

Source: CRWMS M&O 2000 [DIRS 149351], Table 5.2-1.

The effect of dynamic impact on the waste package outer barrier is determined using the empirical relations developed for perforation of plates by a rigid mass. The literature on dynamic impact analyses shows that various empirical equations have been developed for the perforation of ductile metal plates (specifically, mild steel plates). The waste package outer barrier has circular geometry after the plates are rolled into cylinders; however, the effect of the outer barrier curvature is small considering the missile diameter, the radius of curvature of the waste package outer barrier, and the outer barrier thickness. Therefore, the empirical relations of flat plates are used for the purpose of evaluating the missile impact problem.

The perforation of a plate by a projectile involves a complex mechanism of impact and subsequent failure if the projectile has a large amount of kinetic energy. Thus, there is no complete theoretical model that incorporates all of the relevant phenomena and that is capable of predicting accurately all of the aspects of an impact perforation event. However, there are some empirical equations developed for the low-velocity impact analysis. One of these relations used widely in design is the Ballistics Research Laboratory equation (Jones 1994 [DIRS 137700], p. 53). No limitations are associated with this equation in terms of the missile velocity range or the ratio of the target span to the missile diameter. Hence, the use of the Ballistics Research Laboratory equation is more general compared to other equations provided. A second reason for using the Ballistics Research Laboratory equation is that this equation gives reasonable agreement with the experimental results.

The structural response of the waste package to dynamic impact of a pressurized system missile is reported in terms of the minimum velocities required for a pressurized system missile to cause perforation of the waste package barriers. The calculation results are summarized in Table 29.

Table 29. Pressurized System Missile Impact Results for Different Waste Packages

| Waste Package | Minimum required velocity of projectile to cause perforation (m/s) | | |
|---|---|---|---|
| | Case1 | Case 2 | Case 3 |
| 21-PWR | 322 | 383 | 424 |
| 44-BWR | 322 | 383 | 424 |
| 5 DHLW/DOE SNF - Short | 339 | 403 | 446 |
| Naval SNF | 339 | 403 | 446 |

Source: CRWMS M&O 2000 [DIRS 149351], Table 6-1.

#### 7.1.2.2.4 Vertical Drop of 5 DHLW/DOE SNF Short Waste Package

The vertical drop consists of raising the waste package vertically to a maximum height of 2.0 m (6.6 ft) (see Mecham 2004 [DIRS 169790], Section 5.2.8), after which the lifting device carrying the waste package fails and the waste package falls due to gravity. The waste package then impacts an unyielding surface. The simulation is performed using LS-DYNA finite element software. The simulation is performed at room temperature, 100°C, and 300°C to bound potential waste package operational temperatures. The results for the vertical drop of the 5 DHLW/DOE SNF-Short codisposal waste package are shown in Table 30, which is taken from *Vertical Drop of 5-DHLW/DOE SNF Short Waste Package with Trunnion Collars Design Calculation* (BSC 2003 [DIRS 166184], Section 6, Table 5). $\sigma_{int}/\sigma_u$ represents the ratio of the stress intensity ($\sigma_{int}$) and the true tensile strength (presented in Table 3), at room temperature and 100°C.

Table 30. Maximum Stress Intensities in the Outer Corrosion Barrier

| Temperature (°C) | $\sigma_{int}$ (MPa) | $\sigma_{int}/\sigma_u$ | Location |
|---|---|---|---|
| RT | 878 | 0.90 | At bottom weld to lower trunnion sleeve |
| 100 | 834 | 0.85 | At bottom weld to lower trunnion sleeve |
| 300 | 743 | 0.82 | At bottom weld to lower trunnion sleeve |

NOTE: RT = room temperature.
Source: BSC 2003 [DIRS 166184], Table 5.

Table 30 shows that the maximum stress intensities in the outer corrosion barrier exceeds seven-tenths of the true tensile strength of Alloy 22 (UNS N06022) and for the room temperature case is right at nine-tenths of the true tensile strength of Alloy 22 (UNS N06022). To verify this maximum stress intensity does not cause a failure in the outer corrosion barrier requires a more detailed investigation into the source of the stress (see Section 7.1.2.2).

The wall-average of the element total stress intensity on a line of elements through the outer corrosion barrier wall just below the lower trunnion sleeve's upper weld is used. A ratio of this wall-averaged stress intensity is compared to the true tensile strength. Table 31 contains the wall-averaged total $\sigma_{int}$ of the outer corrosion barrier and their ratios to $\sigma_u$ (BSC 2004 [DIRS 167035], Section 6, Table 2).

Table 31. Maximum Wall-Averaged Stress Intensities in the Outer Corrosion Barrier

| Temperature (°C) | Wall-Averaged $\sigma_{int}$ (MPa) | Wall-Averaged $\sigma_{int}/\sigma_u$ |
|---|---|---|
| RT | 370 | 0.38 |
| 100 | 335 | 0.34 |
| 300 | 275 | 0.30 |

NOTE: RT = room temperature.
Source: BSC 2004 [DIRS 167035], Table 2.

From Table 31, the wall-averaged stress intensity in the outer corrosion barrier is well below seven-tenths of the true tensile strength of Alloy 22 (UNS N06022). Therefore, the waste package meets the plastic analysis criteria and no breach of the waste package is expected (see Section 7.1.2.2).

#### 7.1.2.2.5 5 DHLW/DOE - Short Tip Over from Elevated Surface

The tip-over from an elevated surface consists of raising the waste package vertically to a maximum height of 1.52 m (5 ft) (see BSC 2002 [DIRS 161083], Section 5.3), after which the waste package tips about its bottom edge possibly due to seismic occurrences to the point at which the center of gravity is directly above the rotation point. The waste package then continues to tip over due to gravity. The waste package then impacts an unyielding surface with the top edge. The simulation is performed using LS-DYNA finite element software. The simulation is performed at room temperature and 100°C to bound potential waste package operational temperatures. The results for the tip-over from an elevated surface of the 5 DHLW/DOE SNF-Short codisposal waste package are shown in Table 32, which is taken from *5-DHLW/DOE Short Tip Over from Elevated Surface* (BSC 2002 [DIRS 161083], Section 6, Table 6-2).

Table 32. Maximum Stress Intensities in the Outer Corrosion Barrier and Inner Vessel Components

| Part | Temperature (°C) | $\sigma_{int}$ (MPa) | $\sigma_{int} / \sigma_u$ |
|---|---|---|---|
| Inner Vessel | RT | 339 | 0.48 |
| Inner Vessel Upper Lid | | 318 | 0.45 |
| Outer Corrosion Barrier | | 600 | 0.62 |
| Spread Ring | | 239 | 0.34 |
| Inner Vessel | 100 | 323 | 0.49 |
| Inner Vessel Upper Lid | | 299 | 0.45 |
| Outer Barrier | | 604 | 0.62 |
| Spread Ring | | 222 | 0.33 |

NOTE: RT = room temperature.
Source: BSC 2002 [DIRS 161083], Table 6-2.

The previous table shows that for each temperature condition, the maximum stress intensities in the outer corrosion barrier, the inner vessel and lids, and the spread ring did not exceed seven-tenths of the true tensile strength of Alloy 22 (UNS N06022) and stainless steel type 316. Therefore, the waste package meets the plastic analysis criteria and no breach of the waste package is expected (see Section 7.1.2.2). The elevated height in this case results in a higher potential energy and therefore is bounding for a tip over with slap down.

#### 7.1.2.2.6 5 DHLW/DOE SNF- Short Horizontal Drop

The horizontal drop consists of raising the waste package horizontally to a maximum height of 2.4 m (7.9 ft.) (see Mecham 2004 [DIRS 169790], Section 5.2.8). The lifting device carrying the waste package then fails and the waste package falls due to gravity. The waste package then impacts an unyielding surface. The simulation is performed using LS-DYNA finite element software. The simulation is performed at room temperature and 300°C to bound potential waste package operational temperatures. The results for the horizontal drop of the 5 DHLW/DOE SNF-Short codisposal waste package are shown in Table 33, *Horizontal Drop of the 5 DHLW/DOE SNF - Short Waste Package* (BSC 2003 [DIRS 167755], Section 6, Table 4).

Table 33. Maximum Stress Intensities

| Temperature | Inner Vessel and Lids (MPa) | Outer Corrosion Barrier and Lids (MPa) |
|---|---|---|
| RT | 574 | 810 |
| 300°C | 522 | 629 |

NOTE: RT = room temperature.
Source: BSC 2004 [DIRS 167755], Table 4.

The same results are presented in Table 34 as ratios of the stress intensity (presented in Table 34) and the true tensile strengths (presented in Table 3) at the temperatures of interest.

Table 34. Ratio of Maximum Stress Intensity and True Tensile Strength

| Temperature | Inner Vessel and Lids | Outer Corrosion Barrier and Lids |
|---|---|---|
| RT | 0.82 | 0.83 |
| 300°C | 0.84 | 0.69 |

NOTE: RT = room temperature.
Source: BSC 2004 [DIRS 167755], Table 5.

The above table shows that for each temperature condition, the maximum stress intensities are greater than seven-tenths of the true tensile strength of the corresponding material, except for the 300°C case. The outer corrosion barrier and lids meet the seven-tenths criteria for the 300°C case. To verify this maximum stress intensity does not cause a failure in the outer corrosion barrier and inner vessel requires a more detailed investigation into the source of the stress (see Section 7.1.2.2).

The locations of highest stress are examined and the wall-average of the stress intensity on a line of elements through the outer corrosion barrier and inner vessel are reported (see Table 35). The location of highest stress in the room temperature condition is different than that of the 300°C case. Therefore the locations of the wall-averaged stress intensity are denoted as wall section 1 and wall section 2. A ratio of this wall-averaged stress intensity is compared to the true tensile strength.

Table 35. Outer Corrosion Barrier Maximum Average Stress Intensity

| Temperature | Section | Wall-Averaged $\sigma_{int}$ (MPa) | Wall-Averaged $\sigma_{int}/\sigma_u$ |
|---|---|---|---|
| RT | Wall Section 1 | 742 | 0.76 |
| 300 °C | Wall Section 2 | 553 | 0.61 |

NOTE: RT = room temperature.
Source: BSC 2004 [DIRS 167755], Table 7.

The locations of highest stress intensity in the inner vessel was found to be at the corner of the bottom lid and inner vessel wall in both temperature conditions. Since it is highly unlikely that a crack will propagate diagonally through a corner, two adjacent wall sections are used for wall averaging. Wall section 1 is through the inner vessel bottom lid at the lid/wall junction and the wall section 2 is through the inner vessel wall at the lid/wall junction. The wall averaged stress intensities and ratio of this wall-averaged stress intensity compared to the true tensile strength is shown in Table 36.

Table 36. Inner Vessel Maximum Average Stress Intensity

| Temperature | Section | Wall-Averaged $\sigma_{int}$ (MPa) | Wall-Averaged $\sigma_{int}/\sigma_u$ |
|---|---|---|---|
| RT | Wall Section 1 | 319 | 0.45 |
| RT | Wall Section 2 | 269 | 0.38 |
| 300°C | Wall Section 1 | 305 | 0.49 |
| 300°C | Wall Section 2 | 220 | 0.36 |

NOTE: RT = room temperature.
Source: BSC 2004 [DIRS 167755], Table 8.

Tables 35 and 36 show that for each temperature condition, the maximum wall-averaged stress intensities in the outer corrosion barrier and the inner vessel and lids did not exceed 77 percent of the true tensile strength of Alloy 22 (UNS N06022) and stainless steel type 316, and the stress does not extend uniformly around the full circumference of the waste package. Therefore, the waste package meets the plastic analysis criteria and no breach of the waste package is expected (see Section 7.1.2.2).

#### 7.1.2.2.7 5 DHLW/DOE SNF Short Waste Package Drop with Emplacement Pallet

The drop with emplacement pallet consists of raising the waste package while on the emplacement pallet horizontally to a maximum height of 2.0 m (6.6 ft) (see Mecham 2004 [DIRS 169790], Section 5.2.8). The lifting device carrying the waste package and emplacement pallet then fails and the two fall due to gravity. The waste package then impacts an unyielding surface with the emplacement pallet first. The simulation is performed using LS-DYNA finite element software. The simulation is performed at room temperature and 300°C to bound potential waste package operational temperatures. The results for the drop with the emplacement pallet of the 5 DHLW/DOE SNF-Short codisposal waste package are shown in Table 37, which is taken from *5 DHLW/DOE SNF - Short Waste Package Drop with Emplacement Pallet* (BSC 2003 [DIRS 166955], Section 6, Table 6-2).

Table 37. Maximum Stress Intensities

| Part | Temperature | $\sigma_{Int}$ (MPa) | $\sigma_{Int} / \sigma_u$ |
|---|---|---|---|
| Outer Barrier | RT | 725 | 0.75 |
| Inner Vessel | | 297 | 0.42 |
| Outer Barrier | 300°C | 657 | 0.72 |
| Inner Vessel | | 314 | 0.50 |

NOTE: RT = room temperature.
Source: BSC 2004 [DIRS 166955], Table 6-2.

Table 37 shows that for each temperature condition, the maximum wall-averaged stress intensities in the outer corrosion barrier and the inner vessel did not exceed 77 percent of the true tensile strength of Alloy 22 (UNS N06022) and stainless steel type 316, and the stress does not extend uniformly around the full circumference of the waste package. Therefore, the waste package meets the plastic analysis criteria and no breach of the waste package is expected (see Section 7.1.2.2).

#### 7.1.2.2.8 Corner Drop of 5 DHLW/DOE Short Waste Package with Lifting Collars

The corner drop consists of raising the waste package vertically to a maximum height of 2.0 m (6.6 ft) (see Mecham 2004 [DIRS 169790], Section 5.2.8). At this time the waste package swings possibly due to seismic occurrences. The lifting device carrying the waste package fails when the waste package has swung to the point where the center of gravity is vertically aligned with the bottom corner of the waste package. The waste package then falls due to gravity and the waste package impacts an unyielding surface. The simulation is performed using LS-DYNA finite element software. The simulation is performed at room temperature and 100°C to bound potential waste package operational temperatures. The results for the corner drop of the 5 DHLW/DOE SNF-Short codisposal waste package at room temperature and 100°C are shown in Table 38, which is taken from *Corner Drop of 5 DHLW/DOE Short Waste Package with Lifting Collars* (BSC 2003 [DIRS 165501], Section 6, Table 6-2).

Table 38. Maximum Stress Intensities in the Outer Corrosion Barrier and Inner Vessel

| Part | Temperature (°C) | $\sigma_{int}$ (MPa) | $\sigma_{int}/\sigma_u$ |
|---|---|---|---|
| Inner Vessel | RT | 334 | 0.48 |
| Outer Corrosion Barrier | | 1084 | 1.12 |
| Inner Vessel | 100 | 339 | 0.51 |
| Outer Corrosion Barrier | | 1022 | 1.05 |

NOTE: RT = room temperature.
Source: BSC 2003 [DIRS 165501], Table 6-2.

Table 38 shows that the maximum stress intensities in the outer corrosion barrier is greater than seven-tenths of the true tensile strength of Alloy 22 (UNS N06022) at both room temperature and 100°C. To verify this maximum stress intensity does not cause a failure in the outer corrosion barrier requires a more detailed investigation into the source of the stress (see Section 7.1.2.2).

The wall-average of the element total stress intensity on a line of elements through the outer corrosion barrier at the lower trunnion sleeve's upper weld is used and a ratio of this wall-averaged stress intensity is compared to the true tensile strength. Two lines are shown to verify the line of elements containing the element with maximum stress intensity also has the maximum wall-averaged stress intensity. Table 39 contains the wall-averaged total stress intensity of the outer corrosion barrier and their ratios to the true tensile strength of Alloy 22 (UNS N06022) (BSC 2004 [DIRS 167036], Section 6, Table 6-1).

Table 39. Maximum Wall-Averaged Stress Intensities in the Outer Corrosion Barrier

| Line of Elements | Temperature (°C) | Wall-Averaged $\sigma_{int}$ (MPa) | Wall-Averaged $\sigma_{int}/\sigma_u$ |
|---|---|---|---|
| Section 1 | RT | 540 | 0.56 |
| | 100 | 497 | 0.51 |
| Section 2 | RT | 507 | 0.52 |
| | 100 | 464 | 0.47 |

NOTE: RT = room temperature.
Source: BSC 2004 [DIRS 167036], Table 6-1.

From Table 39, the wall-averaged stress intensity in the outer corrosion barrier is well below seven-tenths of the true tensile strength of Alloy 22 (UNS N06022). Therefore, the waste package meets the plastic analysis criteria and no breach of the waste package is expected (see Section 7.1.2.2).

#### 7.1.2.2.9 5 DHLW/DOE SNF - Short Waste Package 10-Degree Oblique Drop with Slap Down

The 10-degree oblique drop with slap down consists of raising the waste package horizontally to a maximum height of 2.4 m (7.9 ft) (see Mecham 2004 [DIRS 169790], Section 5.2.8). The lifting device carrying the bottom half of the waste package then fails and the bottom half of the waste package begins to fall due to gravity. After the bottom end has rotated 10 degrees, the lifting device holding the top of the waste package fails and the entire waste package falls due to gravity. The waste package then impacts an unyielding surface with the bottom edge first followed by the top end. The simulation is performed using LS-DYNA finite element software. The simulation is performed at room temperature and 100°C to bound potential waste package operational temperatures. The results for the 10-degree oblique drop with slap down of the 5 DHLW/DOE SNF-Short codisposal waste package are shown in Table 40, which is taken from *5 DHLW/DOE– SNF - Short Waste Package 10-Degree Oblique Drop with Slap Down* (BSC 2004 [DIRS 169751], Section 6, Table 6-2).

Table 40. Maximum Stress Intensities in the Outer Corrosion Barrier

| Temperature (°C) | $\sigma_{Int}$ (MPa) | $\sigma_{Int}/\sigma_u$ |
|---|---|---|
| RT | 671 | 0.69 |
| 300 | 555 | 0.61 |

NOTE: RT = room temperature.
Source: BSC 2004 [DIRS 169751], Table 6-2.

The previous table shows that for each temperature condition, the maximum stress intensities in the outer corrosion barrier and lids did not exceed seven-tenths of the true tensile strength of Alloy 22 (UNS N06022). However, since the stress intensities are close to seven-tenths of the true tensile strength of Alloy 22 (UNS N06022), an extra step will be taken to verify this maximum stress intensity does not cause a failure in the outer corrosion barrier. This requires a more detailed investigation into the source of the stress (see Section 7.1.2.2).

Table 41 contains the wall-averaged total stress intensities and their ratios to the true tensile strength of Alloy 22 (UNS N06022) (BSC 2004 [DIRS 167036], Section 6, Table 6-2). These ratios are more realistic indicators of potential for outer corrosion barrier material failure.

Table 41. Wall-Averaged Stress Intensity in the Outer Corrosion Barrier

| Temperature (°C) | Wall-Averaged $\sigma_{Int}$ (MPa) | Wall-Averaged $\sigma_{Int}/\sigma_u$ |
|---|---|---|
| RT | 618 | 0.64 |
| 300 | 508 | 0.56 |

NOTE: RT = room temperature.
Source: BSC 2004 [DIRS 169751], Table 6-3.

From Table 41, the wall-averaged stresses in the outer corrosion barrier and lids are below seven-tenths of the true tensile strength of Alloy 22 (UNS N06022). Therefore, the waste package meets the plastic analysis criteria and no breach of the waste package is expected (see Section 7.1.2.2).

### 7.1.2.2.10 5 DHLW/DOE SNF Short Waste Package Swing Down

The swing down consists of raising the waste package horizontally to a maximum height of 2.4 m (7.9 ft) (see Mecham 2004 [DIRS 169790], Section 5.2.8). The lifting device carrying the top half of the waste package then fails and the top of the waste package fall due to gravity. The waste package then impacts an unyielding surface with the top edge. The simulation is performed using LS-DYNA finite element software. The simulation is performed at room temperature and 100°C to bound potential waste package operational temperatures. The results for the swing down of the 5 DHLW/DOE SNF-Short codisposal waste package are shown in Table 42, which is taken from *5 DHLW/DOE SNF - Short Waste Package Swing Down* (BSC 2003 [DIRS 165500], Section 6, Table 6-2).

Table 42. Maximum Stress Intensities in the Outer Corrosion Barrier and Inner Vessel Components

| Part | Temperature (°C) | $\sigma_{Int}$ (MPa) | $\sigma_{Int}$ / $\sigma_u$ |
|---|---|---|---|
| Inner Vessel | RT | 272 | 0.39 |
| Inner Vessel Upper Lid | | 245 | 0.35 |
| Outer Corrosion Barrier | | 438 | 0.45 |
| Spread Ring | | 167 | 0.24 |
| Inner Vessel | 100 | 240 | 0.36 |
| Inner Vessel Upper Lid | | 216 | 0.33 |
| Outer Corrosion Barrier | | 433 | 0.44 |
| Spread Ring | | 138 | 0.21 |

NOTE: RT = room temperature.
Source: BSC 2003 [DIRS 165500], Table 6-2.

Table 42 shows that for each temperature condition, the maximum stress intensities in the outer corrosion barrier, the inner vessel and lids, and the spread ring did not exceed seven-tenths of the true tensile strength of Alloy 22 (UNS N06022) and stainless steel type 316. Therefore, the waste package meets the plastic analysis criteria and no breach of the waste package is expected (see Section 7.1.2.2).

#### 7.1.2.2.11 Waste Package Exposed to Vibratory Ground Motion

The objective of this calculation (BSC 2004 [DIRS 167083], Section 1) is to determine the residual stress distribution in the outer corrosion barrier of a waste package exposed to vibratory ground motion and estimate the area of the waste package outer corrosion barrier for which the residual stress exceeds threshold limits. This calculation has been performed for the 21-PWR waste package. Currently the same calculation has not been performed for any of the codisposal waste packages. However, the codisposal waste package design configurations are similar. Given the nature and conservatism of the results, no significant change of results is anticipated for the 5 DHLW/DOE SNF-Short waste package (see BSC 2004 [DIRS 168217], Appendix A).

### 7.1.2.3 Sources of Uncertainty and Variability

In the past interactions with the NRC (Kelmenson 2000 [DIRS 154350]) sources of uncertainty and variability affecting structural analyses were discussed. This particularly dealt with finite element analysis representations and the failure criterion for waste package structural analyses. Six other areas considered were:

1. Residual and differential thermal expansion stresses
2. Strain-rate effects
3. Dimensional and material variability
4. Seismic effect on ground motion
5. Initial tip-over velocities
6. Sliding and inertial effect of waste package contents.

At this time, additional uncertainties have not been identified. As the design progresses, any additional uncertainties that are identified are addressed as part of the design process. These identified uncertainties will be documented within the documents supporting the license application.

**Finite Element Analysis Discretization and Failure Criterion**—With regard to the adequacy of finite element analysis representations, a process has been developed to ensure that the mesh density is computationally adequate, and this process is followed for all structural calculations. The failure criterion is an application of the Tresca (strength of materials) failure criterion based on the implementation of ASME B&PV Code design-by-analysis primary stress intensity limits. A tiered evaluation approach was implemented that used increasingly less simplified and increasing less conservative screening criterion whose satisfaction will assure meeting the ASME B&PV Code primary stress intensity limits.

For the six specific areas of uncertainty concern, the responses may be summarized as:

**Residual and Differential Thermal Expansion Stresses**—Differential thermal expansion is accommodated by providing adequate gaps between the two shells that comprise the waste package to ensure that there is no mutual loading due to thermal expansion. For residual stresses purposefully imposed on the outer corrosion barrier, the effects on structural analysis results are found to be negligible.

**Strain-rate Effects**—While material-specific strain-rate dependent properties are not currently available for Alloy 22 (UNS N06022) and stainless steel type 316, parametric studies of such effects based on stainless steel 304 strain-rate dependent properties have shown that the use of static properties has negligible effect on the safety assessment.

**Dimensional and Material Variability**—Dimensional variability is addressed by assuming minimum dimensions for those parameters that are important to component performance. Material variability is accommodated by the use of ASME B&PV code—and other codes as necessary—structural properties, which provide for minimum structural performance margins.

**Seismic Effect on Ground Motion**—In the surface facility, in the transporter, and on the emplacement gantry, it is assumed that the fixturing is provided to restrain the waste package during evolutions in that facility, and these devices are sufficient to provide restraint during vibratory ground motion. For vibratory ground motion in the underground, results are provided for a seismic evaluation for an annual frequency of exceedance of $5 \times 10^{-4}$ per year. These results show a very modest waste package movement and large margin to breach.

**Initial Tip-over Velocities**—A study has been performed to demonstrate that the increase in tip-over velocity due to credible vibratory ground motion causes a negligible increase in impact velocity.

**Sliding and Inertial Effect of Waste Package Contents**—The waste form contents are represented in dynamic structural analyses for which such motion is anticipated to be important. Examples of the loads and boundary conditions used in calculations and analyses can be found in the supporting calculations (BSC 2001 [DIRS 152655], BSC 2003 [DIRS 161691], BSC 2004 [DIRS 167083], BSC 2004 [DIRS 169705], and BSC 2003 [DIRS 165497]). In addition, the technical bases and or rationale for the loads and boundary conditions used in calculations supporting the license application will be based on the preclosure safety analysis and derivative design constraints.

### 7.1.2.3.1 Response to General Issue of Adequacy

#### 7.1.2.3.1.1 Mesh Discretization

The main concern is the adequacy of the finite element analysis mesh discretization and the failure criterion.

A set process is followed in the development of the mesh for finite element analysis that provides confidence that the results are stationary in a numerical sense (Mecham 2004 [DIRS 169790], Section 6.2.3).

The purpose of mesh refinement is to ensure the mesh objectivity of the finite element analyses, i.e., the results obtained are not mesh-sensitive. The basis for the validity of this process of successive refinement is that it has been found to produce convergent stress fields in a systematic manner. The acceptable variations in the stress fields are well within the benchmarking basis for the LS-DYNA code. A mesh-refinement study consists of the development of an optimum mesh that yields mesh-objective (mesh-insensitive) results. That mesh is then refined again, and computational results for the two mesh sizes are compared. The finite element representation is considered mesh-objective if the relative difference in results between the two meshes is approximately an order of magnitude smaller than the relative difference in mesh size in the region of interest; otherwise further mesh refinement is needed. The mesh size, as used throughout this section, refers to the volume or the area of the representative element (three-dimensional or two-dimensional, respectively) in the region of interest (for example, the element characterized by the highest stresses or strains).

The optimum mesh is created by the following sequence of steps:

- The initial mesh is created by following the customary engineering practices: the element type is appropriately chosen; the mesh is refined in the regions of interest (the highest stress/strain regions, initial impact regions, stress concentration regions, etc.); the mesh is mapped whenever possible; and the aspect ratio of elements is kept reasonable.

- The initial mesh is—in the region of interest—refined in one direction while the element size in the other two directions is kept unchanged (for example, the mesh is refined across the thickness while kept unchanged in the hoop and axial directions). The mesh-refinement procedure is repeated in this manner until the relative difference in results between the two successive meshes is acceptable (i.e., approximately an order of magnitude smaller than the relative difference in the mesh size). The mesh dimension in this direction is then fixed at the largest value that satisfied the previously mentioned criterion.

- The intention of this one-direction-at-a-time mesh refinement is to create, in a consistent and systematic manner, a mesh that is objective.

- The same procedure is consecutively repeated in the remaining two directions.

- Whether the created mesh meets the requirement is verified by the final step: the simultaneous mesh refinement in all three directions. The level of this mesh refinement should be similar in all three directions. In this final step, the same mesh-acceptance criterion is invoked: the mesh is considered objective if the relative difference in results between the two meshes is approximately an order of magnitude smaller than the relative difference in mesh size in the region of interest.

It should be emphasized that the mesh objectivity is verified by the final step regardless of whether the final mesh is arrived at by the described one-direction-at-a-time mesh refinement or not. The one-direction-at-a-time mesh refinement is optional since its only purpose is to develop an optimum mesh (that satisfies the mesh-objectivity requirement) in a systematic way.

An example of the implementation of this mesh discretization approach may be found in the calculation entitled *44-BWR Waste Package Tip-Over from an Elevated Surface* (BSC 2004 [DIRS 169705], Section 6). While all calculations perform such discretization studies, this calculation is selected because it is the vehicle cited in the balance of this section to assess the importance of strain rates (Section 7.1.2.3.2.2) and initial tip-over velocities (Section 7.1.2.3.2.5).

#### 7.1.2.3.1.2 Selection of the Failure Criterion

For structural analyses of preliminary design configurations that consider material nonlinear behavior, the maximum-shear-stress or Tresca (strength of materials) criterion is used in determining stress limits. In general terms, this criterion assumes that the design is safe as long as stress intensity (defined as the difference between the maximum and minimum principal stress) remains below a certain limit. In particular, the failure criterion chosen was the acceptance criteria for plastic analysis outlined in Appendix F, F-1341.2 of the ASME B&PV Code (ASME 2001 [DIRS 158115], Section III, Division 1). This is an acceptable vessel designer choice of ASME B&PV Code acceptance criteria for service loadings with Level D Service Limits for vessel designs in accordance with NC-3200 (Safety Class 2 Vessels) when a complete stress analysis is performed. (See ASME 2001 [DIRS 158115], NC-3211.1(c), Appendix XIII and Note (4) to Table NC-3217-1).

The ASME B&PV Code (ASME 2001 [DIRS 158115], Section III, Division 1, Appendix F, F-1341.2) suggests the following primary stress intensity limits for plastic analyses:

- The general primary membrane stress intensity shall not exceed 0.7 $S_u$ for ferritic steel materials included in Section II, Part D, Subpart 1, Table 2A and the greater of 0.7 $S_u$ and $S_y + {}^1/_3\,(S_u - S_y)$ for austenitic steel, high-nickel alloy, and copper-nickel alloy materials included in Section II, Part D, Subpart 1, Table 2A, where $S_u$ and $S_y$ are tensile strength and yield strength, respectively.

- The maximum primary stress intensity at any location shall not exceed 0.9 $S_u$.

- The average primary shear across a section loaded in pure shear shall not exceed 0.42 $S_u$.

The Pressure Vessel Research Council of the Welding Research Council provides guidelines (Hechmer 1998 [DIRS 166147]) to the ASME B&PV Code rule committees for assessing stress results from three-dimensional finite element analysis in terms of ASME B&PV Code stress limits in the design-by-analysis rules of ASME (2001 [DIRS 158115], Section III, Class 1, NB and Section VIII, Division 2). These guidelines were developed for linear analyses and Pressure Vessel Research Council recommends that future research work should be conducted to generate state-of-the-art guidelines for applying inelastic, large-deformation analyses. Therefore, a cautious use of the Pressure Vessel Research Council recommendations was made in developing methodologies for post-processing LS-DYNA nonlinear plastic simulations to assure conservative representations of the general primary membrane stress intensity and maximum primary stress intensity.

The Pressure Vessel Research Council recommendations also refer to an earlier Pressure Vessel Research Council (Phase 1) report Hechmer and Hollinger 1998 [DIRS 166147], which recommended that the ASME B&PV Code Appendix F "should be revised to provide a limit on effective plastic strain which is more appropriate for events that are energy controlled, rather than load controlled, which is all that was considered when ASME B&PV Code Appendix F was written." The Yucca Mountain Project recognizes that strain-based or deformation-based criterion may be more appropriate than stress-based limits for evaluation of the credible preclosure sequence events, (see Mecham 2003 [DIRS 169790], Section 4.1.4.1). However, the project is also committed to applying the ASME B&PV Code for structural analyses, and until the ASME B&PV Code rule committees prepare rules in ASME B&PV Code Appendix F for using strain limits, primary stress intensity limits will be used.

The ASME B&PV Code design-by-analysis guidance recognizes the differences in importance of different types of stresses and provides guidance on their correct assignment to the different categories of stress intensity used to evaluate different types of failure modes. The three types of stresses are membrane, bending and peak stresses. The three categories of stress intensity are primary ($P_m$, $P_L$ and $P_b$ [general primary membrane, local primary membrane, and primary bending, respectively]), secondary (Q), and peak (F).

A primary stress is defined in ASME B&PV Code (ASME 2001 [DIRS 158115], Section III, Division 1, Appendix XIII, XIII-1123(h)): "Primary stress is a normal stress developed by the imposed loading which is necessary to satisfy the laws of equilibrium of external and internal forces and moments. The basic characteristic of a primary stress is that it is not self-limiting. Primary stresses which considerably exceed the yield strength will result in failure or, at least, in gross distortion."

A secondary stress is defined in ASME B&PV Code (ASME 2001 [DIRS 158115], Section III, Division 1, Appendix XIII, XIII-1123(i)): "Secondary stress is a normal or a shear stress developed by the constraint of adjacent parts or by self-constraint of the structure. The basic characteristic of a secondary stress is that it is self-limiting. Local yielding and minor distortions can satisfy the conditions which cause the stress to occur and failure from one application of the stress is not expected." A cited example of a secondary stress is "bending stress at a gross structural discontinuity." A gross structural discontinuity is defined in ASME B&PV Code (ASME 2001 [DIRS 158115], Section III, Division 1, Appendix XIII, XIII-1123(b)): "Gross structural discontinuity is a source of stress or strain intensification which affects a relatively large portion of a structure and has a significant effect on the overall stress or strain pattern or on the structure as a whole." Cited examples of gross structural discontinuities are head-to-shell junctions and junctions between shells of different thickness.

A local primary membrane stress is also defined in ASME B&PV Code (ASME 2001 [DIRS 158115], Section III, Division 1, Appendix XIII, XIII-1123(j)): "Cases arise in which a membrane stress produced by pressure or other mechanical loading and associated with a discontinuity would, if not limited, produce excessive distortion in the transfer of load to other portions of the structure. Conservatism requires that such a stress be classified as a local primary-membrane stress even though it has some characteristics of a secondary stress." The other differentiating feature of a local primary membrane stress is that it is localized, and ASME B&PV Code guidance is provided for evaluating if membrane stress fields are adequately "local" to be assigned a $P_L$ classification rather than a more restrictive $P_m$ classification.

The failure mode being addressed by the general primary membrane stress intensity ($P_m$) limit is "collapse" in the sense that collapse includes tensile instability and ductile rupture under short term loading (Hechmer and Hollinger 1998 [DIRS 166147], Guideline 1). The principle failure mode being addressed by the maximum primary stress intensity ($P_L + P_b$) is excessive plastic deformation. However, it also relates to tensile instability due to the nature of $P_b$.

The sequence events considered in this report are not repetitive where fatigue cracking or incremental collapse might be an issue. It follows that evaluation of secondary stress intensities (Q) or maximum total stress intensities ($P_L + P_b + Q + F$) are not appropriate. Brittle fracture is also precluded by the high ductility of the outer boundary material, Alloy 22 (UNS N06022), at the temperatures experienced after waste form loading. Although the high-stress areas are comprised of primary, secondary and peak stresses, only the primary stress intensities ($P_m$, $P_L$ and $P_b$) contribute to tensile instability and ductile rupture (characterized by tearing of metal accompanied by appreciable gross plastic deformation and expenditure of considerable energy), and therefore, only the primary stress intensities are evaluated for the sequence events.

The ASME B&PV Code is used to determine which stress fields should be classified as primary and which should be classified as secondary when evaluating the sequence events (ASME 2001 [DIRS 158115], Section III, Division 1, Appendix XIII, Table XIII-1130-1). All membrane stress fields are conservatively classified as primary. Classification of the bending stresses is more involved.

Review of representative analyses for the sequence events indicated that the most important wall-bending stresses occur near (within $(Rt)^{1/2}$, R = outer barrier mid-radius, t = outer barrier thickness) gross structural discontinuities. Some of these gross structural discontinuities are integral to the outer boundary and some are introduced by the constraint of adjacent parts or impact surfaces.

The integral gross discontinuities in the outer barrier are similar to ASME code vessel details such as shell-to-lid junctures and step-changes in wall thickness. The bending stresses are being created by self-constraint, and (ASME 2001 [DIRS 158115], Section III, Division 1, Appendix XIII, Table XIII-1130-1) classifies these bending stresses as secondary. The only exception is at the shell-lid junction, where concern about the predictability of the central stresses of the lid leads the ASME Code to caution the designer to consider classifying the bending stresses as $P_b$ (ASME 2001 [DIRS 158115], Section III, Division 1, Appendix XIII, Table XIII-1130-1, Note (4)). However, this is not appropriate guidance for inelastic analyses because the increased flexibility of the juncture caused by inelastic behavior is correctly captured and the central stresses of the lid will be accurately predicted.

The bending stresses created by the constraint of adjacent parts or impact surfaces (which can be considered [temporary] "adjacent parts") were reviewed on individual cases with attention to the amount and type of constraint introduced. In the design analyses to date, the constraint of the adjacent part (e.g., trunnion sleeve) or impact surface (e.g., emplacement pallet, crane hook or rock) created local yielding and minor local distortions in the outer barrier. The outer barrier distorted shape reduced the outer barrier bending stresses while increasing the outer barrier membrane stresses. The bending stresses in these locally yielded regions are therefore self-limiting and satisfy the basic characteristic of a secondary stress.

The structural criterion developed for the outer boundary for the sequence events was to directly address the dominant failure mode, tensile instability, and limit the membrane stresses to acceptable limits. The use of inelastic analyses ensures that local thinning or shape changes that could increase membrane stresses will be properly accounted for.

Inelastic analyses are conducted using true stress ($\sigma_u$) and true strain based constitutive relationships, for Alloy 22 (UNS N06022):

The limit on $P_m$ is $0.7\sigma_u$, and

the limit on $P_L$ is $0.9\sigma_u$ ,where $P_b = 0$, where

$\sigma_u$ is the true tensile strength at temperature (ASME 2001 [DIRS 158115], Section III, Division 1, Appendix F, F-1322.3(b) and F-1341.2).

As stated earlier, $P_L$ must be "local" to not be classified as a more restrictive general primary membrane stress intensity, $P_m$ (ASME 2001 [DIRS 158115], Section III, Division 1, Appendix XIII, XIII-1123(j)). Interpretation of this guidance with respect to the ASME B&PV Code Appendix F limits results in requiring $P_L$ values exceeding $0.77\sigma_u$ to not extend for greater than $\sqrt{R \cdot t}$ in any direction (not just the meridional direction), where $R$ is the midsurface radius and $t$ is the thickness of the outer barrier.

Rigorously performed, calculation of the primary membrane stress intensities involves:

- Identifying the governing wall location, which may not necessarily contain the maximum stressed point (Hechmer 1998, Guidelines 3a, 3c and 4d).

- Identifying the orientation of the stress classification line, typically normal to the mid-plane of the shell or lid thickness (Hechmer 1998, Guideline 4d).

- Identifying stress component ($\sigma_x, \sigma_y, \sigma_z$, $\tau_{xy}$, $\tau_{yz}$, $\tau_{zx}$) fields across the wall of the outer barrier

- Averaging the stress component fields to create wall-averaged stress components

- Translating the wall-averaged stresses to principle stress directions by solving a cubic equation

- Calculating the difference between the maximum ($\sigma_1$) and minimum ($\sigma_3$) principle stress direction values.

To simplify the calculation, the wall-average of the element total stress intensity (twice the maximum shear stress) values through the outer corrosion barrier is used to define the primary membrane stress intensities. This is a conservative representation because it ignores the possibly changing principle stress planes through the wall, and it includes the secondary and peak stress contributions.

The third Appendix F (ASME 2001 [DIRS 158115], Section III, Division 1) limit on average section shear is imposed whenever a location was governed by the $0.9\sigma_u$ $P_L$ limit. When the wall-average of the total stress intensity exceeds $0.84\sigma_u$, an additional check is imposed that each of the three wall-averaged shear stresses is less than $0.42\sigma_u$.

### 7.1.2.3.2 Responses to Specific Issues

The following sections address the specific issues enumerated in Section 7.1.2.3

#### 7.1.2.3.2.1 Residual and Differential Thermal Expansion Stresses

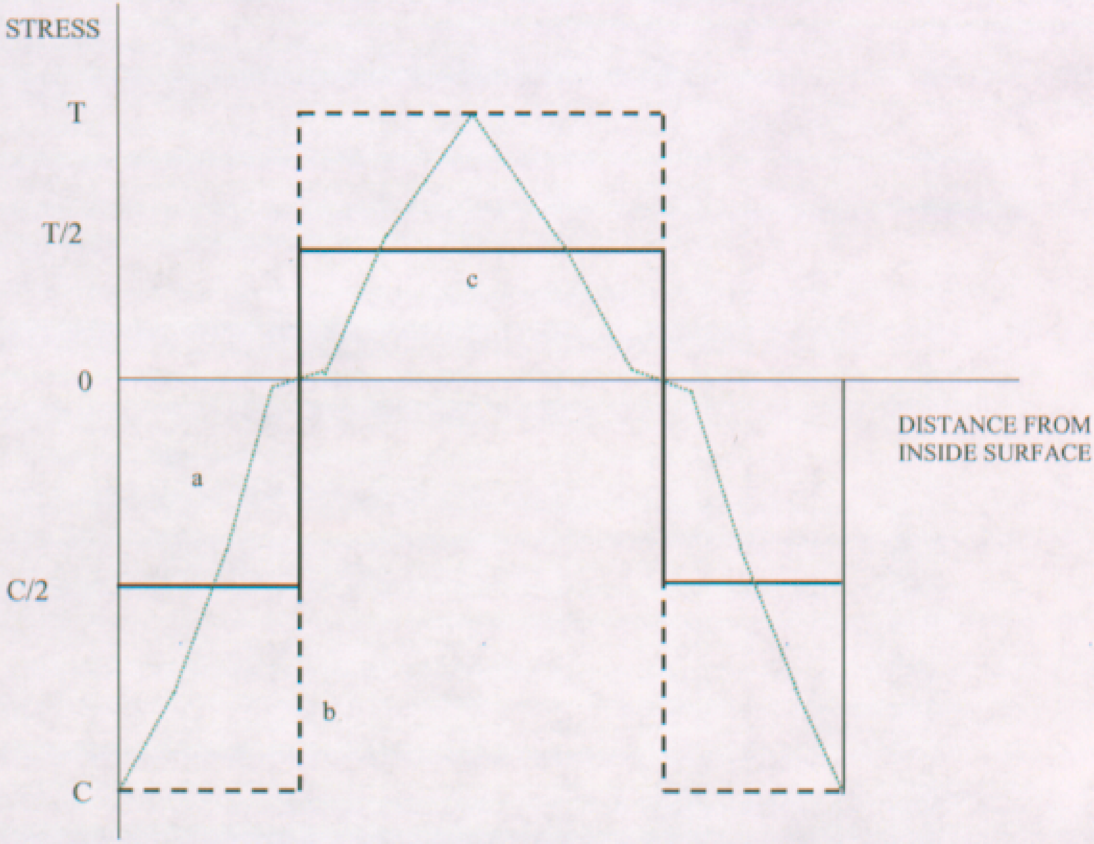
Differential thermal expansion is accommodated by providing adequate gaps between the two shells that comprise the waste package to ensure that there is no mutual loading due to thermal expansion. The required radial gap between the inner vessel and the outer corrosion barrier of the waste package is documented in a calculation entitled *Waste Package Outer Barrier Stress Due to Thermal Expansion with Various Barrier Gap Sizes* (BSC 2001 [DIRS 152655]). This calculation resulted in a minimum gap spacing between the inner vessel and outer corrosion barrier to accommodate radial expansion to be set at 1 mm (0.04 in.) (BSC 2001 [DIRS 152655], Section 6.1, Table 4). The axial gap between the inner vessel and outer corrosion barrier and the lids of each is documented in a calculation entitled *Waste Package Axial Thermal Expansion Calculation* (BSC 2003 [DIRS 161691]). This calculation established a minimum axial gap of 1 cm (0.39 in.) between these two shells (BSC 2003 [DIRS 161691], Section 7, p. 13). A similar approach will be used to ensure clearance between the inner vessel of the waste package and the internals.

The waste package outer corrosion barrier is not in a stress-free condition at the beginning of service life due to residual stresses purposefully induced by solution annealing and quenching. The purpose of these residual stress fields is to create compressive residual stresses at the outside surface, and perhaps the inside surface as well (depending on the quenching techniques) of the outer corrosion barrier to help mitigate corrosion. The effect that this stress profile has on the response of the waste package during dynamic events is documented in a calculation entitled *Drop of Waste Package on Emplacement Pallet-A Mesh Study* (BSC 2003 [DIRS 165497], Section 6). While this calculation was prepared for a postclosure evaluation, it illustrates the basic physics of the phenomenon, and the conclusions are equally appropriate for preclosure evaluations of preclosure dynamic structural calculations.

The residual stresses due to the solution annealing and quenching are analyzed for a mockup waste package outer corrosion barrier in *Residual Stress Analyses on the 21 PWR Mockup Waste Package Outer Shell Due to Quenching and General corrosion Using a Side-wall Thickness of 20mm* (Herrera et al. 2002 [DIRS 166799]). The residual stress analyses are performed in (Herrera et al. 2002 [DIRS 166799], Section 6) for two different quenching techniques: (1) the outside quench (on the outside surface only) and (2) the double-sided quench (on both the inside and outside surfaces). The results reported herein correspond only to the residual stress distribution due to the double-sided quenching.

It must be recognized that the accuracy of this study is limited by the through-wall discretization of the outer corrosion barrier. Since only four layers of solid (brick) elements are used for the finite element analysis representation of the outer corrosion barrier in this calculation, the residual stress distribution is necessarily rather coarse. Furthermore, the one-point-integration solid elements used in this calculation are not best suited for the representation of the initial stress distribution. Nonetheless, no change has been made in the finite element analysis representation for the residual stress calculations since it was important to make a comparison between the results obtained by using the same representation, which was defined by the objective of the source calculation (BSC 2003 [DIRS 165497], Section 1).

Two different magnitudes of the initial stress distribution are used in this study to explore a sensitivity of results to the details of the stress distribution. (Note the schematic representation of the residual stress distribution—generic for both hoop and axial direction—presented as the dotted green line [a] in Figure 8). In the first approximation, the initial stress (i.e., the residual stress caused by the annealing and quenching) in each layer of elements is defined by using the maximum stress value reached anywhere within the element layer (the dashed line [b] in Figure 8; see also row "Full" in Table 43). In the second approximation, the initial stress in each layer of elements is obtained by averaging the actual stress distribution (the green dotted line [a] in Figure 8) over the element layer. Keeping in mind the actual residual stress distribution, the averaging is performed by assigning to the approximated initial stress distribution one half of the maximum stress value reached anywhere within each element layer (solid line [c] in Figure 8; see also row "Half" in Table 43). The approximated initial stress distributions are presented in Figure 8. The actual stress values are obtained from (Herrera et al. 2002 [DIRS 166799], Figures 48 and 52). For the axial stress distribution the maximum compressive stress at both the inside and outside surface is C = -300 MPa; the maximum tensile stress at the middle surface is T = 150 MPa. For the hoop stress profile the maximum compressive stress at both inside and outside surface is C = -260 MPa; the maximum tensile stress at the middle surface is T = 190 MPa.

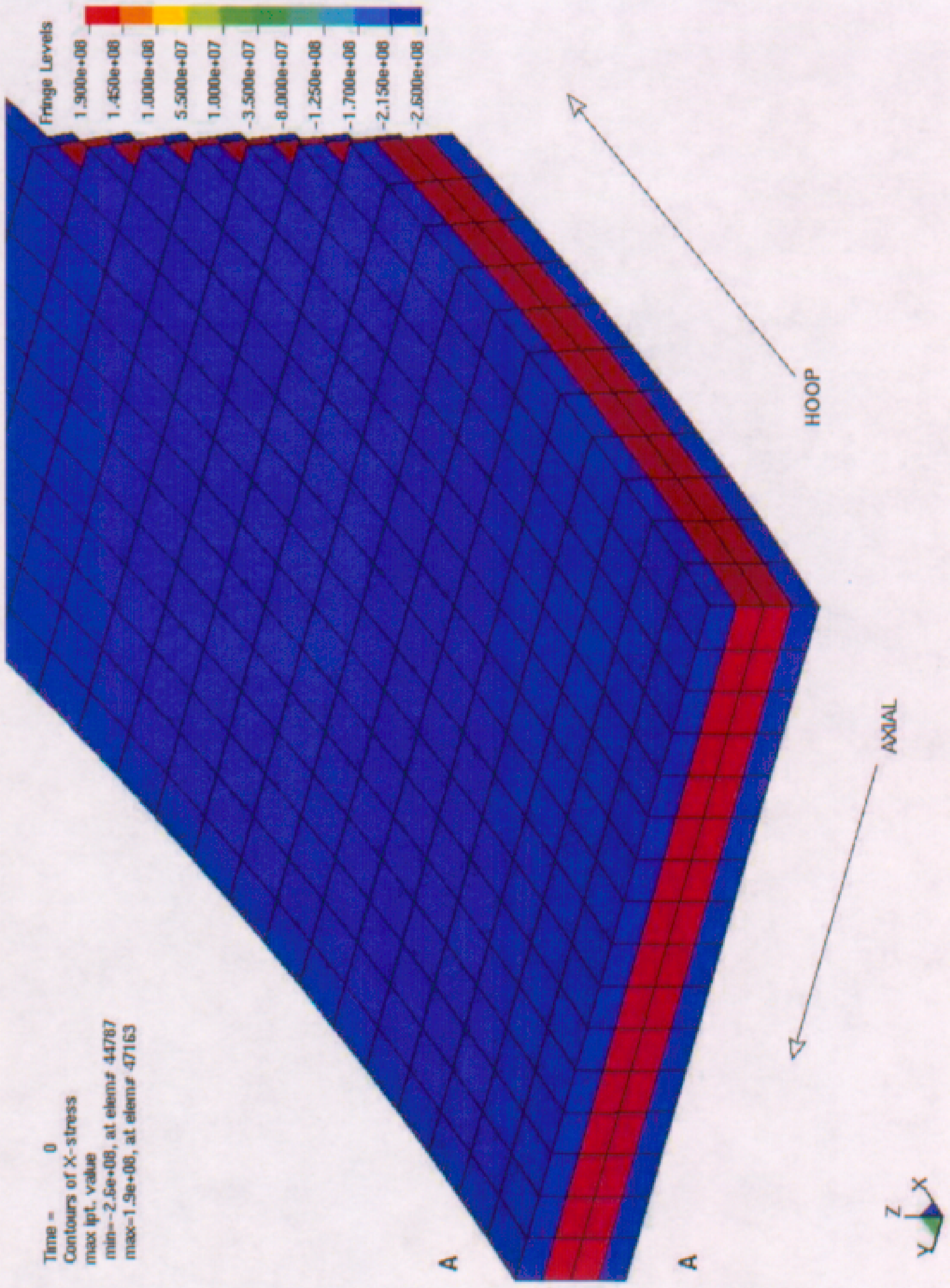



NOTES: (a) Schematic representation of axial and hoop stress distribution from Herrera et al. 2002 [DIRS 166799], Figures 48 and 52 (green dotted line), (b) first ("full") approximation (dashed line), and (c) second ("half") approximation (solid line).

Source: BSC 2003 [DIRS 165497], Figure VII-1.

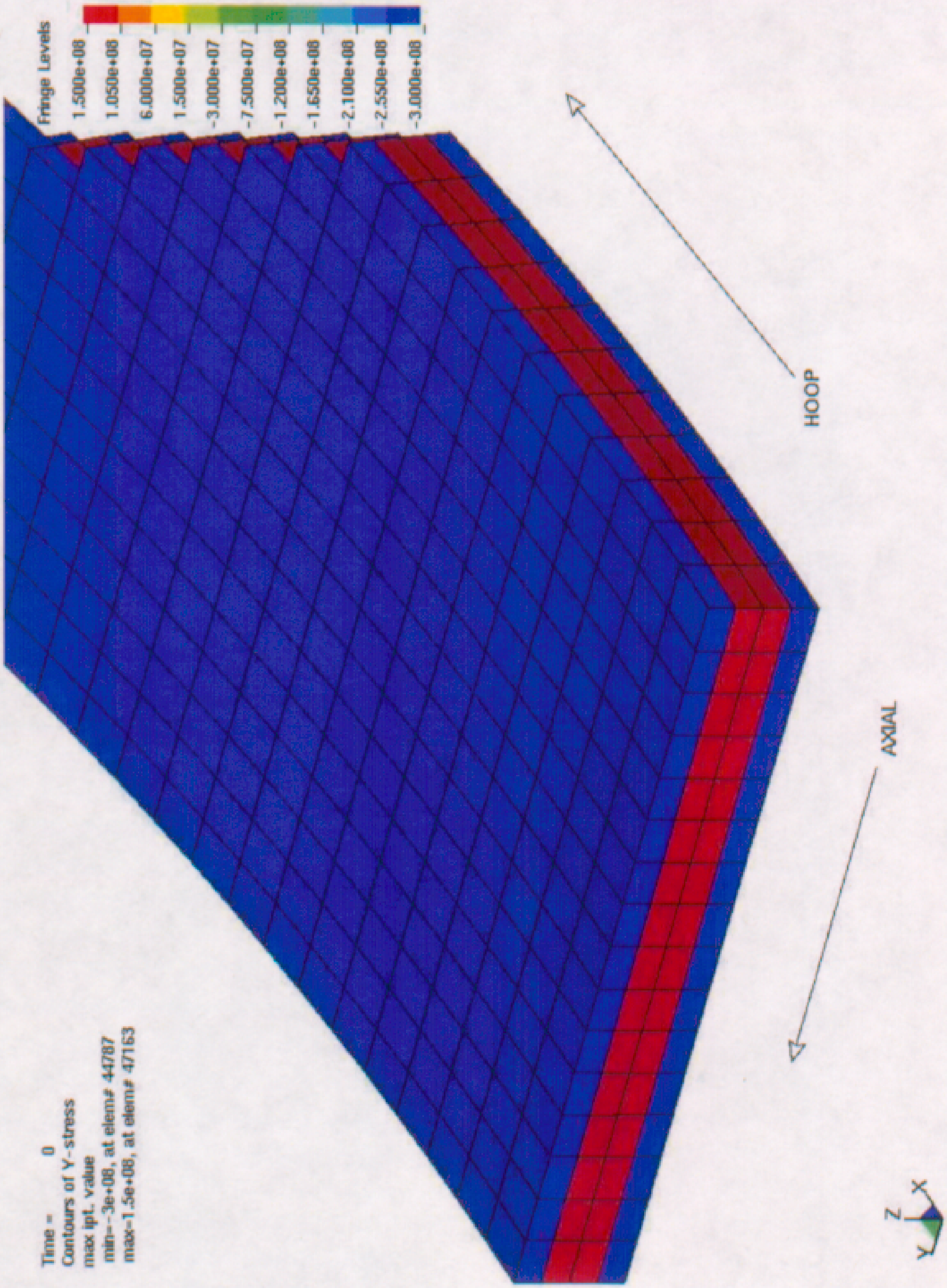
Figure 8. Initial Stress Distribution across the Outer Corrosion Barrier Wall

The resulting initial stress distributions in hoop and axial directions are, for the first approximation ("Full"), presented in Figure 9 and Figure 10, respectively. The results shown are in Pascals. (Note that LS-DYNA finite element analysis code requires the initial stresses to be specified in the global Cartesian coordinate system. Thus, the initial stress distribution in the x direction, presented in Figure 9, corresponds to the hoop stress distribution only at the symmetry plane.) The initial effective plastic strain, used for both approximations, is zero.




NOTE: Normal stress in x-direction is identical to hoop stress at symmetry plane designated as A-A section.
Source: BSC 2003 [DIRS 165497], Figure VII-2.

Figure 9. Initial Stress Distribution in the X Direction in the Outer Corrosion Barrier Caused by Annealing and Double-Sided Quenching




Source: BSC 2003 [DIRS 165497], Figure VII-3.

Figure 10. Initial Axial (Y-) Stress Distribution in the Outer Corrosion Barrier Caused by Annealing and Double-Sided Quenching

The results are presented in Table 43. The row designated with "No" represents the initially stress-free case (i.e., without the initial stress). The results obtained by using the first and second initial stress approximations are presented in rows "Full" and "Half," respectively.

Table 43. Results for Three Different Initial Stress Approximations

| Magnitude of Residual Stress | Maximum Stress Intensity (MPa) | Maximum Effective Plastic Strain (%) | Damaged Area (80% criterion/90% criterion) ($\times 10^{-3}$ $m^2$)[a] |
|---|---|---|---|
| No | 630 | 30.3 | 7.47 / 2.46 |
| Half | 632 | 30.4 | 6.41 / 2.29 |
| Full | 631 | 30.7 | 5.82 / 2.21 |

NOTE: [a]This is the percentage of yield stress and is used in postclosure seismic analyses as a measure of susceptibility to accelerated corrosion.

Source: BSC 2003 [DIRS 165497], Table VII-1.

According to results presented, the maximum stress intensity and the maximum effective plastic strain are not significantly affected by presence of the initial stress (i.e., the residual stress caused by the solution annealing and double-sided quenching). The damaged area is moderately sensitive to the initial stresses. The damaged area is used in postclosure analyses to assess the susceptibility to accelerated corrosion, which is not important for preclosure safety.

### 7.1.2.3.2.2 Strain-Rate Effects

The plastic behavior of materials is sensitive to strain rate, which is known as material strain-rate sensitivity. The strain-rate data for Alloy 22 (UNS N06022) and stainless steel type (the stress-strain curves for different strain rates or the change of a characteristic stress with strain rate) are not available in literature at present. Thus, the effect of strain rate on the mechanical strengths of Alloy 22 (UNS N06022) and stainless steel type 316 was studied parametrically by using as a guidance the strain-rate data for stainless steel type 304 (Nicholas 1980 [DIRS 154072], Figures 10 and 27) for both materials. Stainless steel type 304 is used as an analogue for stainless steel type 316 and Alloy 22 (UNS N06022) insofar as strain rate effects are concerned. The tangent (hardening) moduli for Alloy 22 (UNS N06022) and stainless steel type 316 are assumed to be unaffected by the rate of loading. The rationale is that according to the document, *Dynamic Tensile Testing of Structural Materials Using A Split Hopkinson Bar Apparatus* (Nicholas 1980 [DIRS 154072], Figure 10), the tangent modulus for stainless steel type 304 is not significantly affected by the strain rate. This evaluation is documented in a calculation entitled *44-BWR Waste Package Tip-Over from an Elevated Surface* (BSC 2004 [DIRS 169705], Attachment V).

Strain rate is accounted for in this study by using Cowper and Symonds approach that scales the yield strength with the factor:

$$\beta = 1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{1/p} \qquad \text{(Eq. 1)}$$

Here $\dot{\varepsilon}$ is the strain rate, and $C$ and $p$ are input parameters obtained by fitting the experimental data (Hallquist 1998 [DIRS 155373], p. 16.37).

The test results provided for 304 stainless steel are used to establish reasonable limits for strain-rate factor β. The results obtained at strain rates of 20 $s^{-1}$ and 900 $s^{-1}$ are selected (Nicholas 1980 [DIRS 154072], Figures 10 and 27) for fitting of the strain-rate parameters, since those two values adequately span the strain-rate range relevant for this calculation. From that data (Nicholas 1980 [DIRS 154072], Figure 27, curve 304, $\varepsilon = 0.10$)

$$\beta\left(\dot{\varepsilon} = 20 s^{-1}\right) = 1.135 \qquad \text{(Eq. 2)}$$

$$\beta\left(\dot{\varepsilon} = 900 s^{-1}\right) = 1.37 \qquad \text{(Eq. 3)}$$

To establish the upper bound for strain-rate effects, the change of stress of 13.5 percent at strain rate of 20 $s^{-1}$ (compared to the static test) is increased to 20 percent (corresponding to relative increase of 50 percent). Thus, for the upper bound, $\beta\left(\dot{\varepsilon} = 20 s^{-1}\right) = 1.20$. Similarly, the change of stress of 37 percent at strain rate of 900 $s^{-1}$ (compared to the static test) is increased to 55 percent (corresponding to relative increase of 50 percent); this value is then rounded to 60 percent. Thus, for the upper bound, $\beta\left(\dot{\varepsilon} = 900 s^{-1}\right) = 1.60$.

Results for 304 stainless steel from two additional sources are also presented in the source document for this data (Nicholas 1980 [DIRS 154072], Figure 27). All three test results from this source document are used to establish the lower bound for the strain-rate factor $\beta$, $\beta\left(\dot{\varepsilon} = 20 s^{-1}\right) = 1.05$ and $\beta\left(\dot{\varepsilon} = 900 s^{-1}\right) = 1.15$. The purpose of this lower bound is to explore sensitivity of results with regards to the amount of the strain-rate strengthening of material.

In summary, the scale factor β corresponding to strain rate of 20 $s^{-1}$ is 1.05 and 1.20 for the lower and upper bounds, respectively (see Table 44). The scale factor β corresponding to strain rate of 900 $s^{-1}$ is 1.15 and 1.60 for the lower and upper bounds, respectively (Table 44). Note that at both strain rates the increase of stress (expressed as percent increase compared to the static value) from the lower to the upper bound is four times. Also, for both the upper and lower bound the increase of stress (expressed as percent increase compared to the static value) from 20 $s^{-1}$ to 900 $s^{-1}$ is three times.

Table 44. Strain-Rate Parameters

| | **Lower Bound** | **Upper Bound** |
|---|---|---|
| $\beta\left(20\ s^{-1}\right)$ | 1.05 | 1.20 |
| $\beta\left(900\ s^{-1}\right)$ | 1.15 | 1.60 |
| $p$ | 3.465 | 3.465 |
| $C$ | 644,300 | 5,284 |

Source: BSC 2004 [DIRS 169705], Table V-1.

These values can be used as boundary conditions for determination of strain-rate parameters in Table 44. For example for the lower bound, the expression,

$$1.05 = 1 + \left(\frac{20}{C}\right)^{1/p} \quad \Rightarrow \quad C = \frac{20}{0.05^p} \qquad \text{(Eq. 4)}$$

is obtained by substituting the first boundary condition ( $\beta(\dot{\varepsilon} = 20\ s^{-1}) = 1.05$ ) in Equation 1. Similarly, by substituting ( $\beta(\dot{\varepsilon} = 900\ s^{-1}) = 1.15$ ) in Equation 1,

$$1.15 = 1 + \left(\frac{900}{C}\right)^{1/p} \qquad \text{(Eq. 5)}$$

and adding Equation 4, the parameter p can be readily calculated:

$$0.15 = \left(\frac{900}{20/0.05^p}\right)^{1/p} \quad \Rightarrow \quad p = \frac{\ln(45)}{\ln(0.15) - \ln(0.05)} = 3.465 \qquad \text{(Eq. 6)}$$

From Equation 4 it follows directly that $C = 644{,}300\, s^{-1}$.

By repeating the same calculation for the upper-bound values of β the following parameters can be readily obtained, $p = 3.465$ and $C = 5{,}284\, s^{-1}$ (see Table 44).

Three calculations are performed to explore the strain-rate sensitivity of results presented in this calculation (see Table 45 and Table 47). The first calculation is performed with static material properties without strain-rate effects accounted for (row "No" in Table 45 and Table 47). The second calculation corresponds to the lower-bound strain-rate sensitivity (row "Low" in Table 45 and Table 47). Finally, the third calculation is performed with highly rate-sensitive material strengths (row "High" in Table 45 and Table 47, corresponding to the upper-bound strain-rate parameters in Table 44).

Table 45. Maximum Stress Intensity in the Outer Corrosion Barrier and Inner Vessel for Three Different Levels of Strain-Rate Sensitivity

| Strain-rate Sensitivity | Maximum Stress Intensity (MPa) | |
|---|---|---|
| | Inner Vessel | Outer Corrosion Barrier |
| No | 518 | 902 |
| Low | 528 | 942 |
| High | 601 | 1,037 |

Source: BSC 2004 [DIRS 169705], Table V-2.

Maximum stress intensity, as expected, increases with increased strain-rate sensitivity of the material strengths (see Table 45). The strain-rate strengthening of material implies increase of the true tensile strength, which must be quantified in order to make a meaningful assessment of the material condition upon deformation.

The strain rates encountered in the inner vessel and outer corrosion barrier, at the time when the maximum stress intensities occur, are determined from Figure 11 and presented in Table 45. Note that the effective-strain time histories presented in Figure 11 correspond to elements characterized by the maximum stress intensity (presented in Table 45), i.e., elements 27077 and 27078 (inner vessel) and element 10174 (outer corrosion barrier). Strain-rate factor β is then calculated using Equation 1 for the strain-rate parameters (presented in Table 44) and the strain rate (presented in Table 46). Finally, the true tensile strengths of Alloy 22 (UNS N06022) and stainless steel type 316 are scaled by the factor β.

Table 46. Parameters Defining the Strain-Rate Sensitivity for the Inner Vessel and Outer Corrosion Barrier at the Time Characterized by Maximum Stress Intensity

| Strain-rate Sensitivity | Strain Rate (1/s) | Strain-Rate Factor $\beta$ (-) | True Tensile Strength (MPa) |
|---|---|---|---|
| | Inner Vessel | | |
| No | N/A | 1 | 703 |
| Low | 11 | 1.042 | 733 |
| High | 11 | 1.168 | 821 |
| | Outer Corrosion Barrier | | |
| No | N/A | 1 | 971 |
| Low | 8 | 1.038 | 1,008 |
| High | 8 | 1.154 | 1,121 |

Source: BSC 2004 [DIRS 169705], Table V-3.

The ratio of the maximum stress intensity and true tensile strength is calculated for the inner vessel and outer corrosion barrier for all three strain-rate sensitivity cases. In other words, the maximum stress intensity (Table 45) is divided by the strain-rate-scaled true tensile strength (Table 46). The calculation results are presented in Table 47.

Table 47. Ratio of the Maximum Stress Intensity and True Tensile Strength in the Outer Corrosion Barrier and Inner Vessel for Three Different Levels of Strain-Rate Sensitivity

| Strain-rate Sensitivity | $\sigma_{Int} / \sigma_u$ | |
|---|---|---|
| | Inner Vessel | Outer Corrosion Barrier |
| No | 0.74 | 0.93 |
| Low | 0.72 | 0.94 |
| High | 0.73 | 0.93 |

Source: BSC 2004 [DIRS 169705], Table V-4.

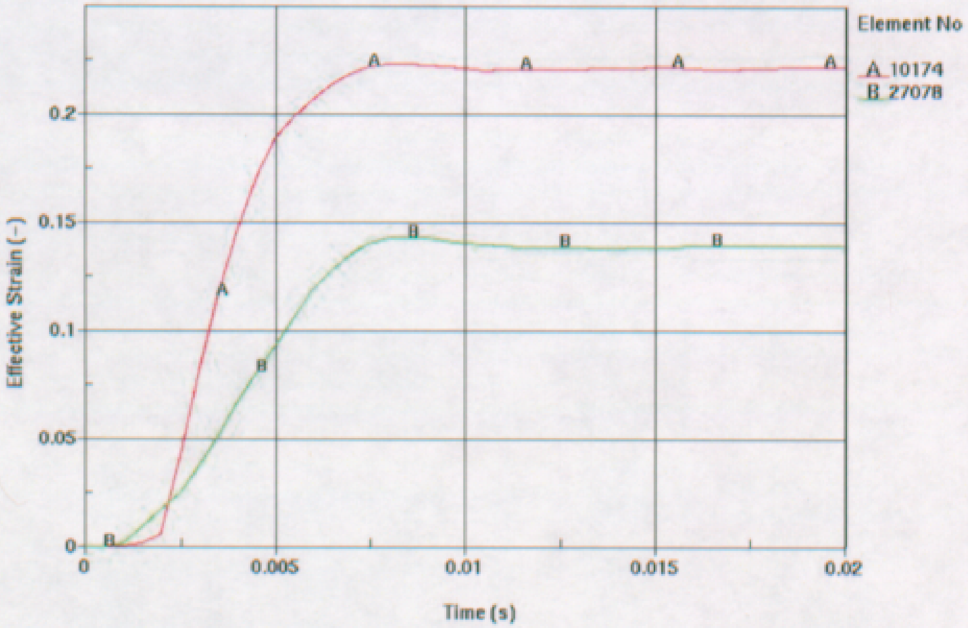
Based on the results presented in Table 47, it can be concluded that:

1. The level of strain-rate sensitivity (i.e., "Low" vs. "High") does not have a significant effect on the ratio of the maximum stress intensity and true tensile strength.

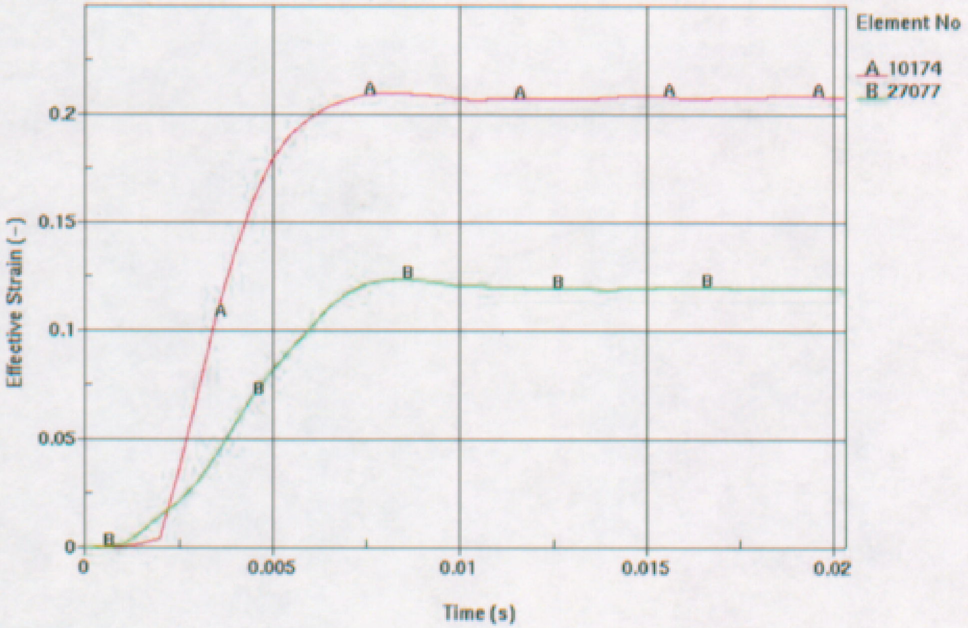
2. The use of the static material properties for the tip-over calculation does not have a significant effect on the ratio of the maximum stress intensity and true tensile strength.

Finally, it is important to note that the strain rates reported in Table 46 are the strain rates corresponding to times when the maximum stress intensities are recorded (as an example, for the outer corrosion barrier it is 0.007 s). At that time, the strain rate in the outer corrosion barrier is in rapid decline. Specifically, for the element characterized by the maximum stress intensity (element 10174; see Figure 12) it is reduced from 70 $s^{-1}$ to 8 $s^{-1}$. This raises fundamental questions. If a material is strengthened by elevated-strain-rate loading and then the rate of loading is reduced, is material strength going to reduce as well? If that is so, what is the characteristic time related to that strength reduction? Can it possibly happen "instantaneously"? These important questions are not addressed in available literature at present. Answering these, and similar, questions would require a detailed insight into mechanical and metallurgical aspects of the strain-rate strengthening of material. However, this is not necessary because the effect of strain-rate strengthening of the material is conservatively accounted for in this calculation by scaling the true tensile strength with the strain-rate factor β corresponding to the instantaneous strain rate at the time when the maximum stress intensity occurs. (As an example, if the strain rate of 70 $s^{-1}$ could be used instead of 8 $s^{-1}$ to scale the true tensile strength for the "High" outer corrosion barrier bound, the increase of the true tensile strength would be from $\sigma_u(\dot{\varepsilon} = 8\ s^{-1}) = 1{,}121$ MPa to $\sigma_u(\dot{\varepsilon} = 70\ s^{-1}) = 1{,}250$ MPa, which would imply the reduction of the stress ratio from 0.93 to 0.90).

Therefore, based on the parametric study for strain-rate effects using stainless steel type 304 strain-rate dependent properties, it has been demonstrated that the use of static properties for stainless steel type 316 and Alloy 22 (UNS N06022) in lieu of material specific strain-rate effects is appropriate.




(a)




(b)

NOTE: (a) Low Strain-Rate Sensitivity and (b) High Strain-Rate Sensitivity.

Source: BSC 2004 [DIRS 169705], Figure V-1.

Figure 11. Effective-Strain Time History for Elements Characterized by the Peak Maximum Stress Intensity in the Inner Vessel (Elements 27077 and 27078) and Outer Corrosion Barrier (Element 10174)

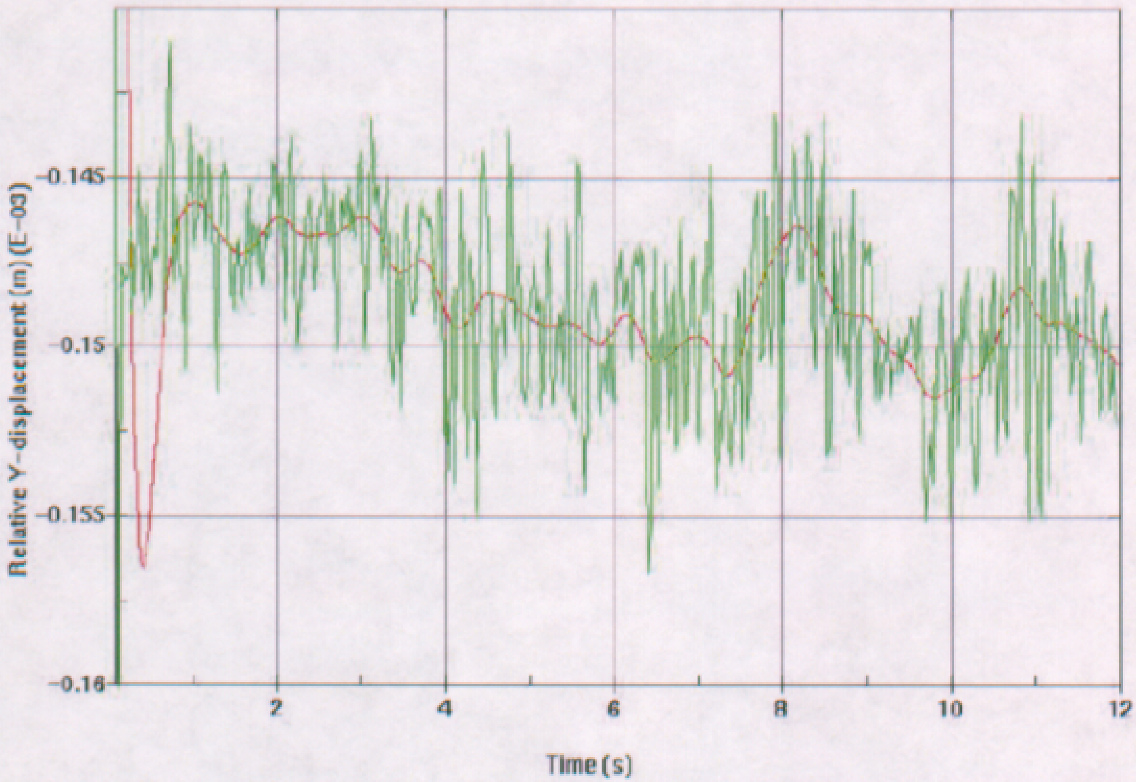
#### 7.1.2.3.2.3 Dimensional and Material Variability

All structural calculations assume the thicknesses for the inner vessel and outer corrosion barrier are the minimum material thicknesses. Future drawings will indicate tolerances that show these dimensions as minimum values. This assures structural design requirements will be achieved.

Maintaining conservative answers due to material variability is managed by using the minimum material-property strengths available (e.g., from the ASME B&PV code and other codes). When available, material properties that are temperature dependent are used for variable-temperature environment calculations. In general, when a range of values is given for material properties, the values that ensure conservative results are used.

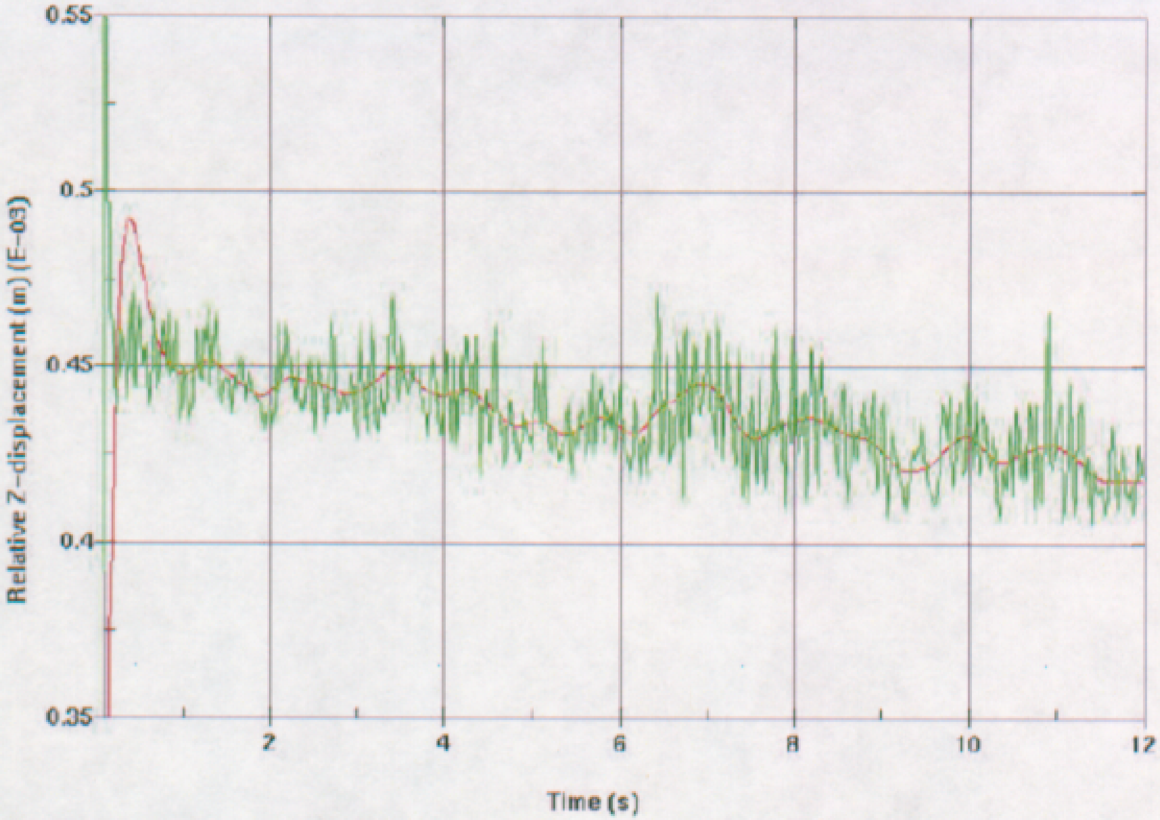
#### 7.1.2.3.2.4 Seismic Effect on Ground Motion

In the surface facility, it is anticipated that fixtures are provided to restrain the waste package during evolutions in that facility, and these devices are sufficient to provide restraint during vibratory ground motion. For vibratory ground motion in the underground, margin to the breach of the waste package has been calculated for vibratory ground motion with an annual exceedance frequency (annual frequency of occurrence) of $5 \times 10^{-4}$ per year. For this calculation, the motion of the waste package was very small, on the order of fractions of millimeters as illustrated in Figure 12 and Figure 13 (BSC 2004 [DIRS 167083], Section 6.3).




Source: BSC 2004 [DIRS 167083], Figure 10.

Figure 12. Relative Longitudinal (Y) Displacement (Raw–green and Filtered–red) of the Waste Package with respect to the Emplacement Pallet for Annual Frequency of Occurrence $5 \times 10^{-4}$ per year




Source: BSC 2004 [DIRS 167083], Figure 11.

Figure 13. Relative Vertical (Z) Displacement (Raw – green and Filtered – red) of the Waste Package with respect to the Emplacement Pallet for Annual Frequency of Occurrence 5 x $10^{-4}$ per year

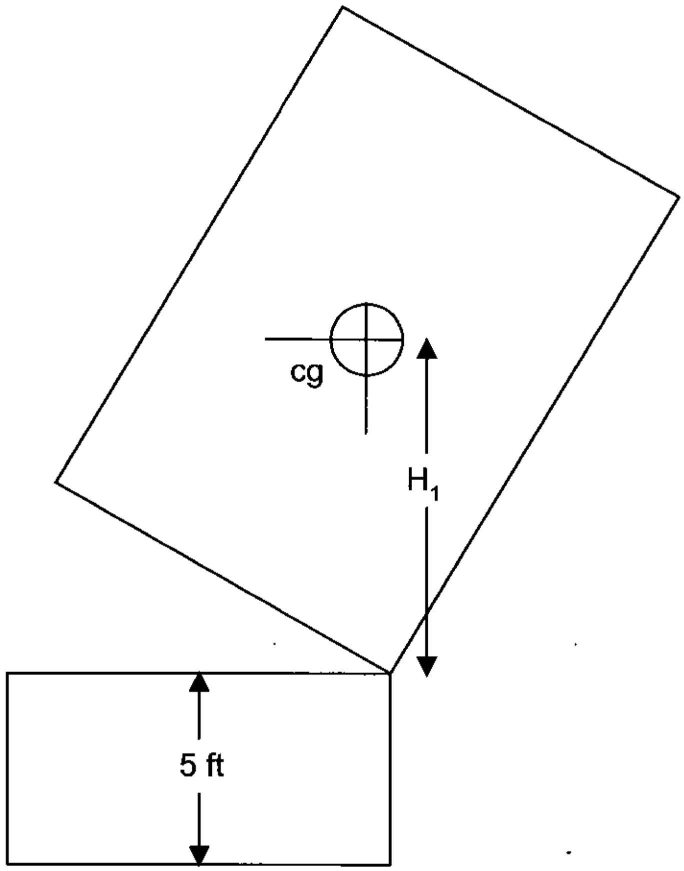
#### 7.1.2.3.2.5 Initial Tip-Over Velocities

A sensitivity study was performed where a range of tip-over velocities were considered and bound those expected in the surface facilities. This evaluation is documented in a calculation entitled *44-BWR Waste Package Tip-Over from an Elevated Surface* (BSC 2004 [DIRS 169705], Attachment IV). The point of incipient toppling is illustrated in Figure 14.

Using the energy method, the rotational velocity of the waste package is calculated at the point just before impact. Table 48 shows a possible range of initial velocities. The peak ground velocity (PGV) is multiplied by values of 0, 1, 5, and 10, to span the parameter space.

$$mg\Delta h = \tfrac{1}{2} I\Delta(\omega^2) \qquad \text{(Eq. 7)}$$

Here, "m" is the mass of the waste package, "g" is the gravitational acceleration constant, "Δh" is the change in the height of the center of gravity of the waste package from the moment of toppling to impact, "I" is the moment of inertia of the waste package, and "ω" is the angular velocity.




Source: BSC 2004 [DIRS 169705], Figure 5-1.

Figure 14. Waste Package Position at Maximum Potential Energy

Evaluating this expression,

$$(43{,}400\,kg)(9.81\,m/s^2)(2.587\,m) = \tfrac{1}{2}(0.4276e^6\,kg \cdot m^2)(\omega^2 - \omega_0{}^2)$$

Here, "$\omega_0$" is the initial angular velocity.

The PGV has a value of 0.4378 m/s (DTN: MO0306SDSAVDTH.000 [DIRS 164033]) on the repository horizon, yielding:

$$\text{PGV } (10^{-4} \text{ event}) = 0.4378\ m/s = V_0$$

(The only ground motions available at this writing for this frequency of exceedance were for the repository horizon. Subsequent to the performance of this work, the PGV for an annual frequency of exceedance of 1x10$^{-4}$ per year at the surface became available (DTN: MO0312WHBDE104.001 [DIRS 167126]). This PGV is 1.17 *m/s*, which is about three times

the velocity at the repository horizon. The corresponding PGVs at the surface are higher and are covered by the sensitivity study range.)
Finally,

$$\omega_0 = V_0/H_1 \qquad \text{(Eq. 8)}$$

In this equation, "$H_1$" is the distance from the center of gravity of the waste package to the bottom edge of the waste package at the point of toppling (see Figure 14).

Note that predicted PGV—albeit at the repository horizon—results in a negligible change in the rotational velocity at impact.

Table 48. Resultant Impact Velocities by Parameter

| Parameter | $V_0$ (m/s) | $\omega_0$ (rad/s) | $\omega$ (rad/s) |
|---|---|---|---|
| PGV*0 | 0 | 0 | 2.27 |
| PGV*1 | 0.438 | 0.161 | 2.27 |
| PGV*5 | 2.19 | 0.812 | 2.41 |
| PGV*10 | 4.38 | 1.62 | 2.79 |

Source: BSC 2004 [DIRS 169705], Table IV-1

The resulting maximum stress intensities for this sensitivity study are shown in Table 49. While substantial increases in initial tip-over velocity result in higher stress levels, the effect is modest and is clearly a second-order effect. Further, for the PGV to be a significant contributor to the angular velocity at impact, the fixturing must fail; the waste package must reach the imminent-toppling configuration at the time of PGV; and the PGV must be applied in the proper direction. These considerations support the conclusion that the current treatment of initial velocity for tip-over calculations is appropriate.

Table 49. Resultant Maximum Stress Intensity by Parameter

| | Part | $\sigma_{int}$ (MPa) | $\sigma_{int} / \sigma_u$ |
|---|---|---|---|
| PGV*0 | Outer Corrosion Barrier | 902 | 0.93 |
| | Inner Vessel | 518 | 0.74 |
| | Inner Lid | 426 | 0.61 |
| | Spread Ring | 286 | 0.41 |
| PGV*5 | Outer Corrosion Barrier | 944 | 0.97 |
| | Inner Vessel | 558 | 0.79 |
| | Inner Lid | 442 | 0.63 |
| | Spread Ring | 292 | 0.42 |
| PGV*10 | Outer Corrosion Barrier | 1079 | 1.1 |
| | Inner Vessel | 644 | 0.92 |
| | Inner Lid | 478 | 0.68 |
| | Spread Ring | 302 | 0.43 |

Source: BSC 2004 [DIRS 169705], Table IV-2.

#### 7.1.2.3.2.6 Sliding and Inertial Effect of Waste Package Contents

Inertial effects of waste package contents are an intrinsic part of dynamic structural calculations performed explicitly by finite element analysis codes. Sliding effects of waste package contents during impacts are evaluated in calculations where the movement of such contents is reasonably anticipated to affect the kinematics and the resulting stress fields. Coefficients of friction are used based on the materials and situation. An example of the treatment of the waste package contents is the calculation entitled *44-BWR Waste Package Tip-Over from an Elevated Surface* (BSC 2004 [DIRS 169705]). In this calculation, the internals of the waste package and the commercial SNF assemblies are explicitly represented (BSC 2004 [DIRS 169705], Section 5.3, p. 17).

When the waste package contents are not considered as important to the resulting measures of waste package performance, those contents are often simplified so that the mass and inertial effects are maintained but geometry is simplified.

## 7.2 POSTCLOSURE

### 7.2.1.1 Thermal

The thermal calculations for normal operations are performed continuously through preclosure and postclosure times. The highest temperatures occur during the postclosure period, a few decades after closure. Temperatures remained about 100°C below the lower 350°C requirement and 250°C below the 500°C requirement. Details are given in Section 7.1.1.1.

### 7.2.1.2 Structural

The same criteria, statically, must be met as in the preclosure time period. Since the calculations were performed using degraded waste packages, the criteria is met (see Section 7.1.1.2).

For seismic concerns, refer to Appendix A of BSC (2004 [DIRS 168217]).

### 7.2.1.3 Criticality

The configurations evaluated for each fuel type include varying degrees of degradation, resulting in many different geometric configurations and fissile distributions. These degraded configurations also bound the other types of fuels in a group as long as the limits on fissile mass, linear fissile loading, and enrichment are not exceeded (DOE 2002 [DIRS 158405], Section 5.2).

Criticality assessments for the different canistered fuels planned for emplacement are not completed at this time for the waste package design configurations as shown in the configuration drawings listed in Section 5.2.

# 8. OPERATIONAL CONSIDERATIONS

## 8.1 INTERFACE REQUIREMENTS

Interface requirements are discussed in this section. Functional requirements are taken from BSC 2004 [DIRS 167273].

Functional Requirement Number: 3.1.3.1

Functional Requirement Title: Waste Package Handling Limits

Functional Requirement Text: Waste package handling shall not introduce any surface defect in the corrosion barrier exceeding those identified by performance assessment and on interface exchange drawings. Surface defects include, but are not limited to, scratches, nicks, dents, and permanent changes to the surface stress condition (Table 50).

Table 50. Waste Package Handling Limits Performance Requirements

| Performance Requirement Number | Performance Requirement Text | Applicability |
|---|---|---|
| 1 | This issue is under investigation and will be resolved prior to construction authorization. A closure weld defect is the area of most concern and shall be limited to 1.6 mm (1/16 inch) (BSC 2004 [DIRS 164475], pp. 59-60). | Yes |

Functional Requirement Number: 3.1.3.2

Functional Requirement Title: Waste Package Closure

Functional Requirement Text: Sealing operations shall be performed on the waste package (Table 51).

Table 51. Waste Package Closure Performance Requirements

| Performance Requirement Number | Performance Requirement Text | Applicability |
|---|---|---|
| 1 | Waste package sealing operations shall meet the requirements for the waste package as specified in the SDD for the waste package closure system. | Yes |

## 8.2 INTERFACE WITH OTHER SYSTEMS

The loaded waste package has its final closure performed by the waste package closure system in accordance with Section 3.1.3.2 of BSC (2004 [DIRS 167273]), at which time it assumes its preclosure and postclosure functions.

During receiving, loading, sealing, and emplacement the waste package is handled by or interfaces with non-nuclear handling system, SNF/HLW transfer system, emplacement and retrieval system, remediation system, and emplacement drift system in addition to the waste package closure system. These systems must comply with Section 3.1.3.1 of BSC (2004 [DIRS 167273]). The waste package passes through the Warehouse and Non-Nuclear Receipt, Dry Transfer, Canister Handling, Remediation, and Subsurface Facilities.

The waste package is handled initially by the trunnions on the trunnion collars. The trunnion collars are installed upon receipt and removed after the waste package is returned to the horizontal position on the pallet. The waste package is loaded and undergoes closure in the vertical position. After the waste package is placed on an emplacement pallet, it is transported to the designated drift for emplacement and the trunnion collar is returned for reuse.

# 9. SUMMARY

This report describes the physical configuration of the HLW/DOE SNF codisposal waste packages, describes the waste forms that they accommodate, and demonstrates how they respond to event sequences and prevent release of radionuclides. Also included are summaries of the assessments of ionizing does rates from the enclosed waste forms and postclosure performance assessments that provide information to Performance Assessment. The results are reasonable compared to the inputs and are suitable for the intended use of this calculation.

The design requirements and the supporting calculations are provided as justification for meeting each criterion in Section 7.1.2. An assessment of applicable design requirements for the 5 DHLW/DOE SNF Short waste package is summarized in Table 52 and are taken from BSC (2004 [DIRS 167273]).

Table 52. Summary of Design Performance Requirements

| Functional Requirement Number | Performance Requirement Number | Performance Requirement | Comment |
|---|---|---|---|
| 3.1.1.1 | 1 | The sealed waste package shall not breach during normal operations or during credible preclosure event sequences. | Compliance demonstrated. |
| 3.1.1.1 | 2 | The waste package shall be designed and constructed to the codes and standards specified in Doraswamy 2004, [DIRS 169548], Section 5.1.1. | Compliance demonstrated. |
| 3.1.1.1 | 3 | Normal operations and credible event sequence load combinations are defined in Mecham 2004, [DIRS 169790], Section 6.2.2.<br><br>Note: The normal operations and credible event sequence load combinations are in Mecham 2004 [DIRS 169790], Section 6.2.2 and are not present in Doraswamy 2004 [DIRS 169548]. | Compliance demonstrated. |
| 3.1.1.1 | 4 | The waste package shall be designed to permit retrieval during the preclosure period until the completion of a performance confirmation program and Commission review of the information obtained from such a program. | Compliance demonstrated. |

| Functional Requirement Number | Performance Requirement Number | Performance Requirement | Comment |
|---|---|---|---|
| 3.1.1.1 | 5 | The waste package shall be designed to permit retrieval during the preclosure period so that any or all of the emplaced waste could be retrieved on a reasonable schedule starting at any time up to 50 years after waste emplacement operations are initiated, unless a different time period is approved or specified by the Commission. | Compliance demonstrated. |
| 3.1.1.1 | 6 | The waste package shall be designed to meet the full range of preclosure operating conditions for up to 300 years after the final waste emplacement. | Compliance demonstrated. |
| 3.1.1.2 | 1 | In conjunction with natural barriers and other engineered barriers, the sealed waste package shall limit transport of radionuclides in a manner sufficient to meet long-term repository performance requirements. | Compliance demonstrated. |
| 3.1.1.2 | 2 | The waste package shall be designed and constructed to the codes and standards specified in Doraswamy 2004 [DIRS 169548], Section 5.1.1. | Compliance demonstrated. |
| 3.1.1.2 | 3 | Normal operations and event load combinations are defined in Mecham 2004 [DIRS 169790], Section 6.2.2.<br><br>Note: The normal operations and credible event sequence load combinations are in Mecham 2004 [DIRS 169790], Section 6.2.2 and are not present in Doraswamy 2004 [DIRS 169548]. | Compliance demonstrated. |
| 3.1.1.3 | 1 | The methodology defined in the *Disposal Criticality Analysis Methodology Topical Report* (YMP 2003 [DIRS 165505]) shall be used to demonstrate acceptable criticality control for waste packages. | Compliance demonstrated. |
| 3.1.1.3 | 2 | The waste package shall meet criteria 4.9.2.2.2 from Doraswamy 2004 [DIRS 169548], Section 4.9.2. | Compliance demonstrated. |
| 3.1.1.4 | 1 | The sealed waste package environment shall provide conditions that maintain waste form characteristics that restrict transport of radionuclides. | Compliance demonstrated. |
| 3.1.1.4 | 2 | The waste package shall maintain all commercial SNF waste forms containing zirconium-based cladding during preclosure and postclosure periods at temperatures that will not accelerate the degradation of the cladding to the point that it affects the performance of the system. | Compliance demonstrated. |
| 3.1.1.4 | 3 | The waste package shall meet the temperature criteria in Doraswamy 2004 [DIRS 169548], Section 5.1.3.2, for all Zirconium clad commercial fuel. | Compliance demonstrated. |
| 3.1.1.4 | 4 | The waste form region of the sealed waste package shall have an inert atmosphere with limited oxidizing agents. | Compliance demonstrated. |
| 3.1.1.5 | 1 | The maximum waste package power at emplacement is 11.8 kW. | Compliance demonstrated. |
| 3.1.2.1 | 1 | Table 9 identifies nominal parameters (size, maximum weight, and materials) of the shipping canisters that may be used in design. | Compliance demonstrated. |
| 3.1.2.3 | 1 | Table 11 identifies the SNF groups that make up DOE SNF. The DOE SNF arrives at the MGR in disposable canisters of the sizes and weights identified in Table 12. | Compliance demonstrated. |

| Functional Requirement Number | Performance Requirement Number | Performance Requirement | Comment |
|---|---|---|---|
| 3.1.3.1 | 1 | This issue is under investigation and will be resolved prior to construction authorization. A closure weld defect is the area of most concern and shall be limited to 1.6 mm (1/16 inch) (BSC 2004 [DIRS 164475], pp. 59-60). | Under investigation |
| 3.1.3.2 | 1 | Sealing operations shall be performed on the waste package. | Compliance demonstrated. |

# 10. REFERENCES

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# APPENDIX A WASTE PACKAGE SURFACE DOSE RATES

The following results are obtained from BSC (2003 [DIRS 166210], Section 6). Tables 53 through 61 present gamma, neutron, and total dose rates averaged over the surface segments of the 5 DHLW/DOE SNF-Short waste package and at 1m (3.3 ft) and 2m (6.6 ft) away from the waste package external surfaces. The MCNP output files associated with the results presented in the tables are provided in the table footnotes. The results for each dose rate component are directly from the associated output file. The waste-package surface dose rates due to secondary gamma rays are negligible as compared to the gamma dose rates; therefore, this dose component is not listed in the summary tables.

Table 53. Dose Rates on the Waste Package Inner Vessel Inner Surface

| Axial Location | Gamma | | Neutron | | Total | |
|---|---|---|---|---|---|---|
| | Dose (rem/hr) | Relative Error | Dose (rem/hr) | Relative Error | Dose (rem/hr) | Relative Error |
| Segment 1 | 2964.48 | 0.0031 | 0.160 | 0.023 | 2964.64 | 0.0031 |
| Segment 2 | 6572.63 | 0.0015 | 0.253 | 0.0143 | 6572.88 | 0.0015 |
| Segment 3 | 7435.69 | 0.0014 | 0.301 | 0.0129 | 7435.99 | 0.0014 |
| Segment 4 | 7521.66 | 0.0014 | 0.309 | 0.0126 | 7521.97 | 0.0014 |
| Segment 5 | 7443.30 | 0.0014 | 0.306 | 0.0131 | 7443.61 | 0.0014 |
| Segment 6 | 6451.38 | 0.0015 | 0.256 | 0.0143 | 6451.64 | 0.0015 |

Source: BSC 2003 [DIRS 166210], Table 21.

Table 54. Dose Rates on the Waste Package Inner Vessel Outer Surface

| Axial Location | Gamma [a] | | Neutron [b] | | Total [c] | |
|---|---|---|---|---|---|---|
| | Dose (rem/hr) | Relative Error | Dose (rem/hr) | Relative Error | Dose (rem/hr) | Relative Error |
| Segment 1 | 141.201 | 0.006 | 0.079 | 0.0205 | 141.280 | 0.0060 |
| Segment 2 | 354.551 | 0.0027 | 0.131 | 0.0133 | 354.682 | 0.0027 |
| Segment 3 | 393.845 | 0.0025 | 0.157 | 0.0121 | 394.002 | 0.0025 |
| Segment 4 | 394.811 | 0.0025 | 0.159 | 0.0118 | 394.970 | 0.0025 |
| Segment 5 | 394.581 | 0.0025 | 0.157 | 0.012 | 394.738 | 0.0025 |
| Segment 6 | 343.236 | 0.0027 | 0.133 | 0.0134 | 343.369 | 0.0027 |

Source: BSC 2003 [DIRS 166210], Table 22.

Table 55. Dose Rates on the Waste Package Outer Barrier Outer Surface

| Axial Location | Gamma | | Neutron | | Total [a] | |
|---|---|---|---|---|---|---|
| | Dose (rem/hr) | Relative Error | Dose (rem/hr) | Relative Error | Dose (rem/hr) | Relative Error |
| Segment 1 | 26.829 | 0.0076 | 0.036 | 0.0184 | 26.866 | 0.0076 |
| Segment 2 | 66.815 | 0.0035 | 0.059 | 0.0125 | 66.874 | 0.0035 |
| Segment 3 | 74.566 | 0.0033 | 0.070 | 0.0114 | 74.636 | 0.0033 |
| Segment 4 | 74.847 | 0.0033 | 0.070 | 0.0111 | 74.918 | 0.0033 |
| Segment 5 | 74.471 | 0.0033 | 0.070 | 0.0113 | 74.541 | 0.0033 |
| Segment 6 | 64.113 | 0.0035 | 0.059 | 0.0125 | 64.172 | 0.0035 |

NOTE: [a] The gamma dose rates in Table 55, and Table 56 vary only within statistical limits.
Source: BSC 2003 [DIRS 166210], Table 23.

Table 56. Dose Rates on the Waste Package Outer Barrier Outer Surface by Source

| Axial Location | DHLW Glass Primary Gamma | | TRIGA Primary Gamma | | Total [a] | |
|---|---|---|---|---|---|---|
| | Dose (rem/hr) | Relative Error | Dose (rem/hr) | Relative Error | Dose (rem/hr) | Relative Error |
| Segment 1 | 23.693 | 0.0078 | 4.458 | 0.009 | 28.151 | 0.0067 |
| Segment 2 | 59.890 | 0.0034 | 6.983 | 0.0048 | 66.873 | 0.0031 |
| Segment 3 | 65.903 | 0.0032 | 8.726 | 0.0043 | 74.629 | 0.0029 |
| Segment 4 | 66.230 | 0.0032 | 8.883 | 0.0042 | 75.114 | 0.0029 |
| Segment 5 | 65.919 | 0.0032 | 8.470 | 0.0044 | 74.389 | 0.0029 |
| Segment 6 | 59.305 | 0.0034 | 5.029 | 0.0055 | 64.334 | 0.0032 |

NOTE: [a] The gamma dose rates in Table 55, and Table 56 vary only within statistical limits.
Source: BSC 2003 [DIRS 166210], Table 24.

Table 57. Dose Rates 1m from the Waste Package Outer Barrier Outer Surface

| Axial Location | Gamma | | Neutron | | Total | |
|---|---|---|---|---|---|---|
| | Dose (rem/hr) | Relative Error | Dose (rem/hr) | Relative Error | Dose (rem/hr) | Relative Error |
| Segment 1 | 15.727 | 0.004 | 0.017 | 0.0078 | 15.744 | 0.0040 |
| Segment 2 | 22.916 | 0.0027 | 0.021 | 0.0068 | 22.937 | 0.0027 |
| Segment 3 | 29.132 | 0.0025 | 0.025 | 0.0064 | 29.157 | 0.0025 |
| Segment 4 | 30.679 | 0.0024 | 0.026 | 0.0062 | 30.705 | 0.0024 |
| Segment 5 | 28.731 | 0.0025 | 0.025 | 0.0064 | 28.756 | 0.0025 |
| Segment 6 | 21.798 | 0.0028 | 0.020 | 0.0069 | 21.818 | 0.0028 |

Source: BSC 2003 [DIRS 166210], Table 25.

Table 58. Dose Rates 2m from the Waste Package Outer Barrier Outer Surface

| Axial Location | Gamma | | Neutron | | Total | |
|---|---|---|---|---|---|---|
| | Dose (rem/hr) | Relative Error | Dose (rem/hr) | Relative Error | Dose (rem/hr) | Relative Error |
| Segment 1 | 11.020 | 0.0035 | 0.013 | 0.0067 | 11.033 | 0.0035 |
| Segment 2 | 13.751 | 0.0026 | 0.014 | 0.006 | 13.765 | 0.0026 |
| Segment 3 | 16.482 | 0.0024 | 0.016 | 0.0059 | 16.497 | 0.0024 |
| Segment 4 | 17.361 | 0.0024 | 0.016 | 0.0058 | 17.377 | 0.0024 |
| Segment 5 | 16.188 | 0.0024 | 0.016 | 0.0059 | 16.203 | 0.0024 |
| Segment 6 | 13.277 | 0.0026 | 0.014 | 0.0060 | 13.290 | 0.0026 |

Source: BSC 2003 [DIRS 166210], Table 26.

Table 59. Dose Rates at the Waste Package Surface

| | | Gamma | | Neutron | | Total | |
|---|---|---|---|---|---|---|---|
| **Axial Location** | **Segment** | **Dose (rem/hr)** | **Relative Error** | **Dose (rem/hr)** | **Relative Error** | **Dose (rem/hr)** | **Relative Error** |
| Lower Inner Vessel top surface | Segment 7 | 6161.90 | 0.0039 | 0.675 | 0.0234 | 6162.58 | 0.004 |
| | Segment 8 | 5453.96 | 0.002 | 0.199 | 0.018 | 5454.16 | 0.002 |
| Lower Inner Vessel bottom surface | Segment 7 | 165.66 | 0.0138 | 0.106 | 0.034 | 165.77 | 0.014 |
| | Segment 9 | 248.02 | 0.0035 | 0.110 | 0.016 | 248.13 | 0.003 |
| Outer Barrier Bottom Surface | Segment 7 | 41.92 | 0.0174 | 0.050 | 0.0327 | 41.97 | 0.017 |
| | Segment 10 | 43.81 | 0.0046 | 0.048 | 0.0153 | 43.86 | 0.005 |
| 1m from Outer Barrier Bottom | WP bottom | 22.14 | 0.005 | 0.019 | 0.013 | 22.16 | 0.005 |
| 2m from Outer Barrier Bottom | WP bottom | 12.38 | 0.0057 | 0.012 | 0.0117 | 12.39 | 0.006 |
| Top of Waste Package Cavity | Segment 7 | 1358.74 | 0.0094 | 0.129 | 0.0517 | 1358.87 | 0.009 |
| | Segment 8 | 3066.65 | 0.0024 | 0.164 | 0.0199 | 3066.81 | 0.002 |
| Outer Lid Bottom Surface | Segment 7 | 91.08 | 0.0155 | 0.069 | 0.0375 | 91.15 | 0.015 |
| | Segment 9 | 88.50 | 0.0048 | 0.069 | 0.0182 | 88.57 | 0.005 |
| Outer Lid Top Surface | Segment 7 | 22.90 | 0.0212 | 0.030 | 0.0375 | 22.93 | 0.021 |
| | Segment 10 | 17.12 | 0.0066 | 0.031 | 0.0175 | 17.15 | 0.007 |
| 1m from Outer Lid Top Surface | WP top | 9.57 | 0.0068 | 0.014 | 0.0141 | 9.59 | 0.007 |
| 2m from Outer Lid Top Surface | WP top | 5.76 | 0.0074 | 0.009 | 0.0121 | 5.77 | 0.007 |

Source: BSC 2003 [DIRS 166210], Table 27.

Table 60. Dose Rates Averaged over the Angular Segment a (Unshadowed)

| | Gamma | | Neutron | | Total | |
|---|---|---|---|---|---|---|
| Axial Location | Dose (rem/hr) | Relative Error | Dose (rem/hr) | Relative Error | Dose (rem/hr) | Relative Error |
| Angular Segment a [a, b] | | | | | | |
| 1 | 26.75 | 0.0245 | 0.036 | 0.0565 | 26.79 | 0.0245 |
| 2 | 68.79 | 0.0109 | 0.058 | 0.038 | 68.84 | 0.0109 |
| 3 | 73.29 | 0.0104 | 0.069 | 0.0364 | 73.36 | 0.0104 |
| 4 | 74.02 | 0.0104 | 0.069 | 0.0339 | 74.09 | 0.0104 |
| 5 | 73.25 | 0.0104 | 0.071 | 0.0354 | 73.32 | 0.0104 |
| 6 | 68.87 | 0.0108 | 0.057 | 0.0376 | 68.92 | 0.0108 |

NOTES: [a]Dose rates on angular sections c, e, g, and i shown in Figure 6 vary only within statistical limits.
[b]See Figure 4 for segment locations.
Source: BSC 2003 [DIRS 166210], Table 28.

Table 61. Dose Rates Averaged over the Angular Segment b (Shadowed)

| | Gamma | | Neutron | | Total | |
|---|---|---|---|---|---|---|
| Axial Location | Dose (rem/hr) | Relative Error | Dose (rem/hr) | Relative Error | Dose (rem/hr) | Relative Error |
| Angular Segment b [a,b] | | | | | | |
| 1 | 30.10 | 0.0251 | 0.038 | 0.0511 | 30.14 | 0.0251 |
| 2 | 65.36 | 0.0114 | 0.059 | 0.0335 | 65.42 | 0.0114 |
| 3 | 77.03 | 0.0104 | 0.072 | 0.0306 | 77.10 | 0.0104 |
| 4 | 76.32 | 0.0104 | 0.074 | 0.0301 | 76.39 | 0.0104 |
| 5 | 75.13 | 0.0101 | 0.071 | 0.0307 | 75.20 | 0.0101 |
| 6 | 61.52 | 0.0112 | 0.061 | 0.0328 | 61.58 | 0.0112 |

NOTES: [a]Dose rates on the angular sections d, f, h, and j shown in Figure 6 vary only within statistical limits.
[b]See Figure 4 for segment locations.
Source: BSC 2003 [DIRS 166210], Table 29

**BSC**

# Engineering Change Notice

*Complete only applicable items.*

1. QA: QA
2. Page 1 of 1

000-00C-DS00-00600-000-00B-ECN1

| 3. Document Identifier: | 4. Rev.: | 5. Title: | 6. ECN: |
|---|---|---|---|
| 000-00C-DS00-00600-000-00B | 00B | HLW/DOE SNF Codisposal Waste Package Design Report | 1 |

7. Reason for Change:

Per LP-3.12Q-BSC Design Calculations and Analyses Section 5.1 [2]c,

"The decision of the DEM, PCSA Manager, Criticality Manager, or PCA Manager to issue calcualtions or analyses with a "committed" status will be based on an experienced assessment of the likelihood that the results of the calculation or analysis will change, and the degree of impact those changes will have on designs that support the regulatory submittals or procurement activities, based on the design bounding conservatism."

The status designation of *HLW/DOE SNF Codisposal Waste Package Design Report* (000-00C-DS00-00600-000-00B) can be changed to "Committed" as the results are not expected to change in such a manner that will affect support of regulatory submittals.

8. Supersedes Change Document: ☐ Yes If, Yes, Change Doc.: ________ ☒ No

9. Change Impact:

| | | | | | |
|---|---|---|---|---|---|
| Inputs Changed: | ☐ Yes | ☒ No | Results Impacted: | ☐ Yes | ☒ No |
| Assumptions Changed: | ☐ Yes | ☒ No | Design Impacted: | ☐ Yes | ☒ No |

10. Description of Change: (Address any "Yes" answers)

Add a "Committed" option in Block 7. On the cover sheet and change the "Document Status Designation" from Preliminary to "Committed". Block 7 on the cover sheet should read as follows

7. Document Status Designation:
☐ Preliminary ☒ Committed ☐ Final ☐ Cancelled

| | | |
|---|---|---|
| 11. Originator: (Print/Sign/Date) Tim Schmitt | Tim Schmitt | 8/12/05 |
| Checker: (Print/Sign/Date) Michael Mullin | Michael Mullin | 8/12/05 |
| Approved: (Print/Sign/Date) Michael J. Anderson | M J Anderson | 8/12/05 |

| BSC | Calculation/Analysis Change Notice | 1. QA: QA |
|---|---|---|
| | *Complete only applicable items.* | 2. Page 1 of 1 |

**000-00C-DS00-00600-000-00B-CACN001**

| 3. Document Identifier: | 4. Rev.: | 5. CACN: |
|---|---|---|
| 000-00C-DS00-00600-000-00B | 00B | 001 |

6. Title:
HLW/DOE SNF Codisposal Waste Package Design Report

7. Reason for Change:
Correct minor errors and omissions. This ECN is justification for closing CA 8293-004 and CA 8293-001.

8. Supersedes Change Notice: ☐ Yes If, Yes, CACN No.: ______ ☒ No

9. Change Impact:

| | | | | | |
|---|---|---|---|---|---|
| Inputs Changed: | ☐ Yes | ☒ No | Results Impacted: | ☐ Yes | ☒ No |
| Assumptions Changed: | ☐ Yes | ☒ No | Design Impacted: | ☐ Yes | ☒ No |

10. Description of Change:
Section 7.1.1.2.1, 1st paragraph, after last sentence insert: "These temperatures bound the range of temperatures shown in Figure 2."

Page 35 of 98, 2nd Paragraph, change 2nd sentence to: "From Tables 16 and 17, the tensile stress at Point A (see Figure 3) cycles from zero to approximately 160 MPa."

Section 7.1.2.2.4, 3rd Paragraph, change 2nd sentence to: "This wall-averaged stress intensity is divided by the true tensile strength."

Section 7.1.2.2.9, 1st Paragraph, 8th line: change "100°C" to "300°C"

Section 7.2.1.2, 1st Paragraph: change " 7.1.1.2" to "7.1.1.2.5"

Page 74 of 98, 1st Paragraph, 3rd Line: Change "Figure 12" to "Figure 11".

Add the following reference in Section 10:
[DIRS 164475] BSC 2003. Analysis of Mechanisms for Early Waste Package/Drip Shield Failure. CAL-EBS-MD-000030 REV 00B. Bechtel SAIC Company. ACC: DOC.20031001.0012.

**11. REVIEWS AND APPROVAL**

| Printed Name | Signature | Date |
|---|---|---|
| 11a. Originator: Del Mecham | Del Mecham | 12/7/06 |
| 11b. Checker: Ken Jaquay | [signature] | 12/7/06 |
| 11c. DEM: Michael Anderson | [signature] | 12/7/06 |
| 11d. Design Authority: Barbara Rusinko | [signature] for BR | 12/7/06 |