SAFETY ANALYSIS REPORT

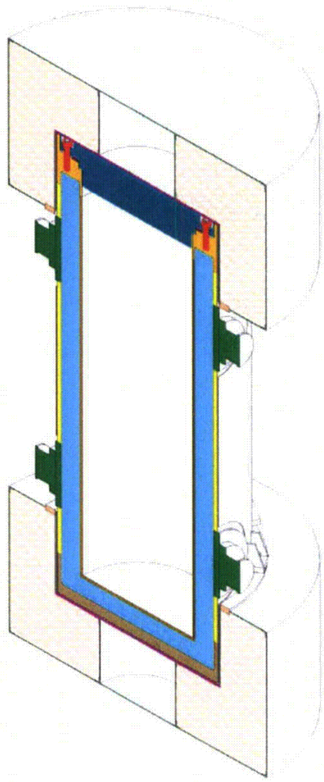
FOR

MODEL 3-60B

TYPE B SHIPPING CASK

Revision 4

January 2014



ENERGYSOLUTIONS

This page intentionally blank.

TABLE OF CONTENTS

1.0 GENERAL INFORMATION 1-1

1.1 Introduction 1-1

1.2 Package Description 1-1

1.2.1 Packaging 1-1

1.2.2 Contents 1-5

1.2.3 Special Requirements For Plutonium 1-6

1.2.4 Operational Features 1-6

1.3 Appendix 1-9

2.0 STRUCTURAL EVALUATION 2-1

2.1 Description of Structural Design 2-1

2.1.1 Discussion 2-1

2.1.2 Design Criteria 2-2

2.1.3 Weight and Center of Gravity 2-4

2.1.4 Identification of Codes and Standards for Package Design 2-4

2.2 Materials 2-4

2.2.1 Material Properties and Specifications 2-4

2.2.2 Chemical Galvanic and Other Reactions 2-5

2.2.3 Effects of Radiation on Materials 2-6

2.3 Fabrications and Examination 2-6

2.3.1 Fabrication 2-6

2.3.2 Examination 2-6

2.4 General Requirements for All Packages 2-7

2.4.1 Minimum Packaging Size 2-7

2.4.2 Tamper-Indicating Features 2-7

2.4.3 Positive Closures 2-7

2.5 Lifting and Tie-down Standards for All Packages 2-7

2.5.1 Lifting Devices 2-8

2.5.2 Tie-Down Devices 2-9

2.6 Normal Conditions of Transport 2-10
2.6.1 Heat 2-11
2.6.2 Cold 2-12
2.6.3 Reduced External Pressure 2-13
2.6.4 Increased External Pressure 2-14
2.6.5 Vibration 2-14
2.6.6 Water Spray 2-17
2.6.7 Free Drop 2-17
2.6.8 Corner Drop 2-18
2.6.9 Compression 2-18
2.6.10 Penetration 2-18

2.7 Hypothetical Accident Conditions 2-19
2.7.1 Free Drop 2-19
2.7.2 Crush 2-30
2.7.3 Puncture 2-30
2.7.4 Thermal 2-31
2.7.5 Immersion – Fissile material 2-32
2.7.6 Immersion – All packages 2-32
2.7.7 Deep Water Immersion Test 2-32
2.7.8 Summary of Damage 2-33

2.8 Accident Conditions for Air Transport of Plutonium 2-33

2.9 Accident Conditions for Fissile Material Packages for Air Transport 2-34

2.10 Special Form 2-34

2.11 Fuel Rods 2-34

2.12 Appedix 2-35
2.12.1 References 2-35

3.0 THERMAL EVALUATION 3-1

3.1 Description of thermal design 3-1
3.1.1 Design Features 3-1
3.1.2 Content's Decay Heat 3-1

3.1.3 Summary Tables of Temperatures 3-1
3.1.4 Summary Table of Maximum Pressures 3-2

3.2 Material Properties and Component Specifications 3-2
3.2.1 Material Properties 3-2
3.2.2 Component Specifications 3-2

3.3 Thermal Evaluation for Normal Conditions of Transport 3-2
3.3.1 Heat and Cold 3-3
3.3.2 Maximum Normal Operating Pressure 3-4
3.3.3 Thermal Stresses 3-8

3.4 Hypothetical Accident Thermal Evaluation 3-8
3.4.1 Initial Conditions 3-9
3.4.2 Fire Test Conditions 3-9
3.4.3 Maximum Temperatures and Pressure 3-10
3.4.4 Maximum Thermal Stresses 3-11
3.4.5 Accident Conditions for Fissile Packages for Air Transport 3-11

3.5 Appendix 3-12
3.5.1 References 3-12
3.5.2 Attachments 3-13

4.0 CONTAINMENT 4-1

4.1 DESCRIPTION OF CONTAINMENT SYSTEM 4-1

4.2 CONTAINMENT UNDER NORMAL CONDITIONS OF TRANSPORT 4-4
4.2.1 Pressurization of Containment Vessel 4-4
4.2.2 Containment Criteria 4-4
4.2.3 Compliance with Containment Criteria 4-4

4.3 CONTAINMENT UNDER HYPOTHETICAL ACCIDENT CONDITIONS 4-4
4.3.1 Pressurization of Containment Vessel 4-4
4.3.2 Containment Criteria 4-4
4.3.3 Compliance with Containment Criteria 4-4

4.4 Leakage Rate Tests for Type B Packages 4-5
4.4.1 Fabrication Leak Rate Test 4-5

4.4.2 Maintenance Leak Rate Test 4-5
4.4.3 Periodic Leak Rate Test 4-5
4.4.4 Pre-shipment Leak Rate Test 4-5
4.5 Appendix 4-9
4.5.1 References 4-9
5.0 SHIELDING EVALUATION 5-1
5.1 DESCRIPTION OF DESIGN FEATURES 5-1
5.1.1 Shielding Design Features 5-1
5.1.2 Maximum Radiation Levels 5-2
5.2 Source Specification 5-3
5.2.1 Gamma Source 5-3
5.2.2 Neutron Sources 5-3
5.3 Model Specification 5-3
5.3.1 Configuration of Source and Shielding 5-3
5.3.2 Material Properties 5-9
5.4 Shielding Evaluation 5-9
5.4.1 Methods 5-9
5.4.2 Input and Output Data 5-9
5.4.3 Flux-to-Dose-Rate Conversion 5-11
5.4.4 External Radiation Levels 5-12
5.5 Appendix 5-14
5.5.1 References 5-14
6.0 CRITICALITY EVALUATION 6-1
7.0 PACKAGE OPERATIONS 7-1
7.1 Package Loading 7-1
7.1.1 Preparation for Loading 7-1
7.1.2 Loading of Contents 7-3
7.1.3 Preparation for Transport 7-5
7.2 Package unloading 7-6

7.2.1 Receipt of Package from Carrier 7-6
7.2.2 Removal of Contents 7-6

7.3 PREPARATION OF AN EMPTY PACKAGE FOR TRANSPORT 7-6
7.3.1 Preparation 7-6
7.3.2 Special Preparations 7-7

8.0 ACCEPTANCE TESTS AND MAINTENANCE PROGRAM 8-1

8.1 Acceptance Tests 8-1
8.1.1 Visual Inspections and Measurements 8-1
8.1.2 Weld Examinations 8-1
8.1.3 Structural and Pressure Tests 8-1
8.1.4 Leakage Tests 8-2
8.1.5 Component and Material Tests 8-2
8.1.6 Shielding Tests 8-3
8.1.7 Thermal Tests 8-3
8.1.8 Miscellaneous Tests 8-3

8.2 Maintenance Program 8-3
8.2.1 Structural and Pressure Tests 8-3
8.2.2 Leakage Tests 8-4
8.2.3 Component and Material Tests 8-7
8.2.4 Thermal Tests 8-9
8.2.5 Miscellaneous Tests 8-9

8.3 Appendices 8-10
8.3.1 References 8-10

This page intentionally blank.

LIST OF TABLES

TABLE NO. DESCRIPTION PAGE

Table 2-1 - Summary of Load Combinations for Normal and Accident Condition Loading.. 2-37

Table 2-2 - Allowable Stresses 2-38

Table 2-3 - Stress Component Definition 2-39

Table 2-4 - Material Properties 2-40

Table 2-5 - Stress Intensities in 3-60B Cask under Hot Environment Loading 2-41

Table 2-6 - Stress Intensities in 3-60B Cask under Cold Environment Loading..... 2-42

Table 2-7 - Stress Intensities in 3-60B Cask under Reduced External Pressure 2-43

Table 2-8 - Stress Intensities in 3-60B Cask under Increased External Pressure and Immersion2-44

Table 2-9 - NCT Free Drop Test Summary 2-45

Table 2-10 - Stress Intensities in 3-60B Cask under 1-ft End Drop – Hot Condition 2-46

Table 2-11 - Stress Intensities in 3-60B Cask under 1-ft End Drop – Cold Condition 2-47

Table 2-12 - Stress Intensities in 3-60B Cask under 1-ft Side Drop – Hot Condition 2-48

Table 2-13 - Stress Intensities in 3-60B Cask under 1-ft Side Drop – Cold Condition..... 2-49

Table 2-14 - Stress Intensities in 3-60B Cask under 1-ft Corner Drop – Hot Condition 2-50

Table 2-15 - Stress Intensities in 3-60B Cask under 1-ft Corner Drop – Cold Condition..... 2-51

Table 2-16 - Hypothetical Accident Condition Drop Test Summary 2-52

Table 2-17 - Stress Intensities in 3-60B Cask under 30-ft End Drop – Hot Condition 2-53

Table 2-18 - Stress Intensities in 3-60B Cask under 30-ft End Drop – Cold Condition 2-54

Table 2-19 - Stress Intensities in 3-60B Cask under 30-ft Side Drop – Hot Condition 2-55

Table 2-20 - Stress Intensities in 3-60B Cask under 30-ft Side Drop – Cold Condition..... 2-56

Table 2-21 - Stress Intensities in 3-60B Cask under 30-ft Corner Drop – Hot Condition 2-57

Table 2-22 - Stress Intensities in 3-60B Cask under 30-ft Corner Drop – Cold Condition..... 2-58

Table 2-23 - Maximum Impact Limiter Attachment Force during Various HAC Drop Tests 2-59

Table 2-24 - Maximum Stress Intensities in 3-60B Cask HAC Fire(1) 2-60

Table 3-1 - Summary of Maximum NCT Temperatures 3-19

Table 3-2 - Summary of Maximum HAC Fire Temperatures 3-19

Table 3-3 - Summary of Cask Cavity Temperatures during NCT and HAC Fire Test 3-20

Table 3-4 - Summary of Maximum Pressures during NCT and HAC Fire Test 3-20

Table 3-5 - Temperature-Independent Metal Thermal Properties 3-20

Table 3-6 - Temperature-Dependent Metal Thermal Properties.. 3-21

Table 3-7 - Temperature-Dependent Air Thermal Properties.. 3-22

Table 4-1 - Leakage Tests of the 3-60B Package 4-6

Table 5-1 - Cask Components.. 5-1

Table 5-2 - Summary of Maximum Radiation Levels - Irradiated Hardware 5-2

Table 5-3 - Summary of Maximum Radiation Levels - Swarf 5-2

Table 5-4 - Model Shielding Elements 5-4

Table 5-5 - Geometry Parameters 5-11

Table 5-6 - Gamma-Ray-Flux-To-Dose-Rate Conversion Factors 5-12

Table 5-7 - NCT Maximum Dose Rates 5-13

Table 5-8 - HAC Maximum Dose Rates at 1 meter from Package 5-13

LIST OF FIGURES

FIG. NO. DESCRIPTION PAGE

Figure 1-1 - 3-60B General Arrangement 1-7

Figure 1-2 - Typical Secondary Container 1-8

Figure 2-1 - 3-60B Cask – Component Nomenclature 2-61

Figure 2-2 - Polyurethane Foam Stress-Strain Properties Parallel to Rise Direction 2-62

Figure 2-3 - Polyurethane Foam Stress-Strain Properties Perpendicular to Rise Direction 2-63

Figure 2-4 - Loads on the Trunnions during Lifting and Handling Operation and per the Regulatory Requirement 2-64

Figure 2-5 - Finite Element Model of the 3-60B Cask Trunnion & its Vicinity 2-65

Figure 2-6 - Stress Intensity Plot – Longitudinal Loading 2-66

Figure 2-7 - Stress Intensity in the Shell – Longitudinal Loading 2-67

Figure 2-8 - Stress Intensity in the Trunnion – Longitudinal Loading 2-68

Figure 2-9 - Stress Intensity Plot – Radial Loading 2-69

Figure 2-10 - Stress Intensity in the Shell – Radial Loading 2-70

Figure 2-11 - Stress Intensity in the Trunnion – Radial Loading 2-71

Figure 2-12 - Stress Intensity Plot – Lateral Loading 2-72

Figure 2-13 - Stress Intensity in the Shell – Lateral Loading 2-73

Figure 2-14 - Stress Intensity in the Trunnion – Lateral Loading 2-74

Figure 2-15 - Stress Intensity Plot – Combined Loading 2-75

Figure 2-16 - Stress Intensity in the Shell – Combined Loading 2-76

Figure 2-17 - Stress Intensity in the Trunnion – Combined Loading 2-77

Figure 2-18 - Finite Element Model of the 3-60B Cask Identifying the Components by Material Numbers 2-78

Figure 2-19 - Temperature Distribution in the Cask – Hot Environment 2-79

Figure 2-20 - Stress Intensity Contour Plot – Hot Environment 2-80

Figure 2-21 - Temperature Distribution in the Cask – Cold Environment ... 2-81

Figure 2-22 - Stress Intensity Contour Plot – Cold Environment ... 2-82

Figure 2-23 - Stress Intensity Contour Plot – Reduced External Pressure ... 2-83

Figure 2-24 - Stress Intensity Contour Plot – Increased External Pressure ... 2-84

Figure 2-25 - LS-DYNA Model of the 3-60B Cask & Rigid Pad ... 2-85

Figure 2-26 - Impact Limiter Shell and Attachment Model ... 2-86

Figure 2-27 - End Drop Orientation ... 2-87

Figure 2-28 - Side Drop Orientation ... 2-88

Figure 2-29 - Corner Drop Orientation ... 2-89

Figure 2-30 - Shallow Angle Drop Orientation ... 2-90

Figure 2-31 - Time-History Result, 30-Ft End Drop, Cold Condition (Resultant Force Plot) 2-91

Figure 2-32 - Time-History Result, 30-Ft End Drop, Cold Condition (Energy Plots) ... 2-92

Figure 2-33 - Finite Element Model of the 3-60B Cask Identifying the Cask Components with Material Numbers ... 2-93

Figure 2-34 - Finite Element Model of the Lid, Seal Plate and Bolts ... 2-94

Figure 2-35 - Finite Element Model of the cask Body without the Lead ... 2-95

Figure 2-36 - Load Distribution on the Model during End Drop ... 2-96

Figure 2-37 - Stress Intensity Plot – 30-ft End Drop – Hot Condition ... 2-97

Figure 2-38 - Stress Intensity Plot – 30-ft End Drop – Cold Condition (Max. Decay Heat) .. 2-98

Figure 2-39 - Stress Intensity Plot – 30-ft End Drop – Cold Condition (No Decay Heat) ... 2-99

Figure 2-40 - Load Distribution on the Model during Side Drop ... 2-100

Figure 2-41 - Stress Intensity Plot – 30-ft Side Drop – Hot Condition ... 2-101

Figure 2-42 - Stress Intensity Plot – 30-ft Side Drop – Cold Condition (Max. Decay Heat) 2-102

Figure 2-43 - Stress Intensity Plot – 30-ft Side Drop – Cold Condition (No Decay Heat) ... 2-103

Figure 2-44 - Load Distribution on the Model during Corner Drop ... 2-104

Figure 2-45 - Stress Intensity Plot – 30-ft Corner Drop – Hot Condition ... 2-105

Figure 2-46 - Stress Intensity Plot – 30-ft Corner Drop – Cold Condition (Max. Decay Heat).. 2-106

Figure 2-47 - Stress Intensity Plot – 30-ft Corner Drop – Cold Condition (No Decay Heat)2-107

Figure 2-48 - 30-ft Bottom-End Down Drop - Displacement.. 2-108

Figure 2-49 - Finite Element Model of the 3-60B Cask for Puncture Drop on the Sidewall Analysis.. 2-109

Figure 2-50 - Force-Deflection Plot at the Point of Impact.. 2-110

Figure 2-51 - Energy versus Deflection Plot 2-111

Figure 2-52 - Maximum Stress Intensity in the Outer Shells of the Cask under Puncture Drop. 2-112

Figure 2-53 - Maximum Stress Intensity in the Cask under Puncture Drop on the Lid 2-113

Figure 2-54 - Maximum Stress Intensity in the Lid under Puncture Drop (Hot Conditions) 2-114

Figure 2-55 - Maximum Stress Intensity in the Lid under Puncture Drop (Cold Conditions).... 2-115

Figure 3-1 - 3-60B Cask Design Features Important to Thermal Performance...................... 3-23

Figure 3-2 - Finite Element Model of the 3-60B Cask Used for the Thermal Analyses 3-24

Figure 3-3 - Materials Used in the Finite Element Model 3-25

Figure 3-4 - Temperature Distribution – Hot Environment.. 3-26

Figure 3-5 - Temperature Distribution – Cold Environment 3-27

Figure 3-6 - Temperature Distribution – Normal Hot 3-28

Figure 3-7 - Temperature Distribution – Normal Cold.. 3-29

Figure 3-8 - HAC Fire Analysis Load Steps and Boundary Conditions................................ 3-30

Figure 3-9 - Identification of the Nodes where Time-History is Monitored 3-31

Figure 3-10 - Temperature Time-History Plot in Various Components of the Cask............... 3-32

Figure 3-11 - Temperature Time-History Plot in Various Components of the Cask (Not Under Direct Contact with the Fire) 3-33

Figure 3-12 - Temperature Distribution – 5,936 Sec. After the Start of the Fire 3-34

Figure 4-2 - Containment System Overview – Configuration B 4-8

Figure 5-1 - 3-60 Cask Top 5-5

Figure 5-2 - 3-60 Cask Bottom 5-5

Figure 5-3 - 3-60 Cask Top (HAC) 5-7

Figure 5-4 - 3-60 Cask Bottom (HAC) 5-7

Figure 8-1 - Pre-Shipment Leak Test Configuration for O-Ring Annulus (Typical) 8-12

1.0 GENERAL INFORMATION

1.1 Introduction

This Safety Analysis Report (SAR) describes a reusable shipping package designed to protect greater than Type A quantities of radioactive material from both Normal Conditions of Transport (NCT) and Hypothetical Accident Conditions (HAC) as required by 10CFR71. The package is designated as the Model 3-60B package. The 3-60B package is a general-purpose transport package that has features that permit its contents to be loaded dry or wet (i.e., submerged in a pool.)

This SAR has been organized and formatted in accordance with Revision 2 of Regulatory Guide 7.9. The SAR has been prepared in accordance with Regulatory Guide 7.9 and includes information on the package required in Subpart D of 10 CFR Part 71. In addition, the general arrangement drawings of the packaging included in Section 1.3 have been formatted in accordance with NUREG/CR-5502, "Engineering Drawings for 10 CFR 71 Package Approvals".

1.2 Package Description

1.2.1 Packaging

The packaging consists of a cylindrical shipping cask with a cylindrical, foam-filled impact limiter attached to each end of the shipping cask. There are two (2) different configurations of the 3-60B package, which are referred to as Configuration A and Configuration B. These two configurations are identical in most respects, and vary primarily in the closure lid seal design and leak testing features. Configuration B also includes a few design features intended to simplify cask fabrication. These differences are discussed in the following paragraphs. A cut-away illustration of Configuration A of the 3-60B packaging is provided in Figure 1-1. A general arrangement drawing of the 3-60B packaging is included in Section 1.3.

The shipping cask includes a body assembly and lid assembly, along with all the associated closure bolts, port plugs and seals. The internal cavity of the shipping cask is 35 inches in diameter and approximately 109 inches in length. The cask body is cylindrical with an open top end and an integral bolting ring skirt that provides a pocket in which the lid assembly is recessed and protected when installed. The cask body bolting ring includes an annular seal ring plate, which is connected to the bolt ring by welds on both its inner and outer edges. The seal ring's inner weld is relied upon to provide containment, but the seal ring's outer weld is only relied upon for contamination control. Alternatively, the bolt rings for both Configurations A and B may be fabricated with an integral seal ring that is machined into the forging.

The side wall and bottom of the cask body are both steel-lead-steel construction. The side wall consists of a 6-inch thick (minimum) lead shield that is sandwiched between a ¾-inch steel inner shell and a 1¼-inch thick steel outer shell. The cask bottom consists of a 5-inch thick (minimum) lead shield that is sandwiched between a ¾-inch steel inner plate and a 3-inch thick steel outer plate. Configuration A includes a bottom corner forging that is welded to the cask outer shell and outer bottom plates. The bottom corner forging is not included in Configuration B. Instead, the outer shell and outer bottom plate extent to the corner and are

directly welded together. UT examination of the Configuration B outer bottom plate is required to assure that there are no lamellar defects in the base metal near plate's edge that could compromise the integrity of the outer shell-to-outer bottom plate weld.

A drain port located at the bottom (rear) end of the cask body is used to drain water from the cask cavity. The drain port is formed by a steel drain port body that is attached to the cask cavity bottom plate by a full penetration weld. The drain port body is machined from a single piece of austenitic stainless steel. Optionally, the drain port body may be fabricated from two pieces connected by a full penetration weld. The outer end of the drain port body, which is recessed within the cask body, is connected to the cask outer shell by a steel coupling. The cask drain port is plugged and sealed with a drain port plug (i.e., socket head cap screw) that threads into the exterior opening of the drain port. The drain port plug is secured by applying a torque in accordance with the requirements of the drawing in Section 1.3. The elastomeric fastener seal (e.g., O-ring seal or Stat-O-Seal), located between the head of the drain port plug and the outer surface of the drain port body, seals the drain port and provides containment. The Configuration B drain port is fitted with a modified (drilled-out) socket set screw on the cavity end. The drain port set screw, which protects the threads in the drain port body from damage and provides contamination control, is removed for maintenance leak testing of the drain port plug containment seal.

The cask lid is an assembly of circular plates with a thickness of 4 inches at the bolt flange interface and 10 ½ inches over the projected area of the cask cavity. The cask lid assembly is formed by welding together an inner plate and an outer plate. The lid outer plate, which forms the containment boundary, fits within the bolt flange skirt of the cask body and includes holes for the sixteen (16) 1½-6 UNC hex head bolts that are used to secure the cask lid assembly to the cask body assembly. The lid outer plates for Configuration A and Configuration B are fabricated from 4-inch thick and 4 ½-inch thick austenitic stainless steel plates, respectively. The lid inner plate, which provides radiation shielding, is welded to the inside of the lid outer plate. The lid inner plate has a 37-inch diameter upper section and a 34 ¾-inch diameter lower section that fit within the stepped opening of the cask body bolting flange. The lid inner plates for Configuration A and Configuration B are fabricated from 6 ½-inch thick and 6-inch thick austenitic stainless steel plates, respectively. The lid inner plate may be fabricated from a single solid plate or from multiple plates welded together, as shown in the general arrangement drawing included in Section 1.3.

The Configuration A and Configuration B lid assemblies differ most significantly in the design of the seal features and the test port configurations. The Configuration A lid assembly includes a separate seal ring that has two O-ring grooves; the inner groove for the containment O-ring seal and the outer groove for the test O-ring seal. The seal ring, which is fabricated from austenitic stainless steel plate, is partially recessed within a machined groove on the inside surface of the lid outer plate, and connected to the lid outer plate by an all-around butt weld on the seal plate's inner edge and by a all-around fillet weld on the seal plate's outer edge. Two (2) diametrically opposed test port holes are provided through the seal ring plate between the O-rings for performing the periodic and pre-shipment leak tests.

Unlike the Configuration A lid, the Configuration B lid does not include a separate seal ring. Instead, the O-ring grooves are machined directly into the inside surface of the lid's outer plate.

In addition, the Configuration B lid includes three (3) O-ring grooves; the middle groove for the containment O-ring seal and the inner and outer grooves for test O-ring seals. Two (2) diametrically opposed test ports are located between the inner test O-ring and the middle containment O-ring, and two (2) diametrically opposed test ports located between the middle containment O-ring and the outer test O-ring. These test ports are used to perform the periodic and pre-shipment leak tests. The test ports located inboard of the containment O-ring include test port plugs and fastener seals that are included in the containment boundary.

A vent port located in the closure lid is used when draining the cask cavity of water. It consists of a stepped, cylindrical penetration through the lid that is plugged and sealed by the vent port plug assembly. The vent port plug assembly consists of a vent port plug cover plate and vent plug bar (i.e., solid steel rod). The inside surface of the vent port plug cover plate includes a seal ring with two (2) machined grooves to accommodate O-rings; an inner containment O-ring and an outer test O-ring. The vent port plug seal ring may be fabricated as a separate piece (Configuration A) that is welded to the vent port plug cover plate on its inner and outer edges, or the seal ring may be integral to the vent port plug cover plate (Configuration B). For the separate seal ring used in Configuration A, the inner weld provides containment, but the outer weld is provided only for contamination control. The Configuration A vent port plug cover plate is penetrated by the vent plug bar (i.e., steel rod), and therefore the vent plug bar and its attachment welds are included in the Configuration A containment boundary. However, the Configuration B vent port plug cover plate is not penetrated by the vent plug bar, and therefore the vent plug bar and its attachment weld are not included in the Configuration B containment boundary.

The vent port plug assembly is attached to the cask closure lid using six (6) ½-inch diameter hex head bolts, which are secured by applying a torque in accordance with the requirements of the general arrangement drawing in Section 1.3. Two (2) test ports, diametrically opposed, are provided in the vent port plug assembly for leak testing the containment O-ring seal. The Configuration B vent port is fitted with a modified (drilled-out) socket head cap screw on the cavity side of the lid. The vent port socket head cap screw, which protects the threads in the vent port from damage and provides contamination control, is removed for maintenance leak testing of the vent port plug containment seal.

Each end of the cask is protected during transport by a foam-filled, cylindrical-shaped impact limiter. Each impact limiter assembly fits over the end of the cask body and is secured to the cask body by four 7/8-inch diameter bolts or threaded studs. The impact limiter assembly has a 40-inch overall length and overlaps the end of the cask by 22 inches. The center region on the end of each impact limiter includes a 24-inch diameter cylindrical volume that is not filled with foam. The side wall of the impact limiter assembly is approximately 15 inches thick. The impact limiter shell assemblies are fabricated entirely from austenitic stainless steel plate and sheet metal components that are welded together to create a sealed cavity to protect the foam core from the external environment. The inner plates of the impact limiter shell are fabricated from ½-inch thick plate and the outer skins are fabricated from 12-gauge sheet. Each impact limiter assembly includes a 1 ¾-inch thick bolting ring that is reinforced by steel gusset plates. The volume inside the shell is filled with closed-cell polyurethane foam which is described in Energy*Solutions* Specification ES-M-172 [8-1]. The polyurethane is poured into the shell to fill the internal cavity.

Package Weight

The maximum gross weight of the 3-60B package is limited to 80,000 pounds. The maximum payload weight, including contents, secondary containers, and cavity spacers, is limited to 9,500 pounds.

Containment Features

The containment boundary is defined as the inner steel shell of the cask body together with closure features, comprised of the cask lid outer plate, the primary lid bolts, plus the containment O-rings on the lid and the fastener seals on the vent and drain port plugs. A detailed description of the containment system is provided in Section 4.1.

Shielding

Gamma shielding in the cask side walls and bottom end is provided primarily by stainless steel and lead. The cask side wall includes a ¾-inch thick steel inner shell, a 6-inch thick (minimum) lead shield, and a 1 ¼-inch thick steel outer shell. In addition, the fire shield (a.k.a. thermal shield) attached to the outer surface of the cask side wall provides additional shielding. The cask bottom end includes a ¾-inch thick steel inner bottom plate, a 5 inch thick (minimum) lead shield, and a 3-inch thick steel outer bottom plate. Gamma shielding in the top end of the cask is provided primarily by the cask lid assembly. The lid assembly consists entirely of stainless steel plate construction, with a total thickness of 10 ½ inches. The lid assembly and bolt flange are designed with a two-step interface to minimize radiation streaming through the annular gap between the lid and bolt flange. The top and bottom ends of the package are also shielded by the impact limiters attached to the ends of the cask.

Shielding specifically for neutrons is not necessary for the specified radioactive material contents.

Criticality Control Features

Neutron absorbers for criticality control are not necessary for the specified radioactive material contents.

Lifting and Tie-down Device

The 3-60B cask body has two sets of trunnions (upper and lower) that function as the lifting and tie-down devices. The upper two trunnions are primarily used for lifting and handling. The package is transported in the horizontal orientation by resting it in the shipping cradle, where it is supported and tied down by the four trunnions. Both sets of trunnions are structural parts of the package, and are analyzed accordingly in Chapter 2.

Packaging Closure Devices

The packaging closure devices include the following:

(1) The recessed closure lid fits inside a protective skirt that is integral with the cask body. The lid has holes through which sixteen (16) 1 ½-inch diameter hex head bolts are threaded into a forged ring attaching and sealing the lid to the cask body.

(2) The cask drain port, located at the bottom corner of the cask body, is used to drain water from the cask cavity. A drain port plug (i.e., socket head cap screw), which is fitted with an elastomeric fastener seal (e.g., O-ring seal or Stat-O-Seal), threads into the exterior opening of the drain port and provides containment. The drain port plug is secured by applying a torque in accordance with the requirements of the drawing in Section 1.3.

(3) The cask vent port located in the closure lid may be used to vent the cask cavity when draining water or removing the cask lid. During transport of the cask the vent port is plugged by a vent port plug assembly and sealed by an elastomeric O-ring. The vent port plug assembly is secured to the cask closure lid by six (6) ½-inch diameter socket head cap screws.

(4) The Configuration B lid inner test ports are used for leak testing the Configuration B lid containment seal. During transport, each inner test ports is plugged with a socket head cap screw, which is fitted with an elastomeric fastener seal (e.g., O-ring seal or Stat-O-Seal) that provides containment. Each test port plug is secured by applying a torque in accordance with the requirements of the drawing in Section 1.3.

Heat Transfer Features

A 12 gauge thermal shield (a.k.a. fire shield) is installed on the exterior of the cask wall. The thermal shield protects the cask during the HAC fire event. It is constructed of Type 304L stainless steel and separated from the cask outer shell by a helically wound 5/32 inch diameter stainless steel wire.

Packaging Markings

The cask nameplate is shown on the general arrangement drawing in Section 1.3.

1.2.2 Contents

Cask Contents

The type and form of permitted contents of the cask will consist of:

1) By-product, source, or special nuclear material, in the form of:

   - de-watered inorganic solids, including powdered or dispersible solids, or
   - inorganic solidified material, or
   - de-watered inorganic resins, or
   - activated and/or contaminated non-fuel-bearing reactor or accelerator components or segments of components

Maximum Quantity of Radioactive Material per Package.

1) Greater than Type A quantities of radioactive materials up to a maximum of 3000 A_2 or 1110 TBq (30,000 Ci), whichever is less.

2) Fissile material provided the mass limits of 10 CFR 71.15 are not exceeded.

3) Decay heat of contents not to exceed 500 watts. For contents with residual water or that contain water, the decay heat is limited such that the total decay heat (in watts) does not exceed 4.46 times the volume fraction divided by the mass fraction of water in the contents, as determined per Chapter 7 Attachment 1.

4) The specific activity of radioactive powdered or dispersible solids (in units of A_2 per gram) shall not exceed 30.

5) Payload weight of 9,500 pounds, including contents, secondary containers, and shoring

Loading Restrictions

Contents shall be packaged in secondary containers. Secondary containers, intended for loading into the cask underwater, shall incorporate features to prevent blocking the cavity drain. A typical secondary container is shown in Figure 1-2. Wet Solid Waste shall be dewatered per ANSI/ANS-55.1-1992. Except for close fitting contents, shoring must be placed between the secondary containers or activated components and the cask cavity to prevent movement during HAC. Explosives, pyrophorics, and corrosives (pH less than 2 or greater than 12.5), are prohibited. Materials that may auto-ignite or change phase (i.e., change from solid to liquid or gas) at temperatures less than 350°F, not including water, shall not be included in the contents. In addition, as required by 10 CFR 71.43(d), the contents shall not include any materials that may cause any significant chemical, galvanic, or other reaction.

For contents loaded underwater, the cavity shall be drained of water to the extent practicable, not to exceed the acceptance criterion of 8.1.8.

1.2.3 Special Requirements For Plutonium

Any contents that contain more than 0.74 TBq (20 Ci) of plutonium must be in solid form.

1.2.4 Operational Features

There are no complex operational requirements associated with this package.

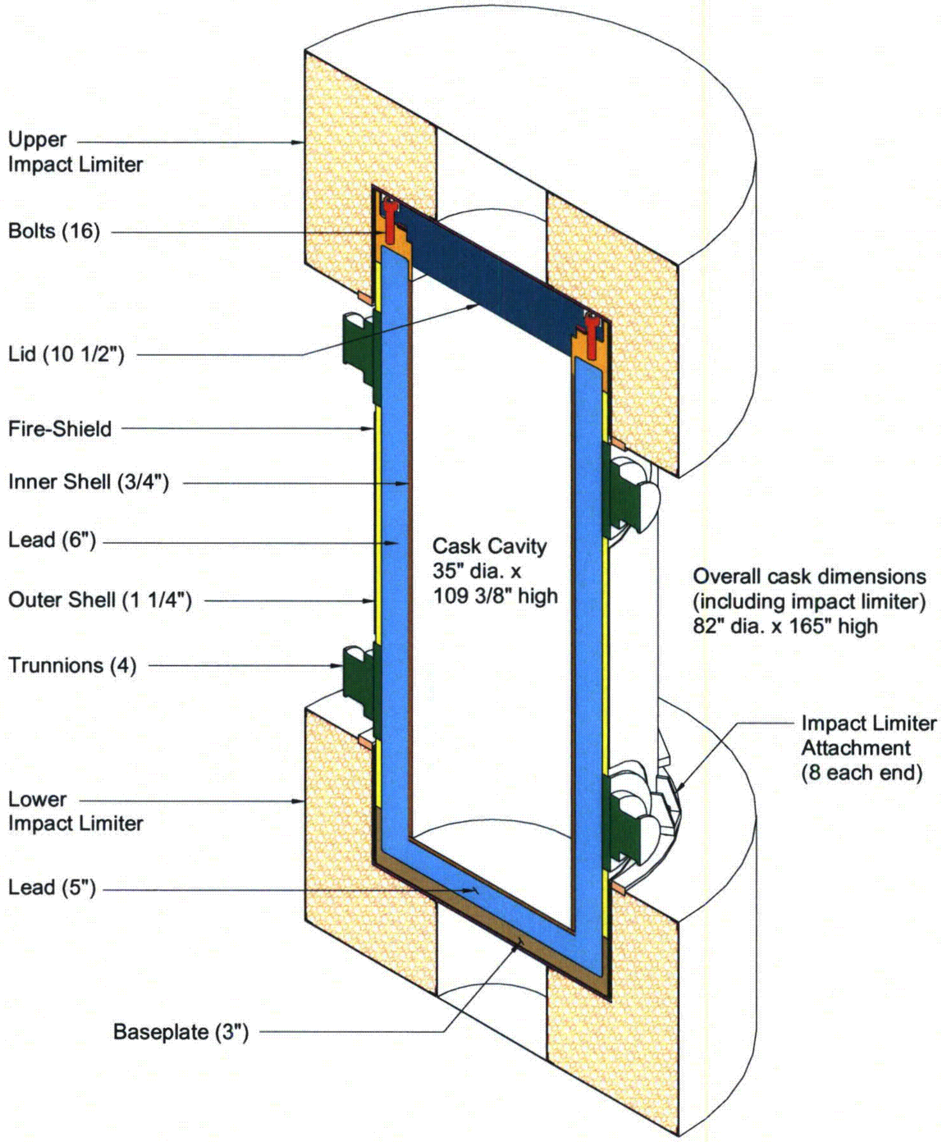


Figure 1-1 - 3-60B General Arrangement

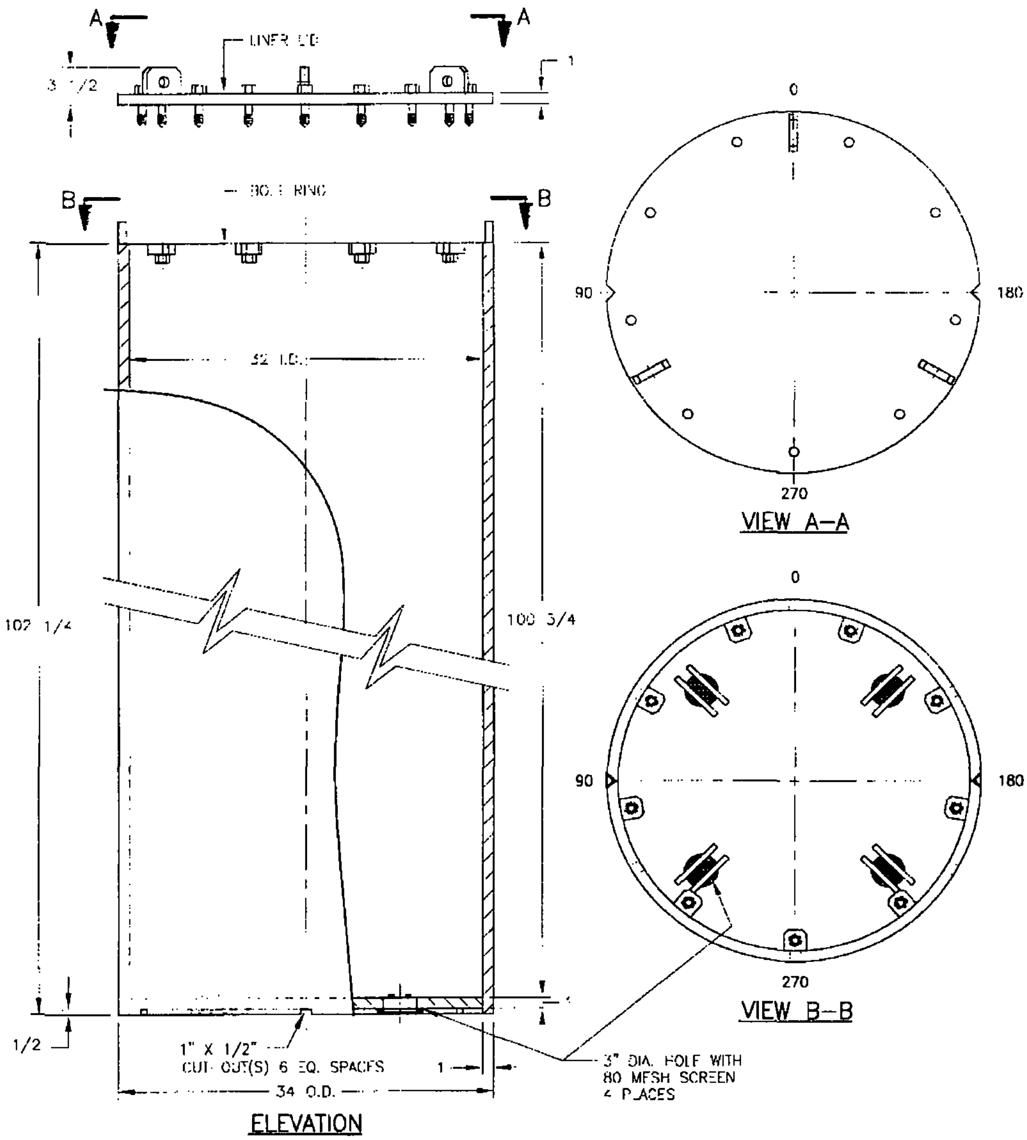


Figure 1-2 - Typical Secondary Container

1.3 **Appendix**

3-60B Shipping Cask Drawing

- C-002-165024-001, 3-60B Cask General Arrangement and Details, Revision 1 (10 sheets).

Drawings withheld on the basis that they are Security-Related Information

This page intentionally blank.

2.0 STRUCTURAL EVALUATION

This Section identifies, describes, discusses and analyzes the structural design of the 3-60B packaging components, and safety systems for compliance with performance requirements of 10 CFR 71 [2-1].

2.1 Description of Structural Design

The package has been designed to provide a shielded containment vessel that can withstand the loading due to the Normal Conditions of Transport (NCT), as well as those associated with the Hypothetical Accident Conditions (HAC).

The 3-60B package is designed to protect the payload from the following conditions: Transport environment, 30-foot drop test, 40-inch puncture test, 1475°F thermal exposure, and transfer of dissipation of any internally generated heat. The design of the package satisfies these requirements.

Principal elements of the system consist of:

- Containment Vessel
- Lead Shielding
- Impact Limiters

These components are identified in Figure 1-1. The pertinent dimensions of the package are also shown in this figure. The design and function of these components in meeting the requirements of 10 CFR 71 are discussed below. Figure 2-1 shows the nomenclature of the components of the cask used throughout this SAR.

2.1.1 Discussion

Containment Vessel

The containment vessel of the package is made up of the cask body and the lid. They are fabricated of austenitic stainless steel. The cask body consists of two shells, which envelop a lead shield. The top end of the cask body consists of a bolting ring that provides sealing and bolting surfaces for the lid. The bottom end of the cask body has two baseplates, sandwiching the lead shielding. The lid is attached to the cask body with sixteen (16) 1½"–6 UNC bolts. The lid-to-cask body joint is sealed by a solid elastomeric O-ring. The cask containment boundary consists of the inner shell, the inner (bottom) baseplate, the bolting ring, the containment O-ring, and the lid. This boundary is penetrated by the vent and drain ports. In addition, the containment boundary of the Configuration B lid assembly is also penetrated by two (2) test ports. Thus, the parts of these ports up to the port plug fastener seals are also included in the containment boundary. The 3-60B package containment system of each 3-60B cask configuration is described further in Section 4.1.

Shielding

The space between the two shells and the two baseplates, discussed above, is filled with lead. This lead shielding is subjected to a Gamma Scan inspection to assure lead integrity. The designed thickness assures that no radiological hazard is presented by the package and all shielding requirements of 10 CFR 71 are met.

Impact Limiters

The impact limiters are designed to protect the package from damage during the HAC drop test and to provide thermal protection during the HAC thermal (fire) test.

They are constructed of fully welded stainless steel shells filled with foamed-in-place closed-cell rigid polyurethane foam. The foam deforms and provides energy absorption during impact. Eight circumferentially located attachment points are provided to connect each of the impact limiters to the cask body.

Detailed discussions of all components and materials utilized in the 3-60B Package including stress, thermal, and pressure calculations are contained in the applicable sections of this SAR.

2.1.2 Design Criteria

The package is designed to satisfy the requirements of 10 CFR 71.71 under NCT and HAC test conditions. Compliance with the "General Standards for All Packages" specified in 10 CFR 71.43 and the "Lifting and Tie-Down Standards" specified in 10 CFR 71.45 are discussed in Section 2.4 and Section 2.5, respectively. Table 2-1 summarizes the NCT and HAC loading and their combination with various initial conditions, used for the design assessment of the 3-60B package. Table 2-1 has been developed from the recommendations of Regulatory Guide 7.8 [2-2].

The allowable stresses in the package containment boundary (other than bolting) are based on the criteria of Regulatory Guide 7.6 [2-3].

The allowable stresses under NCT (RG 7.6, Regulatory Position 2) are:

Primary membrane stresses $< S_m$

Primary membrane + bending stresses $< 1.5\ S_m$

Where, S_m = design stress intensity

Based on ASME Code [2-4], Section II, Appendix 1, Article 1-100, the design stress intensity is defined to be:

S_m = smaller of ($2/3\ S_y$ or $S_u/3.5$)

Where, S_y = material yield stress

S_u = material ultimate strength

The allowable stresses under HAC (RG 7.6, Regulatory Position 5), are:

Primary membrane stresses < smaller of (2.4 S_m or 0.7 S_u)

Primary membrane + bending stresses < smaller of (3.6 S_m or S_u)

Regulatory Guide 7.6 does not provide guidance for the bolting allowable stress limits. The allowable stress in the bolting for the NCT loading is established to be similar to that for the non-bolting components and for the HAC conditions it is established based on the requirements of ASME B&PV Code, Section III, Appendix F, Article F-1335.

For HAC loading, average tensile stress in the bolts shall not exceed smaller of 0.7 S_u or S_y. The direct tension plus bending, excluding stress concentration shall not exceed S_u. The average bolt shear stress shall not exceed the smaller of 0.42 S_u or 0.6 S_y. The combined tensile and shear stress to corresponding allowable stress ratio shall satisfy the following equation:

$$\left(\frac{f_t}{F_{tb}}\right)^2 + \left(\frac{f_v}{F_{vb}}\right)^2 \leq 1.0$$

Where, f_t = computed tensile stress

f_v = computed shear stress

F_{tb} = allowable tensile stress

F_{vb} = allowable shear stress

Table 2-2 lists the allowable stresses for various stress components under NCT and HAC loading conditions. Allowable values for all the materials that are used for the construction of the structural components of the cask are listed in this table. It should be noted that the allowable stress values listed in this table are applicable to elastically calculated stresses only.

Table 2-3 lists the definition of the regulatory and/or the ASME code definition of stress components. This table also explains how these definitions have been incorporated into the 3-60B Cask analyses documented in this SAR.

The acceptance criterion for prevention of buckling is based on the ASME Nuclear Code Case N-284 [2-5]. Factors of safety of 1.34 for the NCT and 2.0 for HAC have been used in the buckling evaluation of the cask.

All the metal components of the package are fabricated from austenitic stainless steel, which is not susceptible to brittle fracture at low temperature. Therefore, brittle fracture has not been addressed explicitly in this SAR.

The design criteria, used for the evaluation of the impact limiters, is based on a proprietary methodology developed by Energy*Solutions* and is fully documented in ST-551 [2-6].

2.1.3 Weight and Center of Gravity

The following is a conservative estimate of the weight of various components of the 3-60B package.

Cask Body	=	56,400 lb	
Lid	=	4,500 lb	
Payload	=	9,500 lb	
Impact Limiters (2)	=	4,200 lb	(each)
Misc.	=	1,200 lb	
Package	=	80,000 lb	

The C.G. of the package is located at approximately the same location as the geometric center of the package.

2.1.4 Identification of Codes and Standards for Package Design

The 3-60B package is designed as a Type-B, Category II package, which establishes limits on the amount of radioactivity in the contents (less than $3000A_2$ and not greater than 30,000 Ci, per [2-7]). Based on the recommendations of NUREG/CR-3854 [2-8] the fabrication, examination, and inspection of the containment boundary components of a Category II package should be per ASME B&PV Code Section III, Subsection ND.

2.2 **Materials**

The material properties of the cask components used in the analysis of the 3-60B package are provided in Table 2-4. This table provides the temperature dependent yield stress, ultimate tensile strength, allowable membrane stress, Young's modulus, and mean coefficient of thermal expansion for stainless steel, carbon steel and lead. The thermal properties of these materials that were used for the evaluation of temperature distribution in the cask are provided in Section 3.2.1.

2.2.1 Material Properties and Specifications

All the metal components of the cask body, except the bolting ring, bottom cover forging, bolting ring skirt, and the inner shell, are specified to be ASTM A-240 or A-479 Type 304L austenitic stainless steel. The bolting ring and bottom cover forging (i.e., corner between outer shell and bottom plate) materials are specified to be ASTM A-182 Grade F45 stainless steel and the inner shell and bolting ring skirt materials are specified ASTM A-240 UNS S30815 (hereafter referred to as "Grade 45") stainless steel. Alternatively, the bolting ring and bottom cover forging may be fabricated from ASTM A-182 Type F XM-11 or Type F XM-19 stainless steels and the inner shell and bolting ring skirt may be fabricated from ASTM A-240, Type XM-19 stainless steel. These alternative stainless steel materials all have yield and tensile strengths that are slightly higher than those of Grade 45 and Grade F45 stainless steels. These materials are approved for the construction of the ASME Section III, Subsection ND vessels. The material properties for these materials have been obtained from the ASME Code.

The bolting used for connecting the lid to the cask body has been specified to be ASTM A-354 Gr. BD material. This material is approved for use in the ASME Section III, Subsection ND vessels. The material properties for this material have been obtained from the ASME Code.

The poured-in-place lead shielding is specified to be ASTM B-29 lead. This material has been used in numerous radioactive shipping casks over the last 30 years. The material properties for lead are obtained from NUREG/CR-0481 [2-9].

The material used for the lid containment O-ring seals, vent port plug containment O-ring seals, drain port plug fastener seal, and test port plug fastener seal must be an elastomer, having a durometer of 50 to 70, a normal service temperature range of -40°F to 250°F, which envelopes the temperature range for NCT, and a maximum short-term (1-hour) temperature limit that is ≥350°F, which envelopes the peak seal temperature for the HAC thermal test.

The impact limiters are filled with closed-cell rigid polyurethane foam. The foam is procured based on Energy*Solutions* specification ES-M-172 [8-1], which specifies, among other things, the mechanical properties, flame retardant characteristics, and the test requirements for the foam material. The type of foam specified by the specification is General Plastics Manufacturing Company's Type FR-3700 or FR-6700, or equivalent. The General Plastics Technical Manual [2-10] provides the stress-strain properties of various density foams. The ES specification uses the 25 lb/ft^3 nominal density foam's stress-strain properties perpendicular-to-rise direction as the required property. However, in the analyses of the impact limiters both parallel-to-rise and perpendicular-to-rise direction properties have been used, as appropriate. These properties are shown in Figure 2-2 and Figure 2-3.

2.2.2 Chemical Galvanic and Other Reactions

The 3-60B cask is fabricated from stainless steel and lead and has impact limiters containing polyurethane foam. These materials will not cause chemical, galvanic, or other reactions in dry or wet environments in which the package is operated. These materials are commonly used in radioactive material (RAM) packages for transport of radioactive wastes and have been so used for many years without incident. The materials of construction were specifically selected to ensure the integrity of the package will not be compromised by any chemical, galvanic or other reactions.

2.2.2.1 Materials of Construction

The 3-60B package is primarily constructed of austenitic stainless steel. This material is highly corrosion-resistant to most environments. The weld material and processes have been selected in accordance with the ASME Boiler and Pressure Vessel Code to provide as good or better material properties than the base material, including corrosion resistance. Both the base and weld materials are 300-series stainless steel, which is highly resistant to corrosion. These materials also have approximately the same electrochemical potential, minimizing any galvanic corrosion that could occur. The polyurethane foam in the impact limiters is closed-cell foam that is very low in free halogens. The foam material is sealed inside a dry cavity in each impact limiter, to prevent exposure to the elements. Even if moisture were available for leaching trace chlorides from the foam, very little chloride would be available, since the material is closed-cell foam and water does not penetrate the material to allow significant leaching. The elastomers used in the O-

ring seals contain no corrosives that would adversely affect the packaging. The elastomers are non-corrosive to the stainless steel body of the 3-60B package.

2.2.2.2 Materials of Construction and Payload Compatibility

The typical contents of the 3-60B will be similar to the materials of construction, i.e., stainless steel, contained in a secondary container typically made of carbon steel. Corrosive materials are prohibited from the payloads. The steel contents of the cask will not react with the cask materials of construction. Contents may be loaded in a dry environment or in a spent fuel pool, particularly highly irradiated stainless steel reactor components. The pool water will not react with the exposed stainless steel surfaces of the cask assembly components. During transport, residual water may undergo radiolysis as discussed in Section 3.3.2 but this reaction will not affect the cask components.

2.2.3 Effects of Radiation on Materials

The material from which the package is fabricated (stainless steel, lead, elastomer O-ring, and foam) along with the contents exhibit no measurable degradation of their mechanical properties under a radiation field produced by the contained radioactivity.

2.3 **Fabrications and Examination**

As discussed in Section 2.1.4, the 3-60B packaging is designed as a Category II container. To assure the fabrication and examination processes used for the package (e.g. material procurement and control, fitting, welding, lead pouring, foaming, examining, testing, personnel qualification, etc.) are appropriately controlled, Energy*Solutions* will apply its USNRC approved 10 CFR 71 Subpart H Quality Assurance Program, which implements a graded approach to quality based on a component's or material's importance to safety consistent with the guidance provided in NUREG/CR-6407 [2-27], NUREG/CR-3854 [2-8], NUREG/CR-3019 [2-11] and Industry practice.

2.3.1 Fabrication

As specified in the above referenced documents, fabrication of the 3-60B containment components will be based on ASME B&PV Code, Section III, Subsection ND and that of the non-containment components will be based on ASME B&PV Code, Section III, Subsection NF.

2.3.2 Examination

As specified in the above referenced documents, examination of the 3-60B containment components will be based on ASME B&PV Code, Section III, Subsection ND-5000 and that of the non-containment components will be based on ASME B&PV Code, Section III, Subsection ND-5000 or NF-5000.

Section 8.0 provides additional information on examination and acceptance criteria for the packaging.

2.4 General Requirements for All Packages

10 CFR 71.43 establishes the general standards for packages. This section identifies these standards and provides the bases that demonstrate compliance.

2.4.1 Minimum Packaging Size

10 CFR 71.43(a) requires that:

"The smallest overall dimension of a package must not be less than 10 cm (4″)."

The smallest overall dimension of the package is the diameter of the cask (51″), which is larger than 4″. Therefore, the minimum package size requirement is satisfied.

2.4.2 Tamper-Indicating Features

10 CFR 71.43(b) requires that:

"The outside of a package must incorporate a feature, such as a seal, which is not readily breakable, and which, while intact, would be evidence that the package has not been opened by unauthorized persons."

The 3-60B package incorporates a tamper resistant seal that is installed between the cask body and each of the two impact limiters after the package has been closed. Breach of these seals would indicate that the package has been tampered with by unauthorized persons.

2.4.3 Positive Closures

10 CFR 71.43(c) requires that:

"Each package must include a containment system securely closed by a positive fastening device that cannot be opened unintentionally or by a pressure that may arise within the package,"

The 3-60B package uses 16 bolts that fasten the lid to the cask body. Additionally, the drain and vent ports are closed with the help of threaded attachments. These closure components are encompassed within the two impact limiters when the package is prepared for the shipment. They cannot be opened unintentionally. Also, it has been shown that the MNOP produces very small bolt loads. These loads are much smaller than the bolt pre-tension and are not capable of loosening them.

2.5 Lifting and Tie-down Standards for All Packages

10 CFR 71.45 specifies the requirements for the lifting and tie-down devices that are "structural parts of the package". The 3-60B package consists of two pairs of trunnions that are used for lifting, handling and tie-down during transportation. These trunnions are a structural part of the package. They have been analyzed for the requirements of 10 CFR 71.45, which limits the maximum stresses in the trunnion to the yield stress of the material under applied loading to the package that is specified to be a load factor times the gross weight of the package. Figure 2-4 shows the trunnion loadings under various loading conditions.

An ANSYS [2-12] finite element model, consisting of 12,268 8-node structural solid elements and 9,870 8-node solid shell and contact/target elements, shown in Figure 2-5, was employed to compute the stresses in the trunnion assembly under various load conditions. The model represents the trunnion assembly, the inner and outer shells and the lead shielding, in the immediate vicinity of the trunnions. The details of the model, including the assumptions, modeling details, boundary conditions, and input and output data are included in the Energy*Solutions* document ST-503 [2-13].

2.5.1 Lifting Devices

According to 10 CFR 71.45(a), "any lifting device, that is a structural part of the package must be designed with a minimum safety factor of three against yield when used to lift the package in the intended manner and it must be designed so that failure of any lifting device under excessive load would not impair the ability of the package to meet other requirements of this subpart."

The 3-60B Cask is designed to be lifted with the help of a lifting yoke that utilizes the two upper trunnions. Depending on the crane characteristics, a dynamic load amplification may result due to such lifting. The dynamic load factor for a typical crane is between 1.0 and 1.1. For conservatism a dynamic load factor of 1.3 is used for the evaluation of the trunnions under lifting conditions. It should be noted that the users of this cask shall perform an evaluation based on their crane characteristics to obtain the dynamic load factor and ensure that it is less than 1.30 in order to use this cask.

The stresses are calculated for the amplified load including the safety factor and are compared with the yield stress.

$$\text{Amplified load} = 1.3\times3.0\times W = 1.3\times3.0\times80{,}000 = 312{,}000 \text{ lb}$$

Each trunnion will be subjected to half of the amplified load. Therefore, load on each trunnion,

$$F = \tfrac{1}{2}\times312{,}000 = 156{,}000 \text{ lb}$$

Under this loading the analyses of ST-503 [2-13] gives the following maximum stresses.

$$\text{Trunnion stress intensity} = 21{,}108 \text{ psi} < 30{,}000 \text{ psi}$$

$$\text{Outer shell stress intensity} = 10{,}920 \text{ psi} < 25{,}000 \text{ psi}$$

It should also be noted that the maximum stress under the lifting condition occurs in the trunnion. The stresses in the shell are much smaller than those in the trunnion. Therefore, under the excessive loading, the failure is expected to occur in the trunnion, not in the shell. Thus, the package integrity will not be compromised under the excessive loading. Hence the regulatory requirement of excessive loading not impairing the ability of the package to meet other requirements is satisfied.

Any other part of the package that could be used to lift it (e.g. impact limiter lifting lugs) will be rendered inoperable during the transportation of the package.

2.5.2 Tie-Down Devices

Trunnions are used for the tie-down of the 3-60B package during transportation. The transportation of the packages in the United States is controlled under the provisions of 49 CFR 393 [2-14]. Loadings are specified by 49 CFR 393.102 for minimum performance criteria for cargo securement devices and systems. However, 10 CFR 71.45(b) requires that:

"If there is a system of tie-down devices that is a structural part of the package, the system must be capable of withstanding, without generating stress in any material of the package in excess of its yield strength, a static force applied to the center of gravity of the package having a vertical component 2 times the weight of the package with its contents, a horizontal component along the direction in which the vehicle travels of 10 times weight of the package with contents, and a horizontal component in the transverse direction of 5 times the weight of the package with its contents."

Since the 10CFR71 loading on the tie-down system is much more severe than the 49CFR393 loading, it is used for the evaluation of the 3-60 package for the transportation conditions. Based on these requirements the trunnions are subjected to the following loading (see Figure 2-4).

Longitudinal = 2.5×W = 2.5×80,000 = 200,000 lb

Lateral = 0.5×W = 0.5×80,000 = 40,000 lb

Radial = 2.5×W = 2.5×80,000 = 200,000 lb

The finite element model described in Section 2.5 is used to compute the stresses under these loading conditions. The comprehensive results are included in the Energy*Solutions* document ST-503 [2-13] and are summarized below.

<u>Longitudinal Loading (Direction of Vehicle Travel)</u>

The stress intensity plots are shown in Figure 2-6 through Figure 2-8.

Trunnion stress intensity = 27,953 psi < 30,000 psi

Outer shell stress intensity = 14,652 psi < 25,000 psi

<u>Radial Loading (Transverse to Vehicle Travel)</u>

The stress intensity plots are shown in Figure 2-9 through Figure 2-11.

Trunnion stress intensity = 14,026 psi < 30,000 psi

Outer shell stress intensity = 9,445 psi < 25,000 psi

<u>Lateral Loading (Vertical)</u>

The stress intensity plots are shown in Figure 2-12 through Figure 2-14.

Trunnion stress intensity = 5,430 psi < 30,000 psi

Outer shell stress intensity = 3,695 psi < 25,000 psi

Combined Loading (All the above loading applied simultaneously)

The stress intensity plots are shown in Figure 2-15 through Figure 2-17.

Trunnion stress intensity = 29,671 psi < 30,000 psi

Outer shell stress intensity = 14,887 psi < 25,000 psi

It should also be noted that the maximum stress under the tie-down loading conditions occurs in the trunnion. The stresses in the shell relative to yield are much smaller than those in the trunnion. Therefore, under excessive loading, failure is expected to occur in the trunnion, not in the shell. Thus, the package integrity will not be compromised under excessive loading. Hence the regulatory requirement of excessive loading not impairing the ability of the package to meet other requirements is satisfied.

Any other part of the package that could be used for the tie-down (e.g. impact limiter lifting lugs) will be rendered inoperable during the transportation of the package.

2.6 Normal Conditions of Transport

This Section demonstrates that the package is structurally adequate to meet the performance requirements of Subpart E of 10 CFR 71 when subjected to NCT as defined in 10 CFR 71.71. Compliance with these requirements is demonstrated by analyses in lieu of testing as allowed by 10 CFR 71.41(a) and Regulatory Guide 7.6 [2-3].

The structural analyses of the 3-60B Cask under NCT events have been performed through the use of finite element models. ANSYS finite element analysis code [2-12] has been employed to perform the analyses. Since the lid of the cask is attached to the body using 16 bolts, the cask geometry has a cyclic symmetry every 11.25° of the circumference. Therefore, an 11.25° model of the cask has been utilized for the analyses.

The model of the cask is made using 3-dimensional 8-node structural solid elements (ANSYS SOLID185) to represent the major components of the cask, the bolting ring, the lid, and the bolts. The shell components of the cask - the inner and outer shells, and the baseplates have been represented in the finite element model by SOLSH190 elements.

The fire shield (a.k.a. thermal shield) does not provide any structural strength to the cask. Therefore, it is not included in the model.

The poured lead in the body is not bonded to the steel. It is free to slide over the steel surface. Therefore, the interface between the lead and the steel is modeled by pairs of 3-d 8 node contact element (CONTA174) and 3-d target (TARGE170) elements. These elements allow the lead to slide over the steel at the same time prevent it from penetrating the steel surface. The interface between the two plates that form the lid is also modeled by the contact-target pairs. The

transition from a coarser mesh to a finer mesh, as well as bondage between various parts of the model, is also modeled using these elements.

Figure 2-18 shows the finite element model used in the analyses of various load cases. The model consists of 2,878 nodes and 2,368 elements. This model has node-to-node and element-to-element correspondence with the thermal finite element model used for the thermal analysis of the package, described in Section 3.3. The nodal temperatures during various NCT events are obtained from the analyses in Section 3.0.

The finite element model is representative of, and applicable to, both cask Configuration A and cask Configuration B. Although the finite element model geometry is specifically based on cask Configuration A, the results obtained from the model are either directly applicable to, or bounding for, cask Configuration B. The primary differences between the two cask configurations, with respect to the finite element model, are: (1) Lid seal ring designs, and (2) Outer shell-to-outer bottom plate connection detail. These differences are discussed and evaluated in the following paragraphs.

Configuration A includes a separate seal ring in the lid assembly, whereas in Configuration B the seal ring is integral to the lid outer plate, as shown on the general arrangement drawing in Section 1.3. The strength of the integral seal ring used in Configuration B is greater than or equal to the strength of the separate seal ring of Configuration A. Therefore, the stress analysis results obtained from the finite element model are considered bounding for Configuration B.

The outer bottom corner of cask Configuration A includes a bottom corner ring forging that connects the outer shell to the outer bottom plate, whereas for Configuration B the outer shell and outer bottom plate are welded directly to one another with a complete joint penetration weld. In terms of geometry, these two configurations are identical. Although the bottom corner forging material used in Configuration A has slightly higher strength properties that the adjacent outer shell and outer bottom plate materials, no credit was taken for the higher strength properties in the structural evaluation and the bottom corner forging is treated as an extension of the outer shell and outer bottom plate. Therefore, the results are applicable to both cask configurations.

The details of the finite element model, including the assumptions, modeling details, boundary conditions, and input and output data are included in the Energy*Solutions* document ST-501 [2-15].

2.6.1 Heat

The thermal evaluation of the 3-60B package is described in Section 3.4. Results from the thermal analyses are used in performing the evaluation in this section.

2.6.1.1 Summary of Pressure and Temperatures

Based on the requirements of 10 CFR 71.71(c)(1), the thermal finite element model described in Section 3.3 computes the nodal temperature of the cask body. Figure 2-19 (reproduced from Figure 3-4) shows the temperature distribution in the structural components of the package. The maximum temperatures in various components of the package are summarized as follows (Reference Table 3-1 and Figure 2-19):

Fire (Thermal) Shield = 177.7°F

Outer Shell = 177.6°F

Inner Shell = 177.8°F

Lead = 178.9°F

Seal = 178.6°F

Lid = 182.7°F

The maximum average cavity temperature during the NCT events is 186 °F (Table 3-3). A conservative temperature of 225 °F has been used for calculating the Maximum Normal Operating Pressure (MNOP) in Section 3.3.2. The MNOP of 35.0 psig is used for the evaluation of the hot environment load conditions.

2.6.1.2 Differential Thermal Expansion

The structural finite element model used for the analyses of the 3-60B package under various loading conditions, described in Section 2.6, uses temperature dependent material properties of the cask components. The differential thermal expansion of various components of the cask is implicitly included in the stress calculation of the package.

2.6.1.3 Stress Calculations

The stresses in the package under the hot environment loading conditions have been performed in [2-15]. The loading combination is listed in Table 2-1. Table 2-5 presents the maximum stresses in various components of the package. Figure 2-20 shows the plot of stress intensity contour in the cask body.

2.6.1.4 Comparison with Allowable Stresses

The stresses in the package under the hot environment loading conditions are compared with their allowable values in Table 2-5. The allowable values in various components of the package are listed in Table 2-2. It is noticed from the comparison with the allowable values that all the components of the package experience stresses well below their allowable values. Of all components, a minimum factor of safety of 1.36 occurs in the baseplate.

2.6.2 Cold

The thermal evaluation of the 3-60B package under cold conditions is described in Section 3.4. Results from the thermal analyses are used in performing the evaluation in this section.

Based on the requirements of 10 CFR 71.71(c)(2), the thermal finite element model described in Section 3.3 computes the nodal temperature of the cask body. Figure 2-21 (reproduced from Figure 3-5) shows the temperature distribution in the structural components of the package.

The structural finite element model used for the analyses of the 3-60B package under various loading conditions, described in Section 2.6, uses temperature dependent material properties of the cask components. The lead shrinkage, caused due to the differential thermal expansion of the lead and cask shells, is implicitly included in the stress calculation of the package.

The stresses in the package under the cold environment loading conditions have been performed in [2-15]. The loading combination is listed in Table 2-1. Table 2-6 presents the maximum stresses in various component of the package. Figure 2-22 shows the plot of stress intensity contour in the cask body.

The stresses in the package under the cold environment loading conditions are compared with their allowable values in Table 2-6. It is noticed from the comparison with the allowable values that all the components of the package experience stresses well below their allowable values. Of all components, a minimum factor of safety of 1.48 occurs in the baseplate.

For the evaluation of the cold environment the ambient temperature of -40°F has been specified by the regulation. However, for the initial conditions for the other load combinations the ambient temperature of -20°F has been specified in 10 CFR 71.73(b). In the load combinations described in Regulatory Guide 7.8 [2-2], this condition is associated with the minimum decay heat load. It is not intuitively obvious that the minimum decay heat load in the cold conditions will result in a conservative estimate of thermal stresses in the package. Therefore, the cold condition's load combinations listed in Table 2-1 have been performed two ways - one with the maximum decay heat load and another with no decay heat load. The combinations that result in larger stresses have been reported in this SAR as the cold combination.

2.6.3 Reduced External Pressure

10 CFR 71.71(c)(3) requires that package be evaluated for a reduced external pressure of 3.5 psi. The MNOP of the 3-60B package is 35.0 psig (14.7 psi atmospheric pressure). With the external pressure reduced to 3.5 psi, the inside pressure of the package will be:

$$p_{reduced\ external} = 35.0 + 14.7 - 3.5 = 46.2 \text{ psi (conservatively use 50.0 psi)}$$

The load combination for the reduced external pressure is listed in Table 2-1 under "Minimum External Pressure". Please note that this nomenclature is retained to be consistent with Regulatory Guide 7.8.

The stresses in the package under the reduced external pressure loading conditions have been performed in [2-15]. Table 2-7 presents the maximum stresses in various components of the package. Figure 2-23 shows the plot of stress intensity contour in the cask body.

The stresses in the package under the reduced external pressure loading conditions are compared with their allowable values in Table 2-7. It is noticed from the comparison with the allowable values that all the components of the package experience stresses well below their allowable values. A minimum factor of safety of 1.45 occurs in the baseplate.

2.6.4 Increased External Pressure

10 CFR 71.71(c)(4) requires that package be evaluated for an increased external pressure of 20 psi. The MNOP of the 3-60B package is 35 psig (14.7 psi atmospheric pressure). To be conservative for this loading the package internal pressure is assumed to be the minimum (i.e., 0 psi) and the external pressure has been increased to 25 psi. The load combination for the increased external pressure is listed in Table 2-1.

The stresses in the package under the increased external pressure loading conditions have been performed in [2-15]. Table 2-8 presents the maximum stresses in various component of the package. Figure 2-24 shows the plot of stress intensity contour in the cask body.

The stresses in the package under the increased external pressure loading conditions are compared with their allowable values in Table 2-8. It is noticed from the comparison with the allowable values that all the components of the package experience stresses well below their allowable values. Of all components, a minimum factor of safety of 1.59 occurs in the baseplate.

2.6.5 Vibration

10 CFR 71.71(c)(5) requires that "vibration normally incident to transport" be evaluated.

The 3-60B package consists of thick section materials that will be unaffected by vibration normally incident to transport, such as over the road vibrations. Fasteners (bolts, impact limiter attachment, etc.) which may be subjected to vibration are retained by locking washers and nuts.

2.6.5.1 Vibration & Fatigue Evaluation of the 3-60B Cask Package

Following the example given in ANSI N14.23 standard [2-16], an evaluation of the 3-60B Cask impact limiter attachment and the trunnions are performed here to show that these components will not be subjected to fatigue damage during their expected service life. It is assumed that the cask will be traveling one million miles at an average speed of 45 miles/hour during its service life. Therefore, the time during which the cask is in transit is:

$$t = 1\times10^6/45 = 22{,}222 \text{ hours} = 8\times10^7 \text{ sec}$$

Assuming that the cask package on the conveyance has a fundamental frequency of 2 Hz, the cask will be subjected to a load cycle of $2\times8\times10^7 = 1.6\times10^8$ cycles. This brings the components of the package into high-cycle fatigue range (> 10^8 cycles). The endurance limit of the material for the high cycle fatigue can be approximated by using a 60% reduction of the ultimate tensile strength (UTS) with an additional 10% reduction for the ground surface. Thus the endurance limit for the material is:

$$S_a = (1 - 0.6) \times (1 - 0.1) \times \text{UTS} = 0.36 \times \text{UTS}$$

ANSI N14.23 gives the following RMS vibration load factors for the road travel,

Vertical = 0.1, Longitudinal = 0.06 Lateral = 0.05

Impact Limiter Attachment

The 3-60B package is transported in the horizontal orientation. The impact limiters will be subjected to vibration in the longitudinal direction. The mass of each impact limiter is 4,200 lb (Section 2.1.3). Each impact limiter is attached to the cask body at 8 locations. The bolts connecting the impact limiter to the cask body are specified to be 7/8"-9UNC ASTM A-193 Gr. B5 bolts. The UTS for this material is 100,000 psi. Therefore,

$$S_a = 0.36\times100{,}000 = 36{,}000 \text{ psi}$$

Average RMS load on each bolt,

$$F = 0.06\times4{,}200/8 = 31.5 \text{ lb}$$

The bolts have stress area of 0.4612 in^2. Using a notch factor of 3.0, the RMS stress in the bolts is:

$$\sigma_{RMS} = 31.5\times3/0.4612 = 205 \text{ psi} \ll 36{,}000 \text{ psi}$$

Since the RMS stress in the bolts is well below the endurance limit of the material, the impact limiter attachment bolts will not be subjected to fatigue damage during their service life.

Trunnions & Shell

During transportation, the package is supported on the four trunnions. These trunnions have been evaluated for the normal handling and transportation conditions in Section 2.5.2. Using the results from these analyses, evaluation is performed for the fatigue as follows:

The trunnions and the cask outer shell are made of ASTM A-240 Type 304L stainless steel. The UTs for this material is 70,000 psi. Therefore,

$$S_a = 0.36\times70{,}000 = 25{,}200 \text{ psi}$$

The package total mass is 80,000 lbs. Therefore, the RMS loads in various directions are:

Vertical = 0.1×80,000 = 8,000 lb

Longitudinal = 0.06×80,000 = 4,800 lb

Lateral = 0.05×80,000 = 4,000 lb

The following stress results are reported in Section 2.5.2 for various loading conditions.

Vertical load = 160,000 => Max stress = 5,430 psi

Longitudinal load = 800,000 => Max stress = 27,953 psi

Lateral load = 400,000 => Max stress = 14,026 psi

Using a notch factor of 3.0, the RMS stresses in the trunnions for various loading directions are as follows:

Vertical = (8,000/160,000) × 5,430×3 = 815 psi << 25,200 psi

Longitudinal = (4,800/800,000) × 27,953×3 = 503 psi << 25,200 psi

Lateral = (4,000/400,000) × 14,026×3 = 421 psi << 25,200 psi

Since the RMS stresses in the trunnion are well below the endurance limit of the material, the trunnions and shell will not be subjected to fatigue damage during their service life.

Cask Lid

The cask lid weighs 4,500 lbs (see Section 2.1.3) and is bolted to the cask body by sixteen 1½-6UNC bolts. Since the cask will be transported in the horizontal orientation, the each lid bolt will be subjected to 0.06×4,500/16 = 16.9 lb RMS load. For ASTM A-354 Gr. BD bolts (UTS = 150,000 psi) this will result in a negligible vibration loading, which can be safely disregarded.

2.6.5.2 Shock Loading During Transportation

The shock loading coefficient that has been specified in ANSI N14.23 standard, in all the three orthogonal directions is 1.5. The components of the 3-60B Cask that will be subjected to shock loading during transportation are the trunnions and shell, the impact limiter attachment assembly, and the cask lid. The shock loading on these components are addressed below.

Trunnions and Shell

The trunnions have been analyzed in Section 2.5.2 for 10W longitudinal, 5W lateral, and 2W vertical loading. The 1.5 load factor is smaller than the load factors for shock loading in all directions. Therefore, the Section 2.5.2 analyses envelope the shock loading evaluation of the trunnions and shell.

Impact Limiter Attachment

Each impact limiter Attachment assembly will be subjected to a shock load of 1.5×4,200/8 = 787.5 pound force due to shock loading. The impact limiter attachment assemblies have been shown to have the capacity of 60,000 lbs (see ST-549, [2-21]). Therefore, they will be able to withstand the shock loading on the cask during transportation.

Cask Lid

The cask lid has been shown to withstand 70×sin 62° = 61.8g loading on the lid in the longitudinal direction (see Section 2.7.1.9). The 1.5W loading is much smaller than this. Therefore, the Section 2.7.1.9 analyses envelop the shock loading evaluation of the lid and its bolting arrangement.

2.6.6 Water Spray

Not applicable, since the package exterior is constructed of steel.

2.6.7 Free Drop

As described in Section 2.7.1 the analyses of the free drop of the package under NCT is performed in two steps. First the dynamic analyses of the package are performed using an Energy*Solutions* proprietary modeling technique outlined in document ST-551 [2-6] that utilizes the ANSYS/LS-DYNA computer code [2-12]. Next, the detailed FEM analyses of the cask are performed using ANSYS. The analyses are performed in the three customary orientations – end, side and corner over C.G. All the load combinations listed in Table 2-1 are analyzed. The details of the package dynamic analyses are documented in proprietary document ST-557 [2-17]. The documentation of the detailed FEM analyses of the package is provided in ST-504 [2-18].

The summary of the results from the package dynamic analyses of the NCT free drop are presented in Table 2-9. The stresses in the cask under the load combinations involving the NCT free drop are described below.

2.6.7.1 End Drop

The following impact limiter reactions are obtained from [2-17].

Cold Conditions $= 1.338\times10^6$ lb (Table 2-9 and Figure 16 of [2-17])

Hot Conditions $= 1.103\times10^6$ lb (Table 2-9 and Figure 20 of [2-17])

For the NCT test in the end drop orientation, the maximum of the two reactions are used in the analyses.

The distribution of reactions and inertia loads used in the FEM analyses are identical to those described in Section 2.7.1.1 for the HAC loading, except that they have been linearly proportioned in the ratio of corresponding impact limiter reactions. The results obtained from the detailed FEM analysis of the cask are presented in Table 2-10 and Table 2-11 for the hot and cold combinations, respectively.

Of all components, a minimum safety factor of 1.19 is computed for the loading combinations involving end drop.

2.6.7.2 Side Drop

The following impact limiter reactions are obtained from [2-17].

Cold Conditions = 453,400 lb (Table 2-9 and Figure 24 of [2-17])

Hot Conditions = 364,800 lb (Table 2-9 and Figure 28 of [2-17])

For the NCT test in the side drop orientation, the maximum of the two reactions are used in the analyses.

The distribution of reactions and inertia loads used in the FEM analyses are identical to those described in Section 2.7.1.2 for the HAC loading, except that they have been linearly proportioned in the ratio of corresponding accelerations. The results obtained from the detailed FEM analysis of the cask are presented in Table 2-12 and Table 2-13 for the hot and cold combinations, respectively.

Of all components, a minimum safety factor of 1.12 is computed for the loading combinations involving side drop.

2.6.7.3 Corner Drop

The following impact limiter reactions are obtained from [2-17].

Cold Conditions	= 335,300 lb	(Table 2-9 and Figure 32 of [2-17])
Hot Conditions	= 303,208 lb	(Table 2-9 and Figure 36 of [2-17])

For the NCT test in the corner drop orientation, the maximum of the two reactions are used in the analyses.

The distribution of reactions and inertia loads used in the FEM analyses are identical to those described in Section 2.7.1.3 for the HAC loading, except that they have been linearly proportioned in the ratio of corresponding accelerations. The results obtained from the detailed FEM analysis of the cask are presented in Table 2-14 and Table 2-15 for the hot and cold combinations, respectively.

Of all components, a minimum safety factor of 1.06 is computed for the loading combinations involving corner drop.

2.6.8 Corner Drop

Not applicable; the 3-60B package is not a fiberboard, wood, or fissile material package.

2.6.9 Compression

Not applicable; the 3-60B package weighs more than 11,000 lbs.

2.6.10 Penetration

The package is evaluated for the impact of the hemispherical end of a vertical steel cylinder of 1¼″ diameter and 13 lb mass, dropped from a height of 40″ onto the exposed surface of the package.

The penetration depth of the 13 lb 1¼″ diameter rod dropped from a height of 40″ is calculated from the Ballistic Research Laboratories (BRL) formula sited in [2-20]. For a steel target, the penetration depth is given by the formula:

$$\left(\frac{e}{d}\right)^{3/2} = \frac{DV_0^2}{1.12\times10^6\times K_s^2}$$

Where,

e	=	penetration depth, inch
d	=	effective projectile diameter, inch = 1.25″
W	=	missile weight, lb = 13 lb
D	=	caliber density of the missile, lb/in^3 = W/d^3
V_0	=	striking velocity of the missile, ft/sec
K_s	=	steel penetrability constant = 1.0

For a 40″ drop of the rod, the striking velocity,

V_0 = $(2\times32.2\times40/12)^{0.5}$ = 14.65 ft/sec

D = $13/1.25^3$ = 6.656 lb/in^3

Solving the penetration equation, we get,

$$e = 1.25\times\left(\frac{6.656\times14.65^2}{1.12\times10^6\times1^2}\right)^{2/3} = 0.0147''$$

The thickness of the 3-60B outer shell is 1¼″, the lid is 4″ (min.), and the outer baseplate is 3″. All these thickness are greater than 0.0147″ required for penetration. Therefore, the penetration test will not cause any damage to the package. It should be noted that in the penetration evaluation, no credit for the lead shielding and the inner shell has been taken.

2.7 Hypothetical Accident Conditions

2.7.1 Free Drop

The 3-60B package is shown to comply with the HAC test requirements by analytical methods in lieu of the physical tests. Advanced finite element methods have been employed in the analyses. A major assumption that is made in performing these analyses is that the dynamic behavior of the 3-60B package, which consists of the cask body and the impact limiters, can be decoupled into a dynamic behavior of the impact limiters and a pseudo-static behavior of the cask body. The rationale for this assumption is based on the relative stiffness of the impact limiters and the cask body. The impact limiters are made of a shock absorbing polyurethane material, which is very low in density compared to the cask body which is made from stainless steel and lead. The fundamental periods of the two components are, therefore, sufficiently far apart such that little or no interaction takes place between their dynamic responses to the drop loading. The overall

dynamic analyses of the package, in various drop orientations, are performed separately and the reactions of the impact limiter on the cask body, obtained from these analyses are used in detailed finite element analyses of the cask body.

Dynamic Analyses of the Package

Proprietary modeling techniques, developed by Energy*Solutions*, LLC, using an explicit dynamic finite element code, ANSYS/LS-DYNA [2-12], for the drop analysis of packages that use closed-cell cellular polyurethane foam impact limiters, have been employed to perform the drop analyses of the 3-60B package. The validation of the modeling techniques have been performed with the actual drop test data of a cask of similar size to the 3-60B. The details of the modeling techniques and the verification and validation with the test results are documented in an Energy*Solutions* proprietary document ST-551 [2-6]. The Energy*Solutions* modeling techniques predict the acceleration results conservatively and the time-history trace of the analyses and test data are reasonably close to each other to validate the analysis.

The finite element model used for the analyses of the 3-60B package is described in details in Energy*Solutions* proprietary document ST-557 [2-17]. Figure 2-25 and Figure 2-26 show the finite element model. It is made of 8-node solid elements, 4-node shell elements, and 3-node spar elements. The model consists of 11,062 nodes and 9,119 elements.

Analyses of the 3-60B package have been performed in three customary drop orientations as well as two other orientations that are deemed to result in a larger impact limiter reaction than any of the three customary orientations. The analyzed orientations are:

End Drop – The cask axis parallel to the drop direction (see Figure 2-27)

Side Drop – The cask axis perpendicular to the drop direction (see Figure 2-28)

Corner Drop – The C.G. of the cask directly over the impact point. The cask axis makes an angle of 28° with the vertical plane (see Figure 2-29).

Shallow Angle Drop – The cask axis making an angle of 7½° (Slapdown-1) and cask axis making an angle of 15° with the horizontal plane (Slapdown-2) have been analyzed. These orientations are similar to the side drop except that one of the impact limiters is higher than the other. The slap-down effect due to the secondary impact is included (see Figure 2-30).

The finite element transient analyses are performed for sufficiently large duration so that the primary as well as secondary impacts, if any, are included. The time-history data of the reaction forces between the package and the rigid contact surface are obtained for each load case (see Figure 2-31 for a typical plot). The time-history of the results are examined for various quantities such as the kinetic energy, internal energy, total energy, hourglass energy, and the external work (see Figure 2-32 for a typical plot). The time-history data of the maximum impact limiter crush are also obtained for each load case. The impact limiter attachment load time-histories are also obtained for each drop orientation.

The HAC drop tests, according to 10 CFR 71.73(b), must be performed at a constant temperature between -20°F and 100°F, which is most unfavorable for the feature under consideration. To

envelop the entire spectrum of the temperature range, the dynamic analyses of the package are performed for two initial conditions – the cold condition (Ambient temperature -20°F) and the hot condition (ambient temperature 100°F). To be conservative, the larger of the two results are used for the detailed analyses of the cask body.

The details of the dynamic analyses of the 3-60B package, including the finite element model details, assumptions, boundary conditions, and the input and output data are included in the Energy*Solutions* proprietary document ST-557 [2-17].

The summary of the results from these analyses are presented in Table 2-16.

Detailed Analyses of the Cask

The detailed analyses of the cask under various drop test conditions have been performed using advanced finite element modeling techniques. ANSYS finite element analysis code [2-12] has been employed to perform the analyses. Since for all the drop orientations (end, side, corner, and slap-down), at least one plane of symmetry exists, a 180° model has been employed in all the analyses. This model has been developed from the 11.25° model developed in Sections 2.6 and 3.3 for the structural and thermal analyses of the cask during NCT.

The model of the cask is made using 3-dimensional 8-node structural solid elements (ANSYS SOLID185) to represent the major components of the cask, the bolting ring, the lid, and the bolts. The shell components of the cask - the inner and outer shells, and the baseplates have been represented in the finite element model by SOLSH190 elements.

Since fire shield does not provide any structural strength to the cask, it is not included in the model.

The poured lead in the body is not bonded to the steel. It is free to slide over the steel surface. Therefore, the interface between the lead and the steel is modeled by pairs of 3-d 8 node contact element (CONTA174) and 3-d target (TARGE170) elements. These elements allow the lead to slide over the steel and at the same time prevent it from penetrating the steel surface. The interface between the two plates that form the lid is also modeled by the contact-target pairs. The transition from a coarser mesh to a finer mesh, as well as bondage between various parts of the model, is also modeled using these elements.

Figure 2-33 shows the outline of the model depicting the material numbering. Figure 2-34 shows the finite element grid of the lid, seal plate, and the bolts. Figure 2-35 shows the finite element grid of the cask body without the lead. The FEM consists of 36,999 nodes and 37,659 elements.

The finite element model is representative of, and applicable to, both cask Configuration A and cask Configuration B. Although the finite element model geometry is specifically based on cask Configuration A, the results obtained from the model are either directly applicable to, or bounding for, cask Configuration B. The primary differences between the two cask configurations, with respect to the finite element model, are: (1) Lid seal ring designs, and (2) Outer shell-to-outer bottom plate connection detail. These differences are discussed and evaluated in the following paragraphs.

Configuration A includes a separate seal ring in the lid assembly, whereas in Configuration B the seal ring is integral to the lid outer plate, as shown on the general arrangement drawing in Section 1.3. The strength of the integral seal ring used in Configuration B is greater than or equal to the strength of the separate seal ring of Configuration A. Therefore, the stress analysis results obtained from the finite element model are considered bounding for Configuration B.

The outer bottom corner of cask Configuration A includes a bottom corner ring forging that connects the outer shell to the outer bottom plate, whereas for Configuration B the outer shell and outer bottom plate are welded directly to one another with a complete joint penetration weld. In terms of geometry, these two configurations are identical. Although the bottom corner forging material used in Configuration A has slightly higher strength properties that the adjacent outer shell and outer bottom plate materials, no credit was taken for the higher strength properties in the structural evaluation and the bottom corner forging is treated as an extension of the outer shell and outer bottom plate. Therefore, the results are applicable to both cask configurations.

To incorporate the loading combinations of Table 2-1 for various drop conditions, the analyses have been performed for three thermal conditions. The loading combinations in hot conditions have been performed per Regulatory Guide 7.8, which requires an ambient temperature of 100°F and the maximum internal decay heat load. The loading combination for the cold conditions, per Regulatory Guide 7.8, requires an ambient temperature of -20°F and the minimum internal decay heat load. It is not intuitively obvious that the minimum decay heat load in the cold conditions will result in a conservative estimate of thermal stresses in the package. Therefore, the cold condition's load combinations listed in Table 2-1 have been performed two ways - one with the maximum decay heat load and another with the minimum decay heat load. The combinations that result in larger stresses have been reported in this SAR as the cold combination. The nodal temperatures for all the thermal conditions are obtained from the analyses in Section 3.0 and are applied to the structural models to get the appropriate load combinations.

The documentation of the detailed analyses of the cask, including the finite element model details, assumptions, boundary conditions, and the input and output data are included in the Energy*Solutions* proprietary document ST-504 [2-18]. ANSYS finite element model grid convergence study has been performed in Energy*Solutions* document ST-608 [2-19]. This document also provides the validation of the major modeling techniques used in the finite element analyses.

2.7.1.1 End Drop

The following impact limiter reactions are obtained from [2-17].

Cold Conditions $= 3.954 \times 10^6$ lb (Table 2-16 and Figure 56 of [2-17])

Hot Conditions $= 3.083 \times 10^6$ lb (Table 2-16 and Figure 61 of [2-17])

The maximum of the two reactions is conservatively used for the analyses of all environmental conditions. The impact limiter reaction is converted to the rigid body acceleration by dividing the reaction by that portion of the mass of the package which causes this reaction. During the end drop test the impact limiter reaction is caused by the total mass of the package less the mass of one impact limiter, i.e. 80,000 - 3,800 = 76,200 lb (SAR Section 2.1.3). Since the FEM

represents only ½ of the package, the total mass is divided by 2 in the calculation of the rigid body acceleration. A factor of 1.1 is used to conservatively increase this reaction in the analyses.

Rigid body acceleration = $1.1 \times 2 \times 3.954 \times 10^6 / 76{,}200 = 114.2$

The value used for rigid body acceleration is conservatively set at 150g. The distribution of reactions and inertia loads used in the quasi-static FEM analyses are shown in Figure 2-36. The plot of the maximum stress intensities in the cask are shown in Figure 2-37 for the hot condition, in Figure 2-38 for the cold condition (maximum decay heat), and in 2-40 for the cold condition (minimum decay heat). The results obtained from the detailed FEM analysis of the cask are presented in Table 2-17 and Table 2-18 for the hot and cold combinations, respectively.

Of all components, a minimum safety factor of 1.28 is computed for the loading combinations involving end drop.

2.7.1.2 Side Drop

The following impact limiter reactions are obtained from [2-17].

Cold Conditions = 1.889×10^6 lb (Table 2-16 and Figure 66 of [2-17])

Hot Conditions = 1.636×10^6 lb (Table 2-16 and Figure 71 of [2-17])

Conservatively use the maximum of the two reactions for the analyses of all environmental conditions. The impact limiter reaction is converted to the rigid body acceleration by dividing the reaction by that portion of the mass of the package which causes this reaction. During the side drop test the impact limiter reaction is caused by the total mass of the package less the mass of the two impact limiters, i.e. 80,000 - 2×3,800 = 72,400 lb (Section 2.1.3). Since the FEM represents only ½ of the package and each impact limiter reaction is caused by ½ the participating mass, the total mass is divided by 4 in the calculation of the rigid body acceleration. A factor of 1.1 is used to conservatively increase this reaction in the analyses.

Rigid body acceleration = $1.1 \times 4 \times 1.889 \times 10^6 / 72{,}400 = 114.8$

The value used for the rigid body acceleration is conservatively set at 120g. The distribution of reactions and inertia loads used in the quasi-static FEM analyses are shown in Figure 2-40. The plot of the maximum stress intensities in the cask are shown in Figure 2-41 for the hot condition, in Figure 2-42 for the cold condition (maximum decay heat), and in Figure 2-43 for the cold condition (minimum decay heat). The results obtained from the detailed FEM analysis of the cask are presented in Table 2-19 and Table 2-20 for the hot and cold combinations, respectively.

The minimum safety factor of 1.07 is computed for the loading combinations involving side drop. This minimum safety factor occurs in the bolting ring skirt extension and is confined in the area near the impact point. The bolting ring skirt extension does not constitute a containment boundary component. A slight deformation will redistribute the stresses in this area, resulting in a larger factor of safety. Of all components, a minimum factor of safety on the containment boundary components is 1.11.

2.7.1.3 Corner Drop

The following impact limiter reactions are obtained from [2-17].

Cold Conditions $= 2.080\times10^6$ lb (Table 2-16 and Figure 76 of [2-17])

Hot Conditions $= 1.847\times10^6$ lb (Table 2-16 and Figure 81 of [2-17])

Conservatively use the maximum of the two reactions for the analyses of all environmental conditions. The impact limiter reaction is converted to the rigid body acceleration by dividing the reaction by that portion of the mass of the package which causes this reaction. During the corner drop test the impact limiter reaction is caused by the total mass of the package less the mass of one impact limiter, i.e. 80,000 - 3,800 = 76,200 lb (Section 2.1.3). Since the FEM represents only ½ of the package, the total mass is divided by 2 in the calculation of the rigid body acceleration. A factor of 1.1 is used to conservatively increase this reaction in the analyses.

Rigid body acceleration $= 1.1\times2\times2.080\times10^6/76{,}200 = 60.1$

The value used for rigid body acceleration is conservatively set at 70g. The distribution of reactions and inertia loads used in the quasi-static FEM analyses are shown in Figure 2-44. The plot of the maximum stress intensities in the cask are shown in Figure 2-45 for the hot condition, in Figure 2-46 for the cold condition (maximum decay heat), and in 2-48 for the cold condition (minimum decay heat). The results obtained from the detailed FEM analysis of the cask are presented in Table 2-21 and Table 2-22 for the hot and cold combinations, respectively.

Of all components, a minimum safety factor of 1.08 is computed for the loading combinations involving corner drop.

2.7.1.4 Oblique Drops

The 3-60B cask package has also been analyzed for two oblique drops also referred to as "shallow angle drop" tests. Under these test conditions, the cask axis makes an angle with the horizontal plane of 7.5° and 15°, respectively. The lower impact limiter makes contact with the rigid target surface. This is followed by a rotation of the cask and the second impact limiter then strikes the rigid surface. It is during the second impact that the maximum impact limiter reaction occurs. At this time the cask is in the horizontal orientation, which is the same orientation as the side drop. Thus the distribution of the impact limiter reaction on the cask is similar to that of the side drop only its magnitude is different. The ratio of the impact limiter reaction for shallow angle-to-the side drop is used to amplify the side drop stresses to obtain the maximum stresses the cask will experience during the shallow angle drop.

The results of the shallow angle drop analyses show that the second impact is more severe than the first impact. The maximum impact limiter reaction during the 7.5° case is:

$R_{\text{shallow-angle}} = 2.009\times10^6$ lb (Table 2-16)

The nature of impact limiter reaction in this case is very similar to that of the side drop test. The maximum impact limiter reaction during the side drop test is:

$R_{\text{side-drop}} = 1.889 \times 10^6$ lb (Table 2-16)

Thus, the shallow angle drop test will result in the impact limiter reaction that is larger than that of the side drop test by a factor of: 2.009/1.889 = 1.06

Therefore, a factor of safety of 1.06 or larger in the cask due to HAC side drop loading will ensure that cask will satisfy the design acceptance criteria for the shallow angle drop orientation also. From the examination of results presented in Table 2-19 through Table 2-20, it is observed that the minimum factor of safety in the containment components is 1.09, which is larger than 1.06 needed for shallow angle drop test.

With the five orientations for the drop test addressed in this document the entire spectrum of initial orientations of the cask package for the hypothetical drop test has been covered. The FEM analyses have been performed for sufficiently large time durations in which both primary as well as secondary impacts, if any, take place. Thus, the slap-down effect of the shallow angle drop, as well as that during the corner-over-C.G. drop has been included in these analyses.

2.7.1.5 Lead Slump Evaluation

The 3-60B package experiences the largest acceleration during the end drop orientation. Analysis of the 3-60B package under HAC drop test has been performed in the end drop orientation with cask top-end down. Since the top end of the cask has a bolted connection between the lid and the cask body, it is more critical than the bottom-end down orientation which includes no bolted connections. However, the cask is most vulnerable, as far as lead slump is concerned, in the bottom end down orientation. To get a conservative estimate of the lead slump, structural analysis of the cask has been performed with the bottom-end down orientation. The most conservative environmental conditions (cold with no decay heat) have been employed in the analysis. Figure 2-48 shows the displacement plot during this drop test. The largest relative displacement of 0.3172 in is calculated at the bolting ring-lead interface. It should be noted this is the total relative displacement. In considering this to be the lead slump, the elastic recovery of the lead and steel has been neglected.

2.7.1.6 Impact Limiter Attachment Evaluation

The impact limiter attachment loads for each drop condition are obtained from the FEM analyses described in Section 2.7.1. These loads are presented in Table 2-23. The maximum load in an individual attachment under any of the HAC event is 56,890 lb. A detailed analysis of the impact limiter attachment is provided in Energy*Solutions* ST-549 [2-21] that shows that the impact limiter attachments are capable of withstanding this load.

2.7.1.7 Shell Buckling

Buckling evaluation of the 3-60B Cask structural components under NCT and HAC loading conditions have been performed using ASME Nuclear Code Case N-284 [2-5]. Factors of safety of 1.34 for the NCT and 2.0 for HAC events have been used in the buckling evaluation of the cask. The details of the calculations are given in [2-28]. The results of the analyses show that the 3-60B Cask satisfies all the loading interactions for elastic and inelastic buckling specified in ASME Code Case N-284.

2.7.1.8 Port Cover Evaluation

The 3-60B package has two penetrations through the containment boundary that are closed with port covers. These include the vent port and the drain port. The port covers for these ports are recessed into the cask body. The drain port covers, along with a cover for the testing of the lid O-ring are totally surrounded by the impact limiter foam. The vent port cover is only partly surrounded by the foam. However, the ½" plate that forms the impact limiter seating totally covers this port. Therefore, during the HAC drop tests none of the port covers directly make contact with the impact surface. Of these ports, only the drain port is susceptible to high loading. This may occur during the side drop of the package, if the orientation is such that the drain port is near the impact surface. A conservative evaluation of the drain port is provided in ST-549 [2-21].

2.7.1.9 Closure Bolt Evaluation

Closure bolts stresses under various loading combinations that were obtained from the FEM analyses have been provided in the appropriate sections of the SAR. They have been compared with the corresponding design allowable values and show that a large factor of safety exists in the design of the bolts under all loading combinations.

A conservative evaluation of the bolting, using the limiting loads is provided in this section to show the adequacy of the bolting design. Additionally, it is shown that under NCT loading conditions, the bolt torque provides sufficient preload in the bolts to overcome the loading arising from the thermal and pressure loadings. It is also shown that the minimum engagement length requirement for the specified bolts and the bolting ring material is also satisfied.

<u>Evaluation under Limiting Conditions</u>

The largest bolt load, under the HAC drop tests could arise in the corner drop orientation. Assuming that the lid in this case is totally unsupported by the impact limiter and the entire inertia loading of the lid and payload is reacted by the lid bolts only, the maximum loads in the bolts are calculated following the methodology of NUREG/CR-6007 [2-22].

The maximum impact limiter reaction during the end drop events are:

Cold Conditions $= 2.080\times10^6$ lb (Table 2-16 and Figure 76 of [2-17])

Hot Conditions $= 1.847\times10^6$ lb (Table 2-16 and Figure 81 of [2-17])

Conservatively use the maximum of the two reactions for the analyses of all environmental conditions. The impact limiter reaction is converted to the rigid body acceleration by dividing the reaction by that portion of the mass of the package which causes this reaction. During the corner drop test the impact limiter reaction is caused by the total mass of the package less the mass of one impact limiter, i.e. 80,000 - 3,800 = 76,200 lb (Section 2.1.3). Since the FEM represents only ½ of the package, the total mass is divided by 2 in the calculation of the rigid body acceleration. A factor of 1.1 is used to conservatively increase this reaction in the analyses.

Rigid body acceleration $= 1.1\times2\times2.080\times10^6/76{,}200 = 60.1$ » Use 70g

Dynamic acceleration factor (DLF) = 1.0

Weight of the cask content (W_c) = 9,500 lb

Weight of the closure lid (W_l) = 3,930 lb

Using an impact angle of x_i = 62° between the cask axis and the target surface (same as the corner drop 28° from vertical plane), the non-prying tensile bolt force per bolt (F_a) is

$$F_a = \frac{1.34 \times \sin(x_i) \times DLF \times a_i \times (W_l + W_c)}{N_b} = \frac{1.34 \times \sin 62 \times 1.0 \times 70 \times (3{,}930 + 9{,}500)}{16} = 69{,}517 \text{ lb}$$

Shear bolt force per bolt (F_s) is:

$$F_s = \frac{\cos(x_i) \times a_i \times W_l}{N_b} = \frac{\cos 62 \times 70 \times 3{,}930}{16} = 8{,}072 \text{ lb}$$

Fixed-edge closure –lid force (F_f) and moment (M_f) are:

$$F_f = \frac{1.34 \times \sin(x_i) \times DLF \times a_i \times (W_l + W_c)}{\pi \times D_{lb}} = \frac{1.34 \times \sin 62 \times 1.0 \times 70 \times (3{,}930 + 9{,}500)}{\pi \times 44.25} = 8{,}001$$
lb/in

$$M_f = \frac{1.34 \times \sin(x_i) \times DLF \times a_i \times (W_l + W_c)}{8 \times \pi} = \frac{1.34 \times \sin 62 \times 1.0 \times 70 \times (3{,}930 + 9{,}500)}{8 \times \pi}$$
$$M_f = 44{,}256 \; in - lb / in$$

Calculating the additional tensile bolt force per bolt (F_{ap}) caused by prying action of closure lid using [2-22] Table 2.1 formulas.

$$F_{ap} = \left(\frac{\pi \times D_{lb}}{N_b}\right) \times \frac{\dfrac{2M_f}{(D_{lo} - D_{lb})} - C_1 \times (B - F_f) - C_2 \times (B - P)}{C_1 + C_2}$$

F_f = 8,001 lb/in is greater than P = 1,841.52 lb/in and therefore the non-prying tensile bolt force is,

B = F_f = 8,001 lb/in

$$F_{ap} = \left(\frac{\pi \times 44.25}{16}\right) \times \frac{\dfrac{2 \times 44{,}256}{(48.75 - 44.25)} - 1.0 \times (8{,}001 - 8{,}001) - 1.11 \times (8{,}001 - 1{,}842.52)}{1.0 + 1.11}$$
$$= 52{,}845 \, lb$$

The bolts are specified to be 1½-6UNC for which the stress area is 1.4041 in^2.

The maximum shear stress is,

$$\tau = 8{,}072/1.4041 = 5{,}749 \text{ psi}$$

The maximum axial stress is,

$$\sigma = (69{,}517+52{,}845)/1.4041 = 87{,}146 \text{ psi}$$

Interaction equation for the axial and shear stresses is:

$$\left(\frac{\sigma}{\sigma_{allow}}\right)^2 + \left(\frac{\tau}{\tau_{allow}}\right)^2 \leq 1.0$$

Using the allowable shear and axial stresses as calculated in Case 1 above, the axial and shear interaction is:

$$\left(\frac{87{,}146}{105{,}000}\right)^2 + \left(\frac{5{,}749}{63{,}000}\right)^2 = 0.697 \quad < 1.0$$

Therefore, bolt design meets the design criteria established in Section 2.1.2.

<u>Lid Bolt Torque Evaluation</u>

In order to maintain the seal during the NCT, the 3-60B package lid bolts are tightened to a sufficient torque value. Under the NCT loading combinations listed in Table 2-1, the largest bolt loads are experienced due to the loading of minimum external pressure, under which the package is subjected to an internal pressure of 50 psig. Also, since the bolts, the bolting ring, and the lid are made with different materials, they expand different amounts during the hot and cold environments. The coefficient of thermal expansion of the bolting ring and the lid is larger than that of the bolts. Therefore, in the cold environment the bolting ring contracts more than the bolts and the bolts experience a loss of tension due to this relative expansion. The amount of loss of tension is conservatively calculated as follows:

Assume that the maximum joint temperature is -40°F. Coefficient of thermal expansion of non-bolting material from Table 2-4 at 70°F is 8.5×10^{-6} in/(in-°F) and for bolting material is 6.4×10^{-6} in/(in-°F). The effective length of the bolt for this relative expansion is that from the bolt-head to the top of the bolting ring = 4.375 -1.75 = 2.625″. Then the relative expansion of the bolt is:

$$\delta = 2.625\times(8.5 - 6.4)\times10^{-6}\times(-40 - 70) = -0.00061''$$

Young's Modulus for the bolting material at 70°F is 29.7×10^{6} psi. Therefore, bolt thermal stress is:

$$\sigma_{thermal} = 29.7\times10^{6}\times0.00061/2.625 = 6{,}902 \text{ psi}$$

For 1½-inch diameter bolts, the load is:

$F_{thermal} = \pi/4 \times 1.5^2 \times 6{,}902 = 12{,}197$ lb

The Maximum internal pressure of the package is 50 psi, which occurs under minimum external pressure load combinations (see Table 2-1). The average bolt load under this pressure is:

$F_{p\text{-}avg} = \pi \times 19.125^2 \times 50/16$ (19.125″ is the radius of inner seal)

$= 3{,}591$ lb

Therefore, the total required preload is:

$F_{preload} = 12{,}197 + 3{,}591 = 15{,}788$ lb

Using the customary torque equation,

$T = K\,D\,F$

Where, T = torque

K = nut factor = 0.1 for lubricated condition

D = nominal diameter of the bolt = 1.5″

F = preload

The required torque is:

$T = 0.1 \times 1.5 \times 16{,}506 = 2{,}368$ in-lb = 197.4 ft-lb

Therefore, the specified torque of 300 ± 30 ft-lb is sufficient to maintain the needed bolt preload for the NCT loading.

Bolt Engagement Length Calculation

Bolt engagement length for 1½″ - 6UNC, Class 2A bolts is calculated based on the formula from Bickford [2-23].

Input Quantities:

Bolt Nominal Diameter, inch	φ	=	1.50	
Number of Threads per inch	n	=	6	
Stress Area of Bolt Threads, inch^2	A_s	=	1.405	
Tensile Strength of Bolt Material, psi	S_{st}	=	150,000	ASTM A 354 Gr. BD
Tensile Strength of Nut Material, psi	S_{nt}	=	70,000	ASTM A 240 Gr. 304L
Maximum I.D. of Nut, inch	K_{nmax}	=	1.350	
Maximum P.D. of Nut, inch	E_{nmax}	=	1.4022	
Minimum P.D. of Bolt, inch	E_{Smin}	=	1.3812	
Nominal Pitch Diameter, inch	E_p	=	1.3917	
Minimum O.D. of Bolt, inch	D_{min}	=	1.4794	

Calculated Quantities:

Nut Material Weaker than Bolt Material

Failure occurs at the root of nut threads Engagement Length,

$$L_e = \frac{S_{st} \cdot (2 \cdot A_s)}{S_{nt} \cdot \pi \cdot n \cdot D_{\min} \cdot \left[\left(\frac{1}{2 \cdot n} \right) + 0.57735 \cdot (D_{\min} - E_{n\max}) \right]} = 1.688''$$

The bolt engagement provided in the design is 2″, which is larger than 1.688″ required.

2.7.2 Crush

Not applicable; the package weighs more than 1,100 lb, and its density is larger than 62.4 lb/ft^3.

2.7.3 Puncture

The puncture drop test specified in 10 CFR 71.73(c)(3) requires that the package be dropped on a 6″ diameter mild steel rod from a height of 40″. The well-known Nelm's Equation [2-24] predicts that a package weighing W, made with steel having an ultimate strength S_u needs a shell thickness t to prevent penetration of the puncture bar, which is given by the formula:

$$t = (W/S_u)^{0.7}$$

For 3-60B package, W = 80,000 lb, S_u = 70,000 psi, then,

$$t = (80{,}000/70{,}000)^{0.7} = 1.10''$$

Since the outer shell of the package is 1¼″ thick, it is predicted that the puncture drop test will not result in the bar piercing through the outer shell.

In order to substantiate the above conclusion, evaluations of the 3-60B package wall and ends have been performed using finite element models. The details of the finite element models, including the assumptions, modeling details, boundary conditions, and input and output data are included in the Energy*Solutions* document ST-505 [2-25]. The analyses are summarized in the following paragraphs.

A nonlinear inelastic analysis of the cask wall was performed using the ANSYS finite element model to show that the entire amount of the potential energy may be converted into mechanical work done, without exceeding the allowable stresses in the cask outer shell. The finite element model is shown in Figure 2-49. The force-deflection curve is show in Figure 2-50. The absorbed energy and available potential energy plot is shown in Figure 2-51. Figure 2-52 shows the stress intensity plot in the outer shell of the package at the energy balance condition. The maximum stress intensity in the package is well below the ultimate tensile strength of the material (70,000 psi). Therefore, it is shown that the package outer wall will not be penetrated during the puncture drop test.

The evaluation of the puncture drop on the cask lid is performed using the linear elastic finite element model that has been used in other evaluations, e.g. NCT conditions. The maximum stress intensity plot in the cask under the hot condition is shown in Figure 2-53. Figure 2-54 and Figure 2-55 show the stress intensity plot in the lid and bolts under hot and cold conditions, respectively. The maximum S.I. of 41,568 psi and 41,157 are well below the allowable stress of 70,000 psi.

The results of the analyses presented in this section show that 3-60B package can withstand the drop on the puncture bar, without rupture. Therefore, the requirements of 10 CFR 71.73(c)(3) are satisfied.

2.7.4 Thermal

The thermal evaluation of the 3-60B package for the HAC fire test specified in 10 CFR 71.73(c)(4) has been performed in Section 3.4. Damage to the package resulting from the free drop and puncture tests have been incorporated into the initial conditions of the analyses. It has been shown in the free drop analyses that the rupture of the impact limiter skin near the point of impact is possible. Also during the puncture test, the bar will pierce through the impact limiter skin and compress the foam. Thus during the HAC fire test, the portion of foam that is incased inside the impact limiter, may be directly exposed to the pool fire. Although the polyurethane foam is self-extinguishing and produces intumescent char when thermally degraded, it is assumed in the analysis that the foam provides no thermal insulation during the fire test. Only the inner casings of the impact limiters, which have been shown to remain intact during the free drop tests (see Section 2.7.1.6), have been used as the thermal insulator during the fire test.

Using the results of the thermal analysis of Section 3.4, structural evaluation of the package has been performed in this section. The finite element model described in Section 2.6 has been employed in the analyses. The details of the model, including the assumptions, modeling details, boundary conditions, and input and output data are included in the Energy*Solutions* document ST-502 [2-26].

2.7.4.1 Summary of Pressure and Temperatures

Based on the thermal analysis of the package during the HAC fire test, presented in Section 3.4, the maximum temperatures in various parts of the package are presented in Table 3-2 and plotted in Figure 3-12. These temperatures are summarized here as follows:

Fire Shield	=	1,331°F
Outer Shell	=	353.5°F
Inner Shell	=	284.1°F
Lead	=	301.6°F
Seal	=	295.7°F
Average Cavity	=	273.2°F

It should be noted that the maximum temperature in various components of the package occur at different time instants. The maximum average temperature of the cask cavity during the entire HAC fires test and subsequent cool-down is 273.2°F (Table 3-3). Conservatively 320°F temperature is used in Section 3.4.3 for calculating the maximum internal pressure of the

package during the HAC fire test. The calculated internal pressure of the package during the HAC fire test is 100.0 psig.

2.7.4.2 Differential Thermal Expansion

The structural finite element model used for the analyses of the 3-60B package under HAC fire test uses temperature dependent material properties of the cask components. The differential thermal expansion of various components of the cask is automatically included in the stress evaluation of the package.

2.7.4.3 Stress Calculations

The stresses in the package under the HAC fire test have been calculated in Energy*Solutions* document ST-502 [2-26]. The loading combination used for the HAC fire test is listed in Table 2-1. Table 2-24 presents the maximum stresses in various component of the package.

2.7.4.4 Comparison with Allowable Stresses

The stresses in the package under the HAC fire test are compared with their allowable values in Table 2-24. The allowable values in various components of the package are listed in Table 2-2. It is noticed from the comparison with the allowable values that all the components of the package experience stresses well below their allowable values. A minimum factor of safety of 1.01 occurs in the bolting ring skirt extension. It should be noted that the largest stresses under the HAC fire test occur at the location where the fire-shield is welded to the bolting ring skirt extension. These stresses are secondary in nature; slight local deformation of the skirt can easily accommodate these stresses. Of all components, a minimum factor of safety in the package at other locations is 1.25.

2.7.5 Immersion – Fissile material

Not applicable for 3-60B package; since it does not contain fissile material.

2.7.6 Immersion – All packages

All the Type-B packages are required to meet the water immersion test specified in 10 CFR 71.73(c)(6). According to which, an undamaged package must be subjected to a pressure of 21.7 psig.

The package has been analyzed for an increased external pressure of 25 psig in Section 2.6.4. Therefore, the stresses presented in that section envelope those that will arise due to the immersion test.

2.7.7 Deep Water Immersion Test

Not applicable; 3-60B package does not contain irradiated nuclear fuel.

2.7.8 Summary of Damage

It has been demonstrated by several analyses performed in Section 2.7 that the 3-60B package can withstand the HAC test, specified in 10 CFR 71.73, including the free drop, puncture and fire. During these drop tests the protective impact limiters may undergo some damage, which is summarized as follows:

- During the HAC drop tests, the impact limiter skin may buckle and/or rupture in the vicinity of impact. The rupture may expose a portion of the polyurethane foam that is contained inside the steel skin.
- During the side and corner drop tests, the skirt extension of the bolting-ring may deform slightly near the point of impact. This component is away from the containment boundary of the package and a slight local deformation will not have any effect on the package performance prior to fire tests. Inelastic analyses of the bolting ring skirt under those loading conditions under which it experiences high stresses (side and corner drop conditions) have been performed in Energy*Solutions* document ST-609 [2-29]. It shows that the skirt, under these loading conditions, will accumulate less than 2% plastic strain. It has also been shown that the bolts in the vicinity of the plastic deformation will experience stresses that are within the allowable values.
- During the puncture drop test on the sidewall of the package, the fire-shield which is designed to have a separation from the outer shell, may come in contact with the outer shell due to deformation of the helically wound wire. The loss of separation will only be in the close vicinity of the puncture bar end. This will decrease the thermal resistance in that local area. The temperature there may increase slightly from those calculated for the intact package. In the area of the outer shell surface, the temperatures are well within the acceptable value. No unacceptable stress increase is expected because of slight increase in the local temperature.
- During the puncture drop test on the impact limiters, the outer steel skin will deform significantly due to large compression of polyurethane foam at the impact point. This may expose a portion of the polyurethane foam that is contained inside the steel skin. The seating surface of the impact limiters, which includes the impact limiter attachments, will remain intact as shown in the analysis. Therefore, during the HAC fires test, only this component of the impact limiters is assumed to provide thermal insulation (see Section 3.1.1)
- Puncture drop test will not cause a direct impact with any of the port closure plates.

Based on the assessment of the above damage it is concluded that the 3-60B package can safely withstand the HAC free drop, puncture, and fire tests performed in sequence. The package structural components under these drop tests have been shown to meet the design criteria set forth in Section 2.1.2.

2.8 Accident Conditions for Air Transport of Plutonium

Not applicable for 3-60B package since it is not transported by air.

2.9 Accident Conditions for Fissile Material Packages for Air Transport

Not applicable for 3-60B package since it is not transported by air.

2.10 Special Form

Not applicable for 3-60B package since the package contents are not limited to special form.

2.11 Fuel Rods

Not applicable for 3-60B package; since the contents do not include fuel rods.

2.12 **Appedix**

2.12.1 References

[2-1] Code of Federal Regulations, Title 10, Part 71, Packaging and Transportation of Radioactive Material, January 2007.

[2-2] U.S. NRC Regulatory Guide 7.8, Revision 1, Load Combinations for the Structural Analysis of Shipping Casks for Radioactive Material, March 1989.

[2-3] U.S. NRC Regulatory Guide 7.6, Revision 1, Design Criteria for the Structural Analysis of Shipping Cask Containment Vessels, 1978.

[2-4] ASME Boiler & Pressure Vessel Code, American Society of Mechanical Engineers, New York, NY, 2007.

[2-5] American Society of Mechanical Engineers (ASME) Boiler & Pressure Vessel Code, Section III, Division 1, Class MC, Code Case N-284, Metal Containment Shell Buckling Design Method, August 25, 1980.

[2-6] Energy*Solutions* Proprietary Document ST-551, Revision 3, Validation of the LS-DYNA Drop Analyses Results with the Test Data.

[2-7] U.S. NRC Regulatory Guide 7.11, Fracture Toughness Criteria of Base Material for Ferritic Steel Shipping Cask Containment Vessel with a Minimum Wall Thickness of 4 inches (0.1 m), June 1991.

[2-8] NUREG/CR-3854, Fabrication Criteria for Shipping Containers, March 1985.

[2-9] NUREG 0481/SAND77-1872, An Assessment of Stress-Strain Data Suitable for Finite Element Elastic-Plastic Analysis of Shipping Containers, Sandia National Laboratories, 1978.

[2-10] General Plastics Manufacturing Company, Last-A-Foam FR-3700 for Crash & Fire Protection of Nuclear Material Shipping Containers, June 1997.

[2-11] NUREG/CR-3019, Recommended Welding Criteria for Use in the Fabrication of Shipping Containers for Radioactive Material, March 1985.

[2-12] ANSYS/LS-DYNA, Computer Software, Version 11.0, ANSYS Inc., Canonsburg, PA, 2007.

[2-13] Energy*Solutions* Document ST-503, Revision 2, Trunnion Analyses of the 3-60B Cask under Various Load Conditions.

[2-14] Code of Federal Regulations, Title 49, Part 393, Parts and Accessories Necessary for Safe Operation.

[2-15] Energy*Solutions* Document ST-501, Revision 2, Structural Analyses of the 3-60B Cask under Normal Conditions of Transport.

[2-16] Design Basis for Resistance to Shock and Vibration of Radioactive Material Packages Greater than One Ton in Truck Transport, Draft American National Standard, ANSI N14.23, 1998.

[2-17] Energy*Solutions* Proprietary Document ST-557, Revision 4, Drop Analyses of the 3-60B Cask Using LS-DYNA Program.

[2-18] Energy*Solutions* Document ST-504, Revision 2, Structural Analyses of the 3-60B Cask under Drop Conditions.

[2-19] Energy*Solutions* Document ST-608, Revision 0, 3-60B Cask ANSYS Finite Element Model Grid Convergence Study.

[2-20] Structural Analyses and Design of Nuclear Plant Facilities, ASCE Publication No. 58, American Society of Civil Engineers.

[2-21] Energy*Solutions* Document ST-549, Revision 1, Structural Analyses of Misc. Components of 3-60B Cask.

[2-22] Stress Analysis of Closure Bolts for Shipping Casks, NUREG/CR-6007, Lawrence Livermore National Laboratory, 1993.

[2-23] An Introduction to the Design and Behavior of Bolted Joints, John H. Bickford, Marcel Dekker Inc., Publication, N.Y., 1981.

[2-24] Cask Designer's Guide, ORNL-NSIC-68, Oak Ridge National Laboratory, 1970.

[2-25] Energy*Solutions* Document ST-505, Revision 1, Structural Analyses of the 3-60B Cask under Puncture Drop Conditions.

[2-26] Energy*Solutions* Document ST-502, Revision 2, Structural Analyses of the 3-60B Cask under Hypothetical Fire Accident Conditions.

[2-27] NUREG/CR-6407, Classification of Transportation Packaging and Dry Spent Fuel Storage System Components Accordance to Importance to Safety, February 1996.

[2-28] Energy*Solutions* Document ST-600, Revision 0, 3-60B Cask Buckling Evaluation under NCT and HAC Loading.

[2-29] Energy*Solutions* Document ST-609, Revision 1, 3-60B Cask Inelastic Analyses of the Bolting Ring Skirt under HAC Drop Loadings.

Table 2-1 - Summary of Load Combinations for Normal and Accident Condition Loading

Loading Conditions	Ambient Temperature (°F)	Insolation	Heat Load (Watt)	Pressure (psi)		Stress Table[2]
				Internal	External	
NORMAL CONDITIONS[1]						
Hot Environment	100	✓	500	35		2-5
Cold Environment	-40		0	0		2-6
Increased External Pressure	-20		0		20	2-8
Minimum External Pressure	100	✓	500	50		2-7
Free Drop + Max. Internal Pressure	100	✓	500	35		2-10, 2-12 & 2-14
Free Drop + Min. Internal Pressure	-20		0		0	2-11, 2-13 & 2-15
ACCIDENT CONDITIONS[1]						
Free Drop + Max. Internal Pressure	100	✓	500	35		2-17, 2-19 & 2-21
Free Drop + Min. Internal Pressure	-20		0		0	2-18, 2-20 & 2-22
Puncture + Max. Internal Pressure	100	✓	500	35		Fig. 2-54
Puncture + Min. Internal Pressure	-20		0		0	Fig. 2-55
Fire	1475		500	55		2-24

NOTES:

(1) These loading combinations have been derived from the NRC Regulatory Guide 7.8 [2-2].

(2) See these tables for the stress analysis results of the corresponding loading combinations.

Table 2-2 - Allowable Stresses

Material →		ASTM A240 Type 304L	ASTM A182 Gr.F45 & A240 Gr. 45	ASTM A354 Gr. BD
Yield Stress, S_y (psi)		25,000[1]	45,000[1]	130,000[1]
Ultimate Stress, S_u (psi)		70,000[1]	87,000[1]	150,000[1]
Design Stress Intensity, S_m (psi)		16,700[1]	24,900[1]	30,000[1]
NCT	Membrane Stress[7]	16,700[2]	24,900[2]	60,000[3]
	Mem. + Bending Stress[7]	25,050[2]	37,350[2]	90,000[3]
HAC	Membrane Stress[7]	40,080[4],[5]	59,760[4],[5]	105,000[6]
	Mem. + Bending Stress[7]	60,120[4],[5]	87,000[4],[5]	150,000[6]

NOTES:

(1) From ASME B&PV Code [2-4], Section II, Part D.

(2) Established from Regulatory Guide 7.6 [2-3], Regulatory Position 2.

(3) Regulatory Guide 7.6 does not provide any criteria for the bolting materials. ASME B&PV Code, Section III, Subsection ND criteria has been used to establish these limits.

(4) Established from Regulatory Guide 7.6 [2-3], Regulatory Position 6.

(5) Buckling Criteria (Regulatory Guide 7.6, Regulatory Position 5) has also been satisfied for these components.

(6) Regulatory Guide 7.6 does not provide any criteria for the bolting materials. ASME B&PV Code, Section III, Appendix F, Article F-1335 criteria has been used to establish these limits.

(7) See Table 2-3 for the definition of the stress component definition.

Table 2-3 - Stress Component Definition

	ASME Definition	3-60B Cask Incorporation
Primary (General) Membrane, P_m [RG 7.6, B-2 & B-4 WB-3213.6 & WB-3213.8]	Average primary stress across solid section. Excludes discontinuities and concentrations. Produced by pressure and mechanical loads.	The stresses caused by thermal expansion (contraction) are also included besides those caused by pressure and mechanical loading. The total stress over a section, *if meeting the allowable of membrane stress*, has been categorized as primary membrane. Otherwise, the stresses obtained from the FEA have been linearized to obtain the membrane component.
Primary Bending, P_b [RG 7.6, B-2 & B-4 WB-3213.7 & WB-3213.8]	Component of primary stress proportional to distance from centroid of solid section. Excluding discontinuities and concentrations. Produced by pressure and mechanical load.	The stresses caused by thermal expansion (contraction) are also included besides those caused by pressure and mechanical loading. The total stress over a section, *if meeting the allowable of membrane plus bending stress*, has been categorized as primary membrane plus bending stress. Otherwise, the stresses obtained from the FEA have been linearized to obtain the membrane plus bending component.
Secondary Membrane Plus Bending, Q [RG 7.6, B-3 WB-3213.9]	Self-equilibrating stress necessary to satisfy continuity of structure. Occurs at structural discontinuities. Can be caused by mechanical loads or by thermal expansion. Excludes local stress concentration.	The total stress over a section, *if meeting the allowable of membrane plus bending stress*, has been categorized as secondary membrane plus bending stress. Otherwise, the stresses obtained from the FEA have been linearized to obtain the membrane plus bending component.

Table 2-4 - Material Properties

Material	Temp. (°F)	Strength (ksi)			Young's Modulus (10^6 psi)	Coefficient of Thermal Expansion (10^{-6} in/in)
		Yield (S_y)	Ultimate (S_u)	Membrane Allowable (S_m)		
ASTM A240 Type 304L		(1)	(1)	(1)	(1)	(1)
	-20	25.0	70.0	16.7	28.8	-
	70	25.0	70.0	16.7	28.3	8.5
	100	25.0	70.0	16.7	-	8.6
	200	21.4	66.1	16.7	27.5	8.9
	300	19.2	61.2	16.7	27.0	9.2
	400	17.5	58.7	15.8	26.4	9.5
	500	16.4	57.5	14.7	25.9	9.7
ASTM A240 Gr. 45 & ASTM A182 Gr. F45		(1)	(1)	(1)	(1)	(1)
	-20	45.0	87.0	24.9	28.8	-
	70	45.0	87.0	24.9	28.3	8.5
	100	45.0	87.0	24.9	-	8.6
	200	37.5	86.4	24.7	27.5	8.9
	300	33.0	81.6	23.3	27.0	9.2
	400	29.9	78.5	22.4	26.4	9.5
	500	27.8	76.4	21.8	25.9	9.7
ASTM A354 Gr. BD (Lid Bolts)		(1)	(1)	(1)	(1)	(1)
	-20	130	150	30	29.7	-
	70	130	150	30	29.2	6.4
	100	130	150	30	-	6.5
	200	119.1	150	30	28.6	6.7
	300	115	150	30	28.1	6.9
	400	111	150	30	27.7	7.1
	500	105.9	150	30	27.1	7.3
ASTM B29 Lead		(2)			(2)	(2)
	-20	-	-	-	2.43	15.65
	70	5	-	-	2.27	16.06
	100	-	-	-	2.21	16.22
	200	-	-	-	2.01	16.70
	300	-	-	-	1.85	17.33
	400	-	-	-	1.70	18.16
	500	-	-	-	1.52	19.12

NOTES:

(1) From ASME B&PV Code [2-4], Section II, Part D.

(2) From NUREG/CR 0481 [2-9].

Table 2-5 - Stress Intensities in 3-60B Cask under Hot Environment Loading

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I.[1] (psi)	F.S.[2]
Bolting Ring	P_m	24,900	17,334	1.44
	$P_m + P_b$	37,350	17,334	2.15
Bolting Ring Shell Extension	P_m	24,900	14,050[3]	1.77
	$P_m + P_b$	37,350	24,070[3]	1.55
Bolting Ring Skirt	P_m	24,900	3,762	6.62
	$P_m + P_b$	37,350	3,762	9.93
Inner Shell	P_m	24,900	7,558	3.30
	$P_m + P_b$	37,350	7,558	4.94
Outer Shell	P_m	16,700	9,727[4]	1.72
	$P_m + P_b$	25,050	17,720[4]	1.41
Lid	P_m	16,700	4,699	3.55
	$P_m + P_b$	25,050	4,699	5.33
Base Plates	P_m	16,700	12,237	1.36
	$P_m + P_b$	25,050	12,237	2.05
Seal Plates	$P_m + P_b$	25,050	12,223	2.05
Bolts	P_m	60,000	20,871	2.87
	$P_m + P_b$	90,000	20,871	4.31

Notes:

(1) Unless otherwise indicated in this column, the maximum stress intensity values have been conservatively reported as P_m and $P_m + P_b$ stress intensities.

(2) Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.).

(3) See Figure 20 of ST-501 [2-15] for the location of the section over which the stresses are linearized.

(4) See Figure 21 of ST-501 [2-15] for the location of the section over which the stresses are linearized.

Table 2-6 - Stress Intensities in 3-60B Cask under Cold Environment Loading

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I.[(1)] (psi)	F.S.[(2)]
Bolting Ring	P_m	24,900	13,838	1.80
	$P_m + P_b$	37,350	13,838	2.70
Bolting Ring Shell Extension	P_m	24,900	9,477[(3)]	2.63
	$P_m + P_b$	37,350	16,420[(3)]	2.27
Bolting Ring Skirt	P_m	24,900	4,139	6.02
	$P_m + P_b$	37,350	4,139	9.02
Inner Shell	P_m	24,900	9,713	2.56
	$P_m + P_b$	37,350	9,713	3.85
Outer Shell	P_m	16,700	1,731	9.65
	$P_m + P_b$	25,050	1,731	14.47
Lid	P_m	16,700	7,346	2.27
	$P_m + P_b$	25,050	7,346	3.41
Base Plates	P_m	16,700	11,264	1.48
	$P_m + P_b$	25,050	11,264	2.22
Seal Plates	$P_m + P_b$	25,050	12,696	1.97
Bolts	P_m	60,000	9,941	6.04
	$P_m + P_b$	90,000	9,941	9.05

Notes:

(1) Unless otherwise indicated in this column, the maximum stress intensity values have been conservatively reported as P_m and $P_m + P_b$ stress intensities.

(2) Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.)

(3) See Figure 22 of ST-501 [2-15] for the location of the section over which the stresses are linearized.

Table 2-7 - Stress Intensities in 3-60B Cask under Reduced External Pressure

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I.[1] (psi)	F.S.[2]
Bolting Ring	P_m	24,900	7,851	3.17
	$P_m + P_b$	37,350	7,851	4.76
Bolting Ring Shell Extension	P_m	24,900	13,169	1.89
	$P_m + P_b$	37,350	13,169	2.84
Bolting Ring Skirt	P_m	24,900	2,356	10.57
	$P_m + P_b$	37,350	2,356	15.85
Inner Shell	P_m	24,900	6,420	3.88
	$P_m + P_b$	37,350	6,420	5.82
Outer Shell	P_m	16,700	9,404	1.78
	$P_m + P_b$	25,050	9,404	2.66
Lid	P_m	16,700	2,515	6.64
	$P_m + P_b$	25,050	2,515	9.96
Base Plates	P_m	16,700	11,544	1.45
	$P_m + P_b$	25,050	11,544	2.17
Seal Plates	$P_m + P_b$	25,050	5,882	4.26
Bolts	P_m	60,000	10,962	5.47
	$P_m + P_b$	90,000	10,962	8.21

Notes:

(1) Unless otherwise indicated in this column, the maximum stress intensity values have been conservatively reported as P_m and $P_m + P_b$ stress intensities.

(2) Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.)

Table 2-8 - Stress Intensities in 3-60B Cask under Increased External Pressure and Immersion

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I.[(1)] (psi)	F.S.[(2)]
Bolting Ring	P_m	24,900	15,915	1.56
	$P_m + P_b$	37,350	15,915	2.35
Bolting Ring Shell Extension	P_m	24,900	11,610[(3)]	2.14
	$P_m + P_b$	37,350	19,860[(3)]	1.88
Bolting Ring Skirt	P_m	24,900	4,213	5.91
	$P_m + P_b$	37,350	4,213	8.87
Inner Shell	P_m	24,900	11,890	2.09
	$P_m + P_b$	37,350	11,890	3.14
Outer Shell	P_m	16,700	2,406	6.94
	$P_m + P_b$	25,050	2,406	10.41
Lid	P_m	16,700	6,925	2.41
	$P_m + P_b$	25,050	6,925	3.62
Base Plates	P_m	16,700	10,510[(4)]	1.59
	$P_m + P_b$	25,050	15,070[(4)]	1.66
Seal Plates	$P_m + P_b$	25,050	13,854	1.81
Bolts	P_m	60,000	10,044	5.97
	$P_m + P_b$	90,000	10,044	8.96

Notes:

(1) Unless otherwise indicated in this column, the maximum stress intensity values have been conservatively reported as P_m and $P_m + P_b$ stress intensities.

(2) Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.)

(3) See Figure 23 of ST-501 [2-15] for the location of the section over which the stresses are linearized.

(4) See Figure 24 of ST-501 [2-15] for the location of the section over which the stresses are linearized.

Table 2-9 - NCT Free Drop Test Summary

Drop Orientation	Thermal Environment	Maximum Impact Limiter Reaction[1] (lb)	Approximate Pulse Duration (msec)	Maximum Crush[2] (in)
End	Cold	1.338×10^6	20	0.607
	Hot	1.103×10^6	20	0.741
Side	Cold	453,400	30	1.174
	Hot	364,800	30	1.416
Corner	Cold	335,300	120	4.289
	Hot	303,300	120	3.104
Slapdown-1 (7.5°)	Cold	631,900	50	1.761
	Hot	499,400	50	2.137
Slapdown-2 (15°)	Cold	711,800	50	2.033
	Hot	611,600	60	2.499

NOTES:

(1) See Figures 16, 20, 24, 28, 32, 36, 40, 44, 48 and 52 of ST-557 [2-17] for the time-history plots of the impact limiter reactions during various drop tests.

(2) See Figures 19, 23, 27, 31, 35, 39, 43, 47, 51 and 55 of ST-557 [2-17] for the time-history plots of the impact limiter crush during various drop tests.

Table 2-10 - Stress Intensities in 3-60B Cask under 1-ft End Drop – Hot Condition

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I.[1] (psi)	F.S.[2]
Bolting Ring	$P_m + P_b$	37,350	14,825	2.52
Bolting Ring Shell Extension	P_m	24,900	9,477[3]	2.63
	$P_m + P_b$	37,350	18,420[3]	2.03
Bolting Ring Skirt	P_m	24,900	7,951	3.13
	$P_m + P_b$	37,350	7,951	4.70
Inner Shell	P_m	24,900	4,244	5.87
	$P_m + P_b$	37,350	4,244	8.80
Outer Shell	P_m	16,700	13,760[3]	1.21
	$P_m + P_b$	25,050	15,030[3]	1.67
Lid	P_m	16,700	10,138	1.65
	$P_m + P_b$	25,050	10,138	2.47
Base Plates	P_m	16,700	10,182	1.64
	$P_m + P_b$	25,050	10,182	2.46
Seal Plates	$P_m + P_b$	25,050	16,808	1.49
Bolts	P_m	60,000	6,725	8.92
	$P_m + P_b$	90,000	6,725	13.38

Notes:

(1) Unless otherwise indicated in this column, the maximum stress intensity values have been conservatively reported as P_m and $P_m + P_b$ stress intensities.

(2) Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.)

(3) The stress intensity has been linearized over the cross-section. Print-out of the stress linearization is included in ST-504 Appendix 2.

Table 2-11 - Stress Intensities in 3-60B Cask under 1-ft End Drop – Cold Condition

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I.[1] (psi)	F.S.[2]
Bolting Ring	$P_m + P_b$	37,350	16,002	2.33
Bolting Ring Shell Extension	P_m	24,900	18,410[3]	1.35
	$P_m + P_b$	37,350	30,400[3]	1.23
Bolting Ring Skirt	P_m	24,900	5,097	4.89
	$P_m + P_b$	37,350	5,097	7.33
Inner Shell	P_m	24,900	21,183	1.18
	$P_m + P_b$	37,350	21,183	1.76
Outer Shell	P_m	16,700	7,562	2.21
	$P_m + P_b$	25,050	7,562	3.31
Lid	P_m	16,700	11,125	1.50
	$P_m + P_b$	25,050	11,125	2.25
Base Plates	P_m	16,700	12,590	1.33
	$P_m + P_b$	25,050	17,040	1.47
Seal Plates	$P_m + P_b$	25,050	19,186	1.31
Bolts	P_m	60,000	5,301	11.32
	$P_m + P_b$	90,000	5,301	16.98

Notes:

(1) Unless otherwise indicated in this column, the maximum stress intensity values have been conservatively reported as P_m and $P_m + P_b$ stress intensities.

(2) Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.)

(3) The stress intensity has been linearized over the cross-section. Print-out of the stress linearization is included in ST-504 Appendix 2.

Table 2-12 - Stress Intensities in 3-60B Cask under 1-ft Side Drop – Hot Condition

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I.[(1)] (psi)	F.S.[(2)]
Bolting Ring	$P_m + P_b$	37,350	21,532	1.73
Bolting Ring Shell Extension	P_m	24,900	12,960[(3)]	1.92
	$P_m + P_b$	37,350	21,690[(3)]	1.72
Bolting Ring Skirt	P_L[(4)]	37,350	28,830[(3)]	1.30
	$P_L + P_b$	37,350	33,680[(3)]	1.11
Inner Shell	P_m	24,900	16,467	1.51
	$P_m + P_b$	37,350	16,467	2.27
Outer Shell	P_m	16,700	9,915	1.68
	$P_m + P_b$	25,050	20,060	1.25
Lid	P_m	16,700	7,439	2.24
	$P_m + P_b$	25,050	7,439	3.37
Base Plates	P_m	16,700	12,645	1.32
	$P_m + P_b$	25,050	12,645	1.98
Seal Plates	$P_m + P_b$	25,050	5,415[(5)]	4.63
Bolts	P_m	60,000	24,328	2.47
	$P_m + P_b$	90,000	24,328	3.70

Notes:

(1) Unless otherwise indicated in this column, the maximum stress intensity values have been conservatively reported as P_m and $P_m + P_b$ stress intensities.

(2) Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.)

(3) The stress intensity has been linearized over the cross-section. Print-out of the stress linearization is included in ST-504 Appendix 2.

(4) The stresses in the bolting skirt are mostly longitudinal. These stresses are the highest near the impact location and subside greatly away from the plane of impact. Therefore, they are classified as average linearized stress, P_L and not P_m.

(5) The maximum stress intensity in the seal plates is 22,040 psi. However, the plates are under compression and the maximum stress intensity may be categorized as bearing stress. The maximum principal stress (tensile) has been used for the seal plate's qualification.

Table 2-13 - Stress Intensities in 3-60B Cask under 1-ft Side Drop – Cold Condition

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I.[(1)] (psi)	F.S.[(2)]
Bolting Ring	$P_m + P_b$	37,350	22,443	1.66
Bolting Ring Shell Extension	P_m	24,900	18,408	1.35
	$P_m + P_b$	37,350	19,130	1.95
Bolting Ring Skirt	P_L[(4)]	37,350	30,040[(3)]	1.24
	$P_L + P_b$	37,350	35,100[(3)]	1.06
Inner Shell	P_m	24,900	16,167	1.54
	$P_m + P_b$	37,350	16,167	2.31
Outer Shell	P_m	16,700	14,816	1.13
	$P_m + P_b$	25,050	16,800[(3)]	1.49
Lid	P_m	16,700	11,179	1.49
	$P_m + P_b$	25,050	11,179	2.24
Base Plates	P_m	16,700	14,290[(3)]	1.17
	$P_m + P_b$	25,050	22,330[(3)]	1.12
Seal Plates	$P_m + P_b$	25,050	10,399[(5)]	2.41
Bolts	P_m	60,000	21,543	2.79
	$P_m + P_b$	90,000	21,543	4.18

Notes:

(1) Unless otherwise indicated in this column, the maximum stress intensity values have been conservatively reported as P_m and $P_m + P_b$ stress intensities.

(2) Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.)

(3) The stress intensity has been linearized over the cross-section. Print-out of the stress linearization is included in ST-504 Appendix 2.

(4) The stresses in the bolting skirt are mostly longitudinal. These stresses are the highest near the impact location and subside greatly away from the plane of impact. Therefore, they are classified as average linearized stress, P_L and not P_m.

(5) The maximum stress intensity in the seal plates is 24,543 psi. However, the plates are under compression and the maximum stress intensity may be categorized as bearing stress. The maximum principal stress (tensile) has been used for the seal plate's qualification.

Table 2-14 - Stress Intensities in 3-60B Cask under 1-ft Corner Drop – Hot Condition

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I.[1] (psi)	F.S.[2]
Bolting Ring	$P_m + P_b$	37,350	- [3]	-
Bolting Ring Shell Extension	P_L[4]	37,350	26,202	1.43
	$P_L + P_b$	37,350	26,202	1.43
Bolting Ring Skirt	P_m	24,900	- [3]	-
	$P_m + P_b$	37,350	- [3]	-
Inner Shell	P_m	24,900	14,534	1.71
	$P_m + P_b$	37,350	14,534	2.57
Outer Shell	P_m	16,700	8,248	2.02
	$P_m + P_b$	25,050	16,270	1.54
Lid	P_m	16,700	9,966[5]	1.68
	$P_m + P_b$	25,050	18,347[6]	1.37
Base Plates	P_m	16,700	10,896	1.53
	$P_m + P_b$	25,050	10,896	2.30
Seal Plates	$P_m + P_b$	25,050	12,606[7]	1.99
Bolts	P_m	60,000	18,243	3.29
	$P_m + P_b$	90,000	18,243	4.93

Notes:

(1) Unless otherwise indicated in this column, the maximum stress intensity values have been conservatively reported as P_m and $P_m + P_b$ stress intensities.

(2) Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.)

(3) The bolting ring skirt experiences inelastic deformation. Analyses of [2-12] have been used to qualify these components.

(4) The stresses in the inner shell are mostly longitudinal. These stresses are the highest near the impact location and subside greatly away from the plane of impact. Therefore, they are classified as average linearized stress, P_L and not P_m.

(5) The stress intensity has been linearized over the cross-section. Print-out of the stress linearization is included in ST-504 Appendix 2.

(6) The reported stress here is the maximum principle stress (tensile).

(7) The maximum stress intensity in the seal plates is 77,292 psi. However, the plates are under compression and the maximum stress intensity may be categorized as bearing stress. The maximum principal stress (tensile) has been used for the seal plate's qualification.

Table 2-15 - Stress Intensities in 3-60B Cask under 1-ft Corner Drop – Cold Condition

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I.[1] (psi)	F.S.[2]
Bolting Ring	$P_m + P_b$	37,350	- [3]	-
Bolting Ring Shell Extension	P_L[4]	37,350	31,460[5]	1.19
	$P_L + P_b$	37,350	34,720[5]	1.08
	Q	74,700	49,500[5]	1.51
Bolting Ring Skirt	P_m	24,900	- [3]	-
	$P_m + P_b$	37,350	- [3]	-
Inner Shell	P_L	37,350	32,217	1.16
	$P_L + P_b$	37,350	32,217	1.16
Outer Shell	P_m	16,700	12,611	1.32
	$P_m + P_b$	25,050	14,390	1.74
Lid	P_m	16,700	9,943[5]	1.68
	$P_m + P_b$	25,050	18,346[6]	1.37
Base Plates	P_m	16,700	11,656	1.43
	$P_m + P_b$	25,050	18,310	1.37
Seal Plates	$P_m + P_b$	25,050	19,456[7]	1.29
Bolts	P_m	60,000	14,026	4.28
	$P_m + P_b$	90,000	14,026	6.42

Notes:

(1) Unless otherwise indicated in this column, the maximum stress intensity values have been conservatively reported as P_m and $P_m + P_b$ stress intensities.

(2) Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.)

(3) The bolting ring skirt experiences inelastic deformation. Analyses of ST-609 have been used to qualify these components.

(4) The stresses in the inner shell are mostly longitudinal. These stresses are the highest near the impact location and subside greatly away from the plane of impact. Therefore, they are classified as average linearized stress, P_L and not P_m. Stresses at the discontinuity are classified as Q and away from it are classified as $P_L + P_b$.

(5) The stress intensity has been linearized over the cross-section. Print-out of the stress linearization is included in Appendix 2.

(6) The reported stress here is the maximum principle stress (tensile).

(7) The maximum stress intensity in the seal plates is 69,165 psi. However, the plates are under compression and the maximum stress intensity may be categorized as bearing stress. The maximum principal stress (tensile) has been used for the seal plate's qualification.

Table 2-16 - Hypothetical Accident Condition Drop Test Summary

Drop Orientation	Thermal Environment	Maximum Impact Limiter Reaction[(1)] (lb)	Approximate Pulse Duration (msec)	Maximum Crush[(2)] (in)
End	Cold	3.954×10^6	30	4.64
	Hot	3.083×10^6	30	5.99
Side	Cold	1.889×10^6	30	6.50
	Hot	1.636×10^6	40	8.02
Corner	Cold	2.080×10^6	120	27.99
	Hot	1.847×10^6	120	15.59
Slapdown-1 (7.5°)	Cold	2.009×10^6	50	7.44
	Hot	1.828×10^6	60	9.04
Slapdown-2 (15°)	Cold	1.897×10^6	40	7.23
	Hot	1.684×10^6	50	8.86

NOTES:

(1) See Figures 56, 61, 66, 71, 76, 81, 86, 91, 96 and 101 of ST-557 [2-17] for the time-history plots of the impact limiter reactions during various drop tests.

(2) See Figures 60, 65, 70, 75, 80, 85, 90, 95, 100 and 105 of ST-557 [2-17] for the time-history plots of the impact limiter crush during various drop tests.

Table 2-17 - Stress Intensities in 3-60B Cask under 30-ft End Drop – Hot Condition

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I.[1] (psi)	F.S.[2]
Bolting Ring	$P_m + P_b$	87,000	32,803	2.65
Bolting Ring Shell Extension	P_m	59,760	32,727	1.83
	$P_m + P_b$	87,000	32,727	2.66
Bolting Ring Skirt	P_m	59,760	30,895	1.93
	$P_m + P_b$	87,000	30,895	2.82
Inner Shell	P_m	59,760	17,652	3.39
	$P_m + P_b$	87,000	17,652	4.93
Outer Shell	P_m	40,080	31,224	1.28
	$P_m + P_b$	60,120	31,224	1.93
Lid	P_m	40,080	30,311	1.32
	$P_m + P_b$	60,120	30,311	1.98
Base Plates	P_m	40,080	14,924	2.69
	$P_m + P_b$	60,120	14,924	4.03
Seal Plates	$P_m + P_b$	60,120	4,185[3]	14.37
Bolts	P_m	105,000	9,023	11.64
	$P_m + P_b$	150,000	9,023	16.62

Notes:

(1) Unless otherwise indicated in this column, the maximum stress intensity values have been conservatively reported as P_m and $P_m + P_b$ stress intensities.

(2) Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.)

(3) The maximum stress intensity in the seal plates is 51,854 psi. However, the plates are under compression and the maximum stress intensity may be categorized as bearing stress. The maximum principal stress (tensile) has been used for the seal plate's qualification.

Table 2-18 - Stress Intensities in 3-60B Cask under 30-ft End Drop – Cold Condition

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I.[1] (psi)	F.S.[2]
Bolting Ring	$P_m + P_b$	87,000	35,803	2.43
Bolting Ring Shell Extension	P_m	59,760	52,643	1.14
	$P_m + P_b$	87,000	61,390[3]	1.42
Bolting Ring Skirt	P_m	59,760	21,036	2.84
	$P_m + P_b$	59,760	21,036	2.84
Inner Shell	P_m	59,760	43,700	1.37
	$P_m + P_b$	87,000	43,700	1.99
Outer Shell	P_m	40,080	24,782	1.62
	$P_m + P_b$	60,120	24,782	2.43
Lid	P_m	40,080	35,126	1.14
	$P_m + P_b$	60,120	35,126	1.71
Base Plates	P_m	40,080	27,593	1.45
	$P_m + P_b$	60,120	27,593	2.18
Seal Plates	$P_m + P_b$	60,120	4,971[4]	12.09
Bolts	P_m	105,000	7,592	13.83
	$P_m + P_b$	150,000	7,592	19.76

Notes:

(1) Unless otherwise indicated in this column, the maximum stress intensity values have been conservatively reported as P_m and $P_m + P_b$ stress intensities.

(2) Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.)

(3) The stress intensity has been linearized over the cross-section. Print-out of the stress linearization is included in ST-504 Appendix 2.

(4) The maximum stress intensity in the seal plates is 57,706 psi. However, the plates are under compression and the maximum stress intensity may be categorized as bearing stress. The reported stress here is the maximum principal stress (tensile).

Table 2-19 - Stress Intensities in 3-60B Cask under 30-ft Side Drop – Hot Condition

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I.[1] (psi)	F.S.[2]
Bolting Ring	$P_m + P_b$	87,000	- [3]	-
Bolting Ring Shell Extension	P_m	59,760	45,723	1.31
	$P_m + P_b$	87,000	45,723	1.90
Bolting Ring Skirt	P_m	59,760	- [3]	-
	$P_m + P_b$	59,760	- [3]	-
Inner Shell	P_m	59,760	36,420[4]	1.64
	$P_m + P_b$	87,000	44,210[4]	1.97
Outer Shell	P_m	40,080	33,800[4]	1.19
	$P_m + P_b$	60,120	44,150[4]	1.36
Lid	P_m	40,080	26,280[4]	1.53
	$P_m + P_b$	60,120	40,680[4]	1.48
Base Plates	P_m	40,080	31,876	1.26
	$P_m + P_b$	60,120	31,876	1.89
Seal Plates	$P_m + P_b$	60,120	45,515[5]	1.32
Bolts	P_m	105,000	57,103	1.84
	$P_m + P_b$	150,000	57,103	2.63

Notes:

(1) Unless otherwise indicated in this column, the maximum stress intensity values have been conservatively reported as P_m and $P_m + P_b$ stress intensities.

(2) Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.)

(3) The bolting ring skirt experiences inelastic deformation. Analyses of [2-12] have been used to qualify these components.

(4) The stress intensity has been linearized over the cross-section. Print-out of the stress linearization is included in ST-504 Appendix 2.

(5) The maximum stress intensity in the seal plates is 104,460 psi. However, the plates are under compression and the maximum stress intensity may be categorized as bearing stress. The maximum principal stress (tensile) has been used for the seal plate's qualification.

Table 2-20 - Stress Intensities in 3-60B Cask under 30-ft Side Drop – Cold Condition

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I.[1] (psi)	F.S.[2]
Bolting Ring	$P_m + P_b$	87,000	- [3]	-
Bolting Ring Shell Extension	P_m	59,760	52,021	1.15
	$P_m + P_b$	87,000	52,021	1.67
Bolting Ring Skirt	P_m	59,760	- [3]	-
	$P_m + P_b$	59,760	- [3]	-
Inner Shell	P_m	59,760	43,486	1.37
	$P_m + P_b$	87,000	43,486	2.00
Outer Shell	P_m	40,080	36,710	1.09
	$P_m + P_b$	60,120	49,360	1.22
Lid	P_m	40,080	27,640[4]	1.45
	$P_m + P_b$	60,120	42,430[4]	1.42
Base Plates	P_m	40,080	29,690	1.35
	$P_m + P_b$	60,120	53,950	1.11
Seal Plates	$P_m + P_b$	60,120	46,227[5]	1.30
Bolts	P_m	105,000	55,860	1.88
	$P_m + P_b$	150,000	55,860	2.69

Notes:

(1) Unless otherwise indicated in this column, the maximum stress intensity values have been conservatively reported as P_m and $P_m + P_b$ stress intensities.

(2) Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.)

(3) The bolting ring skirt experiences inelastic deformation. Analyses of ST-609 have been used to qualify these components.

(4) The stress intensity has been linearized over the cross-section. Print-out of the stress linearization is included in ST-504 Appendix 2.

(5) The maximum stress intensity in the seal plates is 106,333 psi. However, the plates are under compression and the maximum stress intensity may be categorized as bearing stress. The maximum principal stress (tensile) has been used for the seal plate's qualification.

Table 2-21 - Stress Intensities in 3-60B Cask under 30-ft Corner Drop – Hot Condition

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I.[1] (psi)	F.S.[2]
Bolting Ring	$P_m + P_b$	87,000	- [3]	-
Bolting Ring Shell Extension	P_L[4]	87,000	47,453	1.83
	$P_L + P_b$	87,000	47,453	1.83
Bolting Ring Skirt	P_m	59,760	- [3]	-
	$P_m + P_b$	59,760	- [3]	-
Inner Shell	P_m	59,760	35,571	1.68
	$P_m + P_b$	87,000	35,571	2.45
Outer Shell	P_m	40,080	31,297	1.28
	$P_m + P_b$	60,120	31,297	1.92
Lid	P_m	40,080	27,550[5]	1.45
	$P_m + P_b$	60,120	42,817[6]	1.40
Base Plates	P_m	40,080	10,203	3.93
	$P_m + P_b$	60,120	10,203	5.89
Seal Plates	$P_m + P_b$	60,120	34,765[7]	1.73
Bolts	P_m	105,000	27,642	3.80
	$P_m + P_b$	150,000	27,642	5.43

Notes:

(1) Unless otherwise indicated in this column, the maximum stress intensity values have been conservatively reported as P_m and $P_m + P_b$ stress intensities.

(2) Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.)

(3) The bolting ring skirt experiences inelastic deformation. Analyses of ST-609 have been used to qualify these components.

(4) The stresses in the inner shell are mostly longitudinal. These stresses are the highest near the impact location and subside greatly away from the plane of impact. Therefore, they are classified as average linearized stress, P_L and not P_m.

(5) The stress intensity has been linearized over the cross-section. Print-out of the stress linearization is included in ST-504 Appendix 2.

(6) The reported stress here is the maximum principle stress (tensile).

(7) The maximum stress intensity in the seal plates is 185,156 psi. However, the plates are under compression and the maximum stress intensity may be categorized as bearing stress. The maximum principal stress (tensile) has been used for the seal plate's qualification.

Table 2-22 - Stress Intensities in 3-60B Cask under 30-ft Corner Drop – Cold Condition

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I.[1] (psi)	F.S.[2]
Bolting Ring	$P_m + P_b$	87,000	- [3]	-
Bolting Ring Shell Extension	P_L[4]	87,000	58,930[5]	1.48
	$P_L + P_b$	87,000	80,750[5]	1.08
Bolting Ring Skirt	P_m	59,760	- [3]	-
	$P_m + P_b$	59,760	- [3]	-
Inner Shell	P_L[4]	87,000	55,586	1.57
	$P_L + P_b$	87,000	55,586	1.57
Outer Shell	P_m	40,080	26,917	1.49
	$P_m + P_b$	60,120	26,917	2.23
Lid	P_m	40,080	26,240[5]	1.53
	$P_m + P_b$	60,120	42,737[6]	1.41
Base Plates	P_m	40,080	21,989	1.82
	$P_m + P_b$	60,120	21,989	2.73
Seal Plates	$P_m + P_b$	60,120	37,834[7]	1.59
Bolts	P_m	105,000	26,079	4.03
	$P_m + P_b$	150,000	26,079	5.75

Notes:

(1) Unless otherwise indicated in this column, the maximum stress intensity values have been conservatively reported as P_m and $P_m + P_b$ stress intensities.

(2) Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.)

(3) The bolting ring skirt experiences inelastic deformation. Analyses of ST-609 have been used to qualify these components.

(4) The stresses in the inner shell are mostly longitudinal. These stresses are the highest near the impact location and subside greatly away from the plane of impact. Therefore, they are classified as average linearized stress, P_L and not P_m.

(5) The stress intensity has been linearized over the cross-section. Print-out of the stress linearization is included in ST-504 Appendix 2.

(6) The reported stress here is the maximum principle stress (tensile).

(7) The maximum stress intensity in the seal plates is 169,949 psi. However, the plates are under compression and the maximum stress intensity may be categorized as bearing stress. The maximum principal stress (tensile) has been used for the seal plate's qualification.

Table 2-23 - Maximum Impact Limiter Attachment Force during Various HAC Drop Tests

Drop Orientation	Thermal Environment	Maximum Attachment Force (lb)
End	Cold	51,000
	Hot	49,650
Side	Cold	48,030
	Hot	48,130
Corner	Cold	56,890
	Hot	54,160
Slap-Down (7.5°)	Cold	48,040
	Hot	48,070
Slap-Down (15°)	Cold	48,170
	Hot	48,040

NOTES:

(1) See Figures 58, 63, 68, 73, 78, 83, 88, 93, 98 and 103 of ST-557 [2-17] for the time-history plots of the maximum attachment forces during various drop tests.

Table 2-24 - Maximum Stress Intensities in 3-60B Cask HAC Fire[1]

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I.[2] (psi)	F.S.[3]
Bolting Ring	$P_m + P_b$	87,000	65,848	1.32
Bolting Ring Shell Extension	$P_m + P_b$	87,000	65,241	1.33
Bolting Ring Skirt	$P_m + P_b$	87,000	–[4]	–[4]
Inner Shell	$P_m + P_b$	87,000	21,080	4.13
Outer Shell	$P_m + P_b$	60,120	46,666	1.29
Lid	$P_m + P_b$	60,120	59,543[5]	1.01
Base Plates	$P_m + P_b$	87,000	80,106	1.09
Seal Plates	$P_m + P_b$	60,120	58,328[6]	1.03
Bolts	$P_m + P_b$	150,000	132,370	1.13

Notes:

(1) ST-502 [2-25] presents the plot of temperature distribution and stresses in the cask at various time instants. The stress values presented here are the maximum stress in a particular component during the entire HAC fire.

(2) Unless otherwise indicated in this column, the maximum stress intensity values, obtained from the finite element model, have been conservatively reported as $P_m + P_b$ stress intensities.

(3) Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.)

(4) Stress intensity in the skirt of the bolting ring exceeds the $P_m + P_b$ allowable value. However, the stresses are concentrated at the fire-shield weld (see ST-502 Figure 17). Local yielding at this location will easily accommodate these high stresses. If the skirt is disregarded, the stresses are much lower (see ST-502 Figure 18).

(5) Average stress intensity is reported. See ST-502 Figure 19.

(6) Average stress intensity is reported. See ST-502 Figure 20.

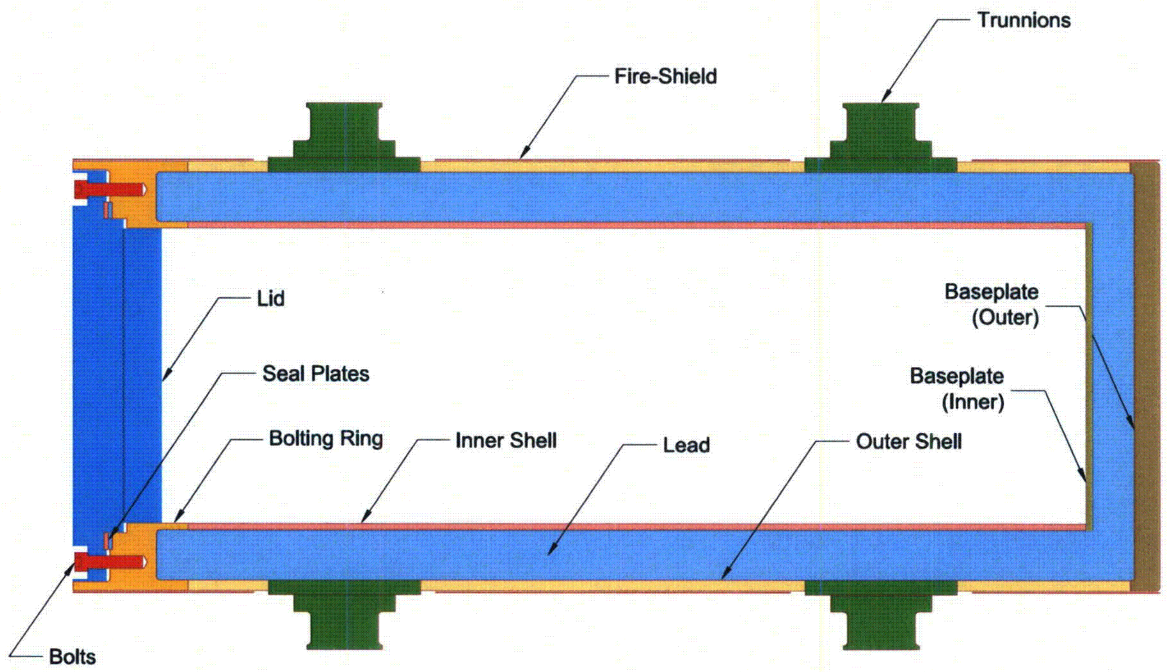


Figure 2-1 - 3-60B Cask – Component Nomenclature

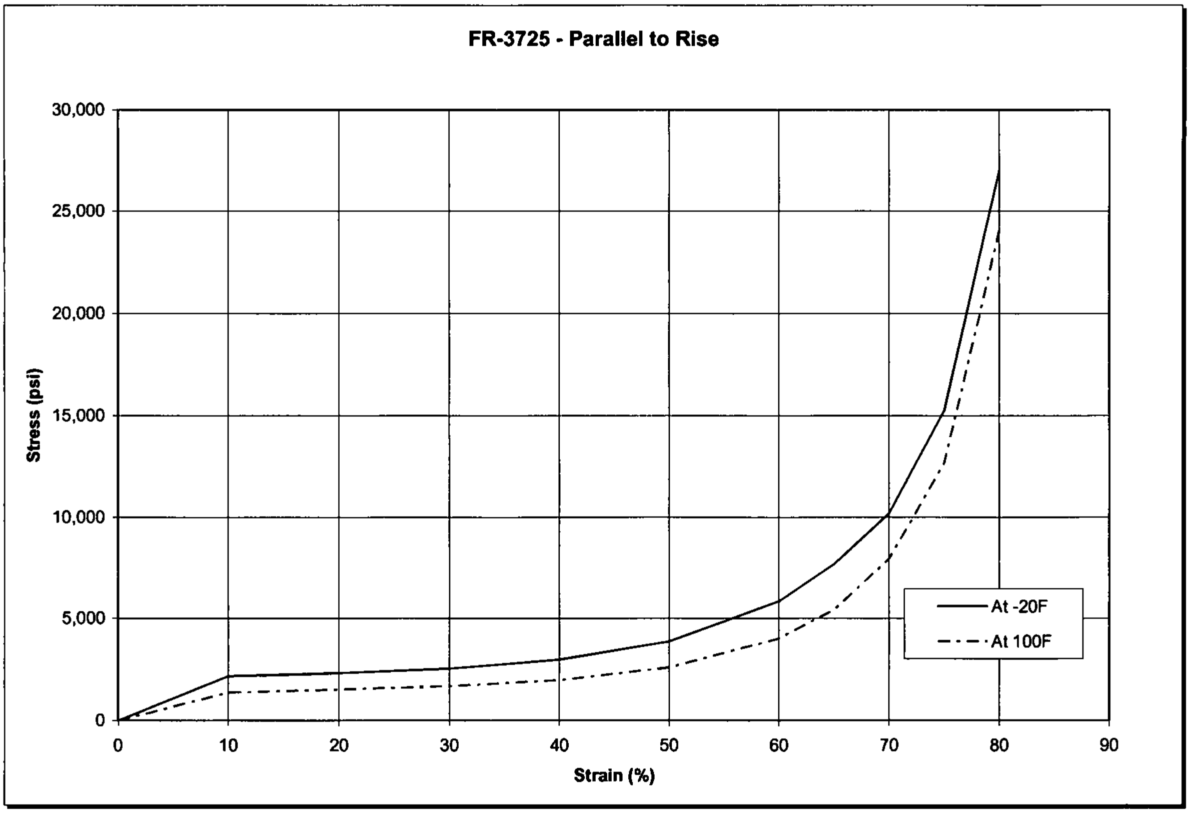


Figure 2-2 - Polyurethane Foam Stress-Strain Properties Parallel to Rise Direction

(Source: General Plastics Last-A-Foam FR-3700 Sales Brochure)

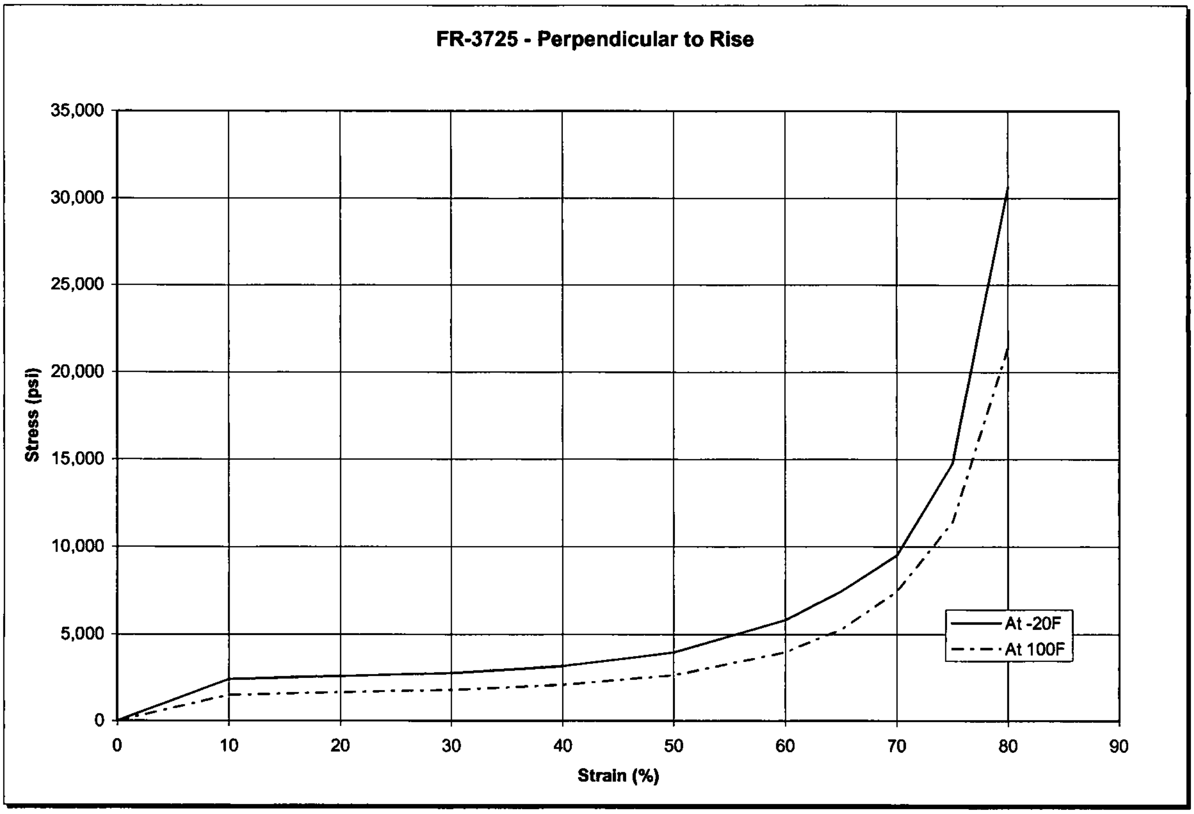


Figure 2-3 - Polyurethane Foam Stress-Strain Properties Perpendicular to Rise Direction

(Source: General Plastics Last-A-Foam FR-3700 Sales Brochure)

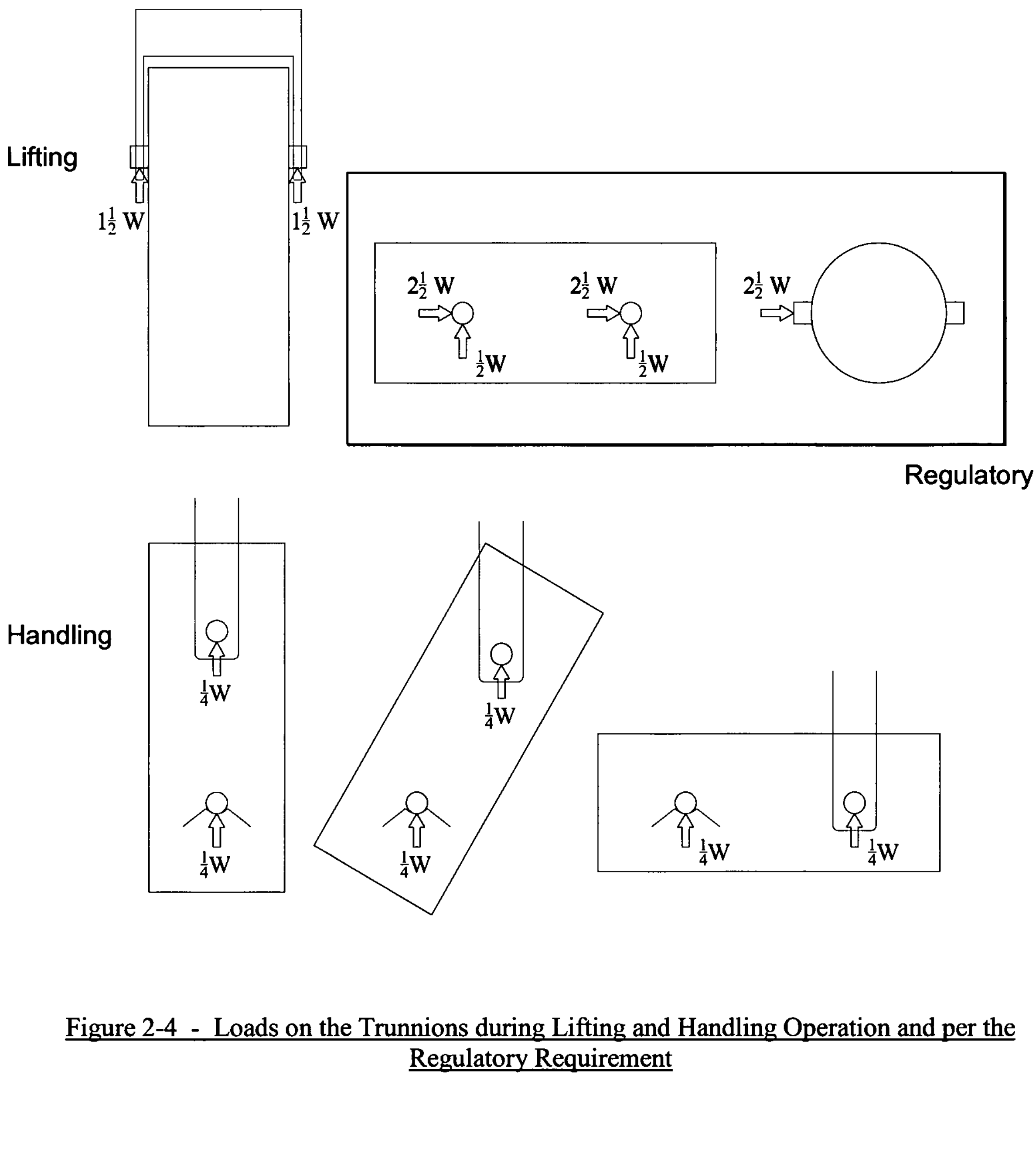


Figure 2-4 - Loads on the Trunnions during Lifting and Handling Operation and per the Regulatory Requirement

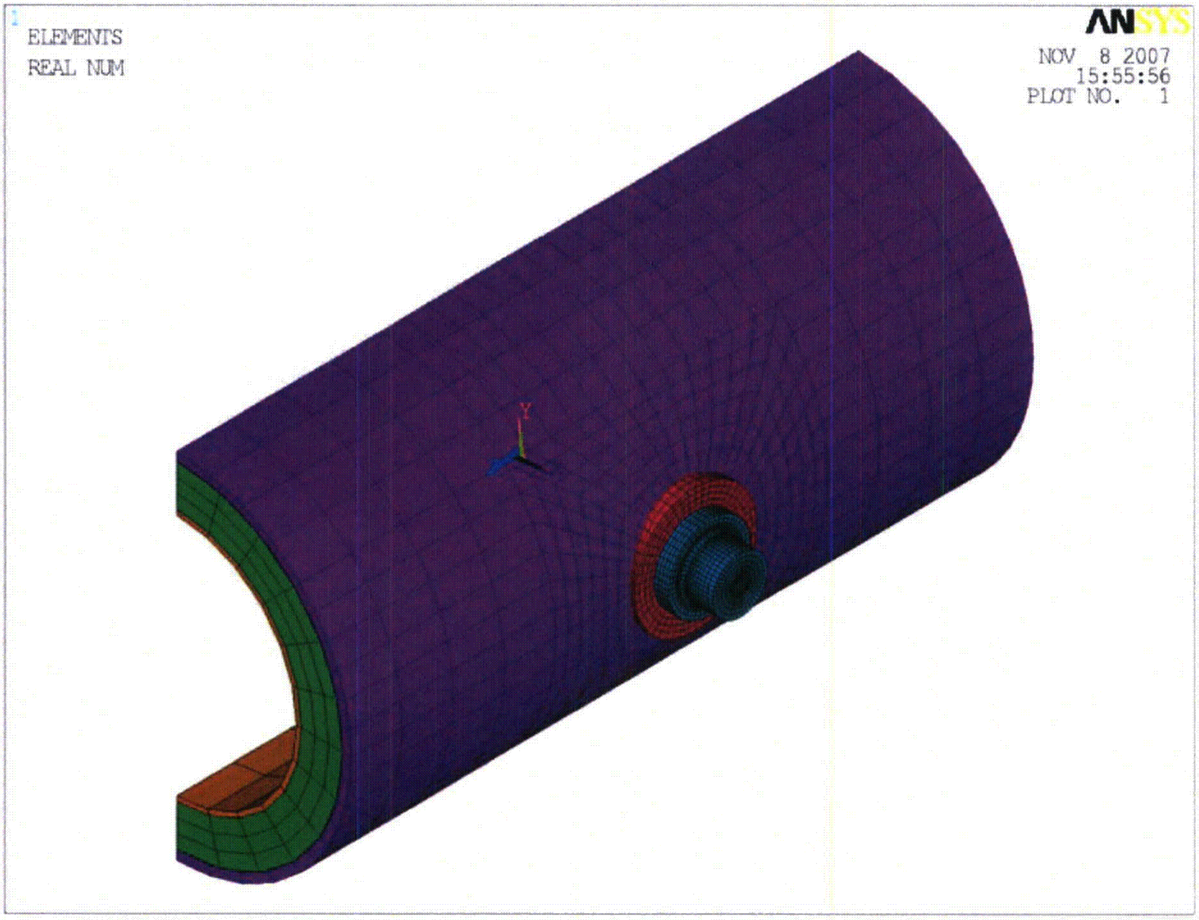


Figure 2-5 - Finite Element Model of the 3-60B Cask Trunnion & its Vicinity

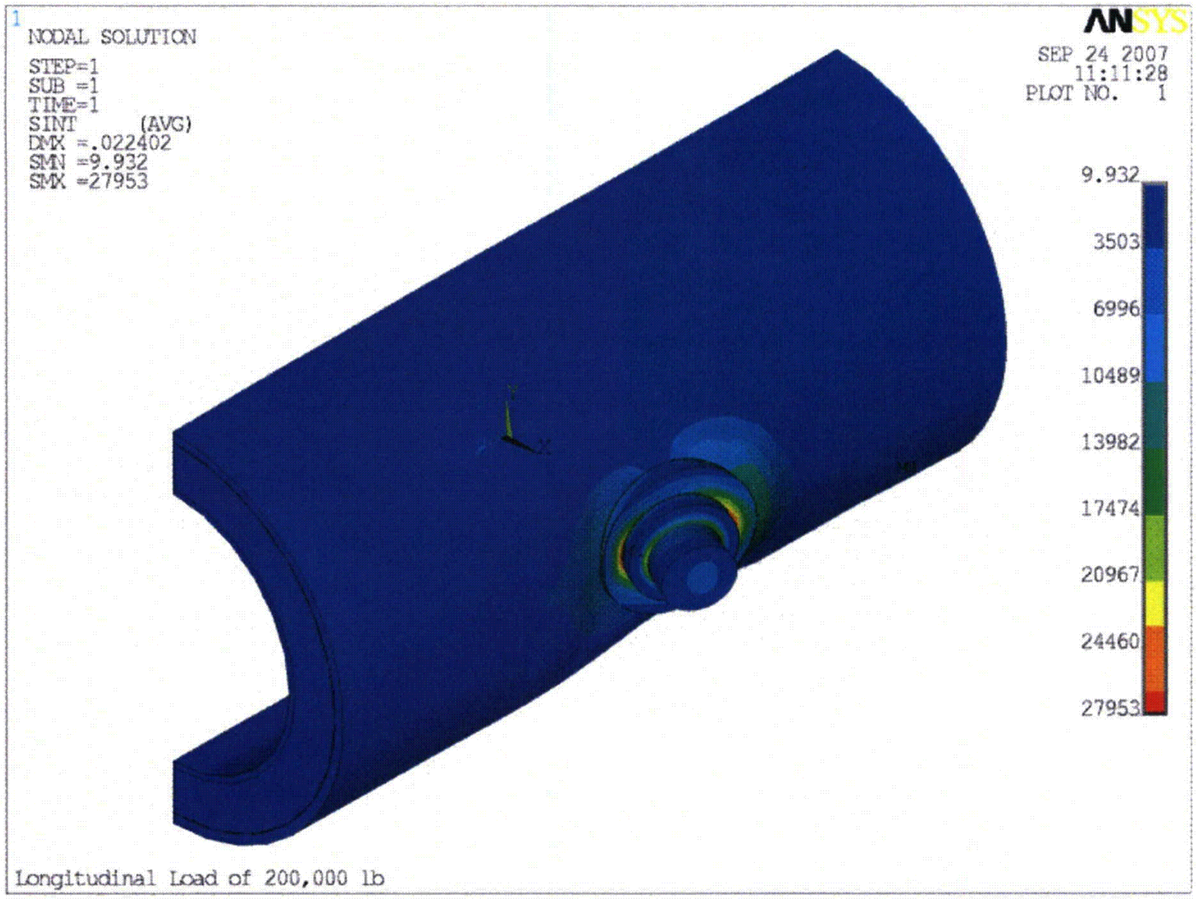


Figure 2-6 - Stress Intensity Plot – Longitudinal Loading

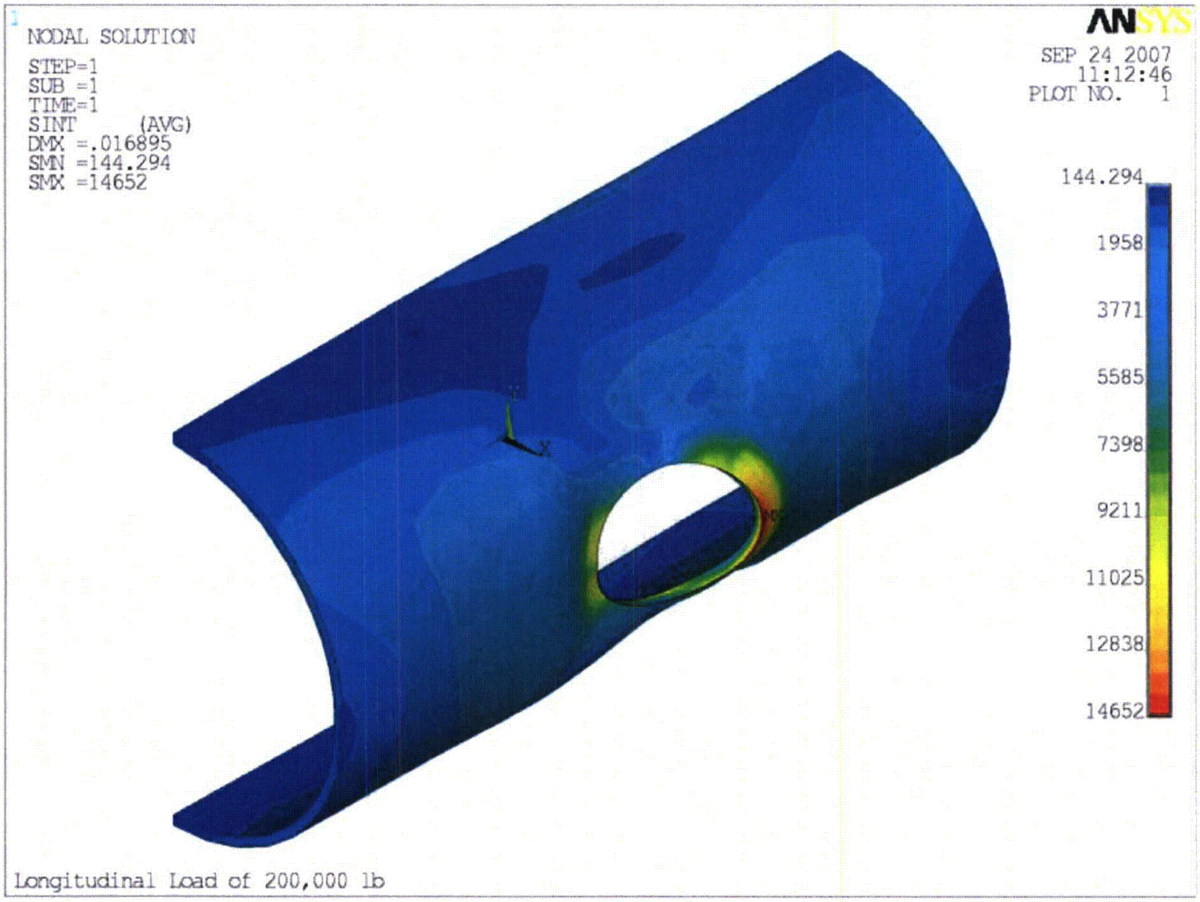


Figure 2-7 - Stress Intensity in the Shell – Longitudinal Loading

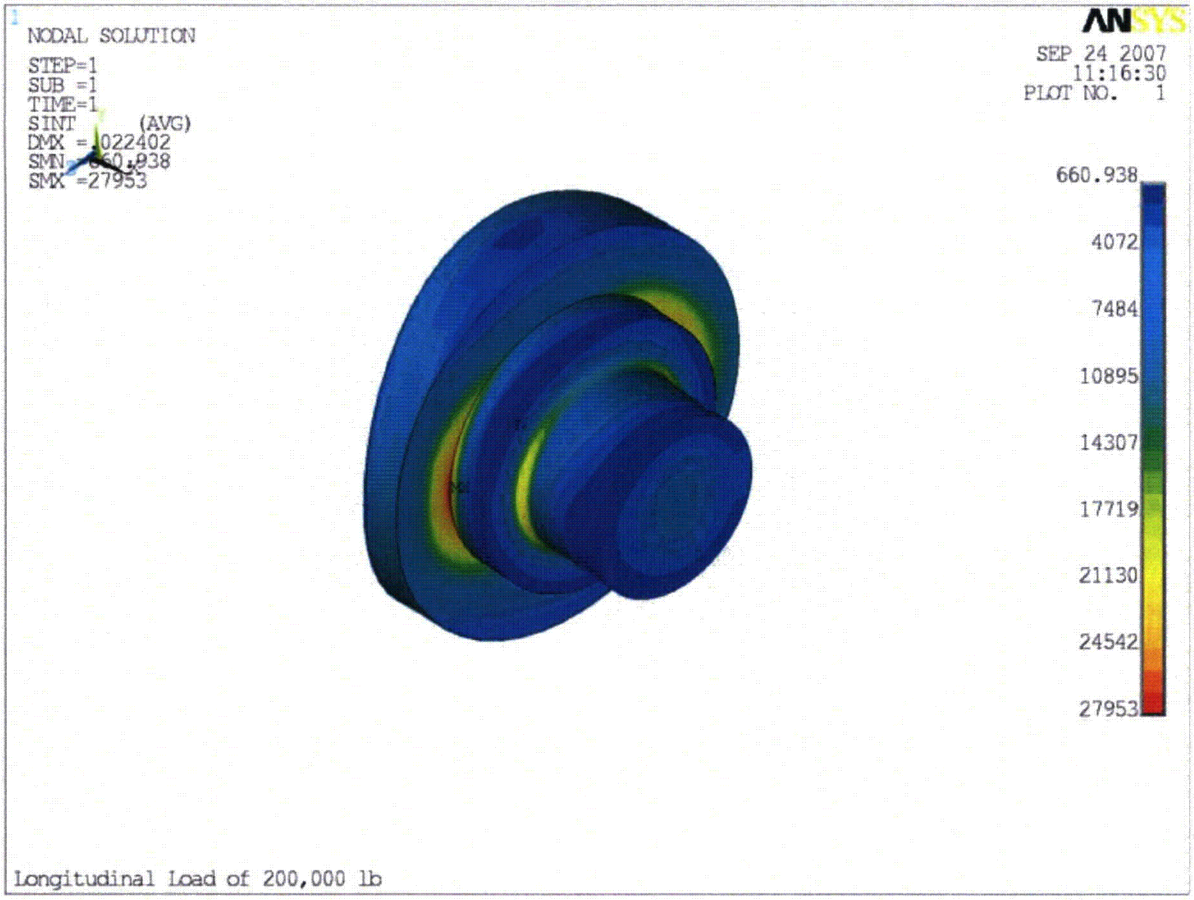


Figure 2-8 - Stress Intensity in the Trunnion – Longitudinal Loading

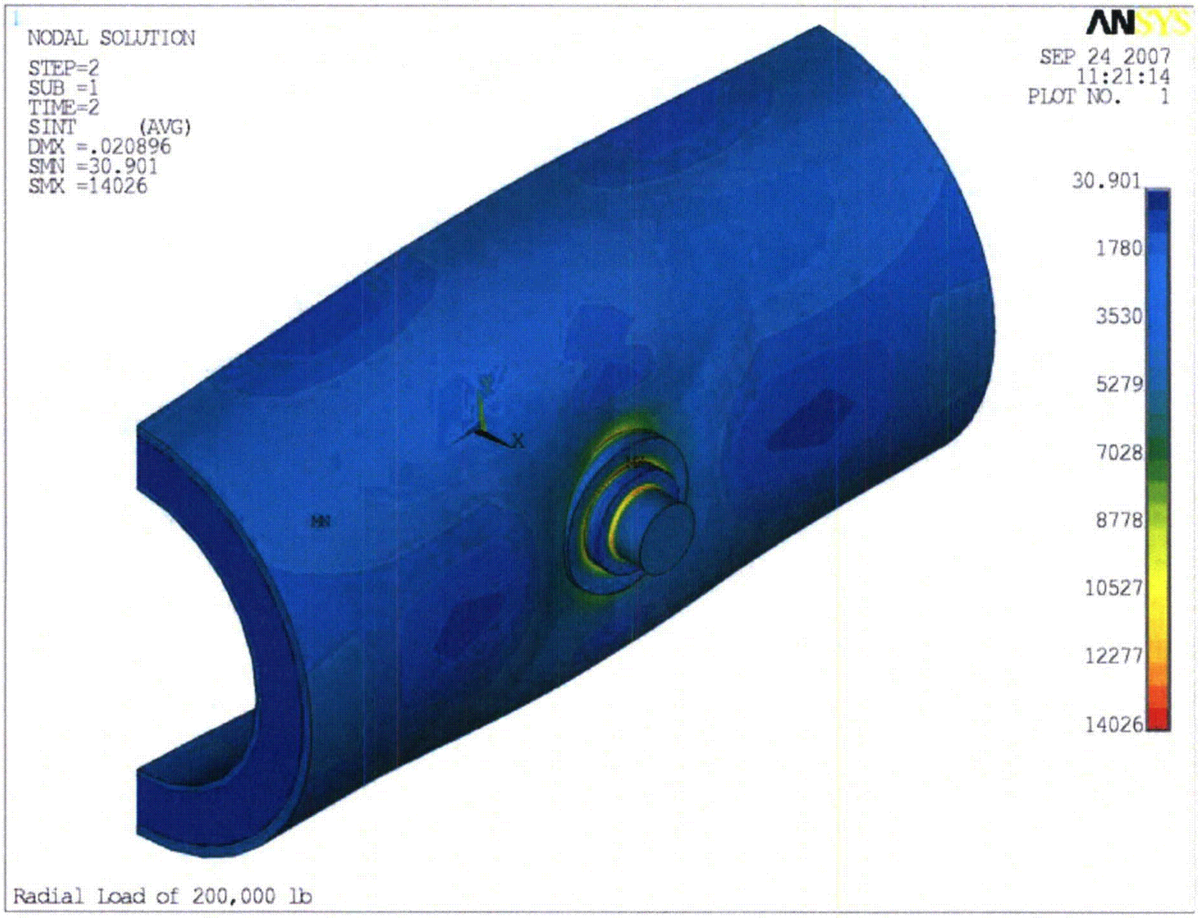


Figure 2-9 - Stress Intensity Plot – Radial Loading

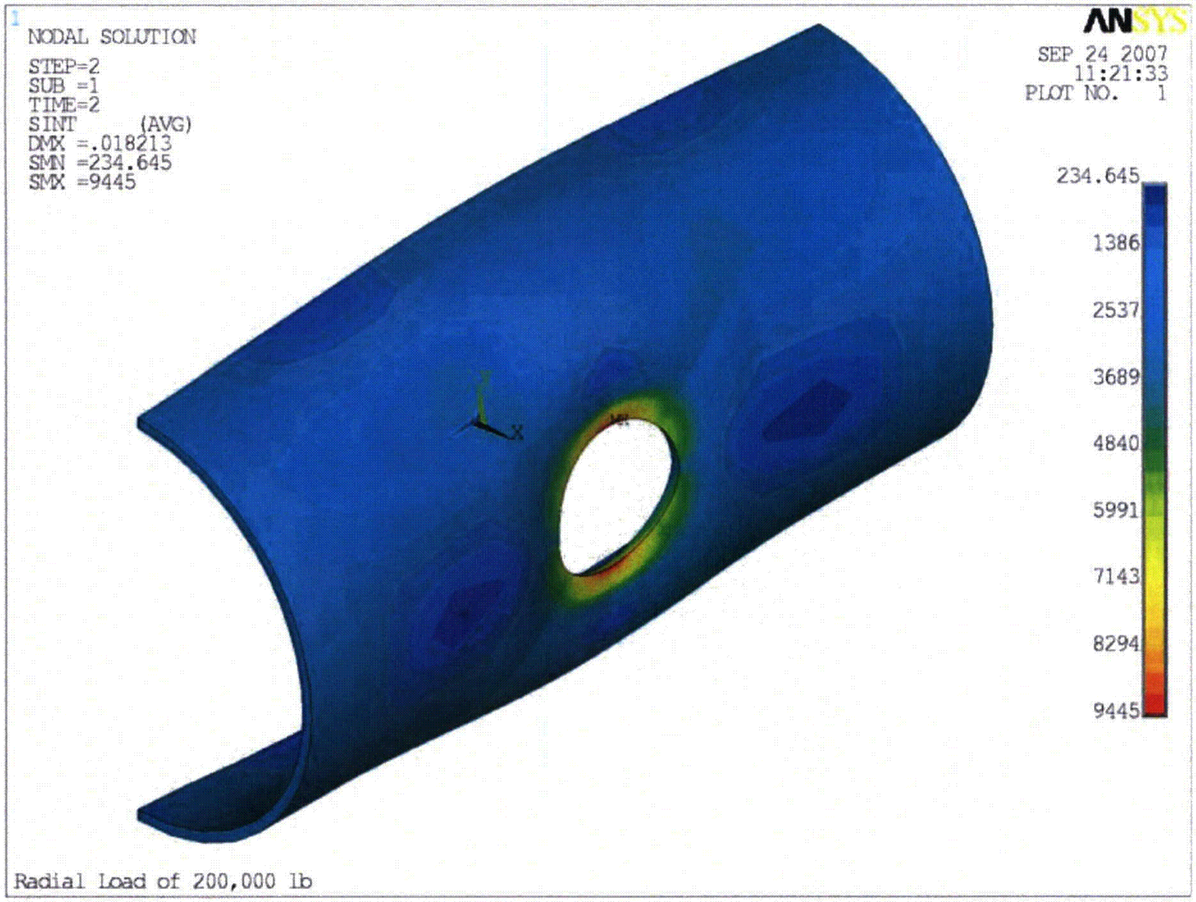


Figure 2-10 - Stress Intensity in the Shell – Radial Loading

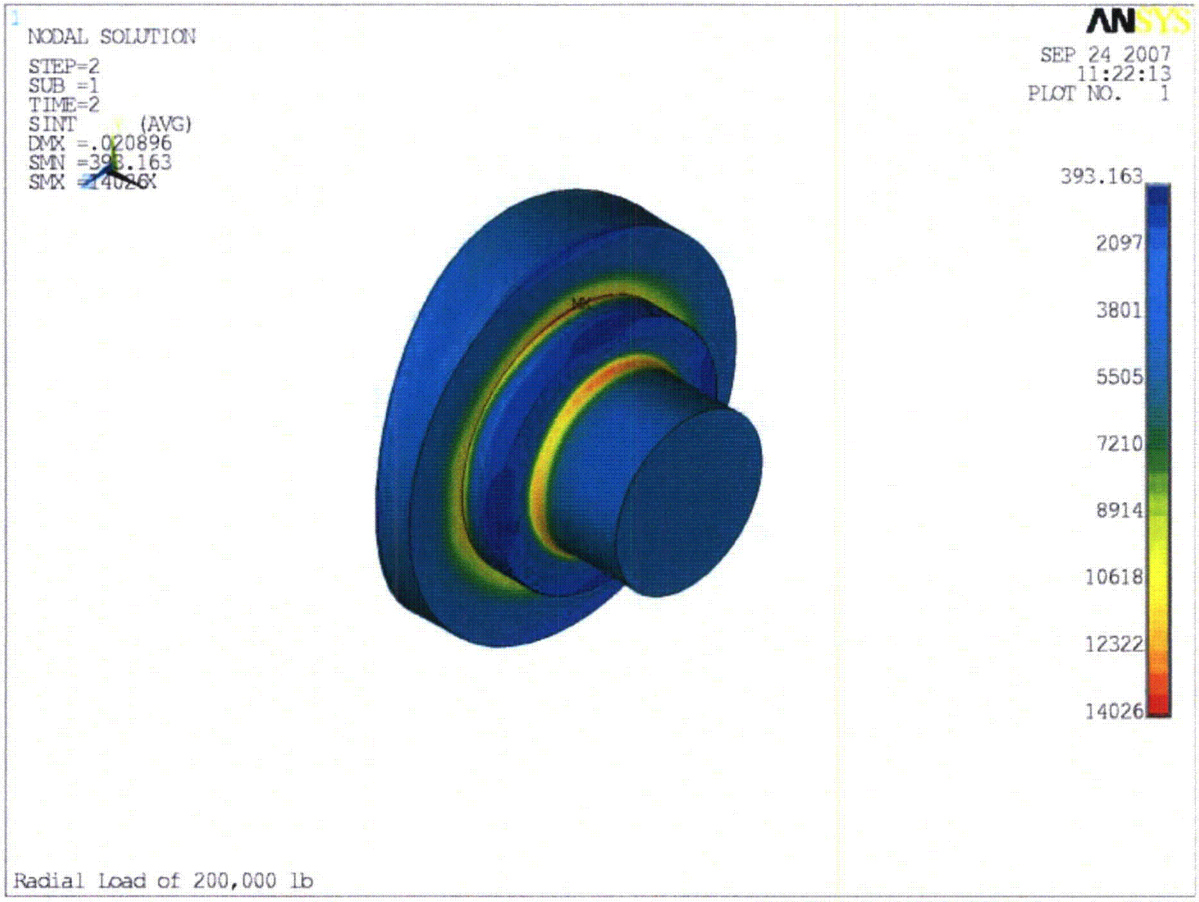


Figure 2-11 - Stress Intensity in the Trunnion – Radial Loading

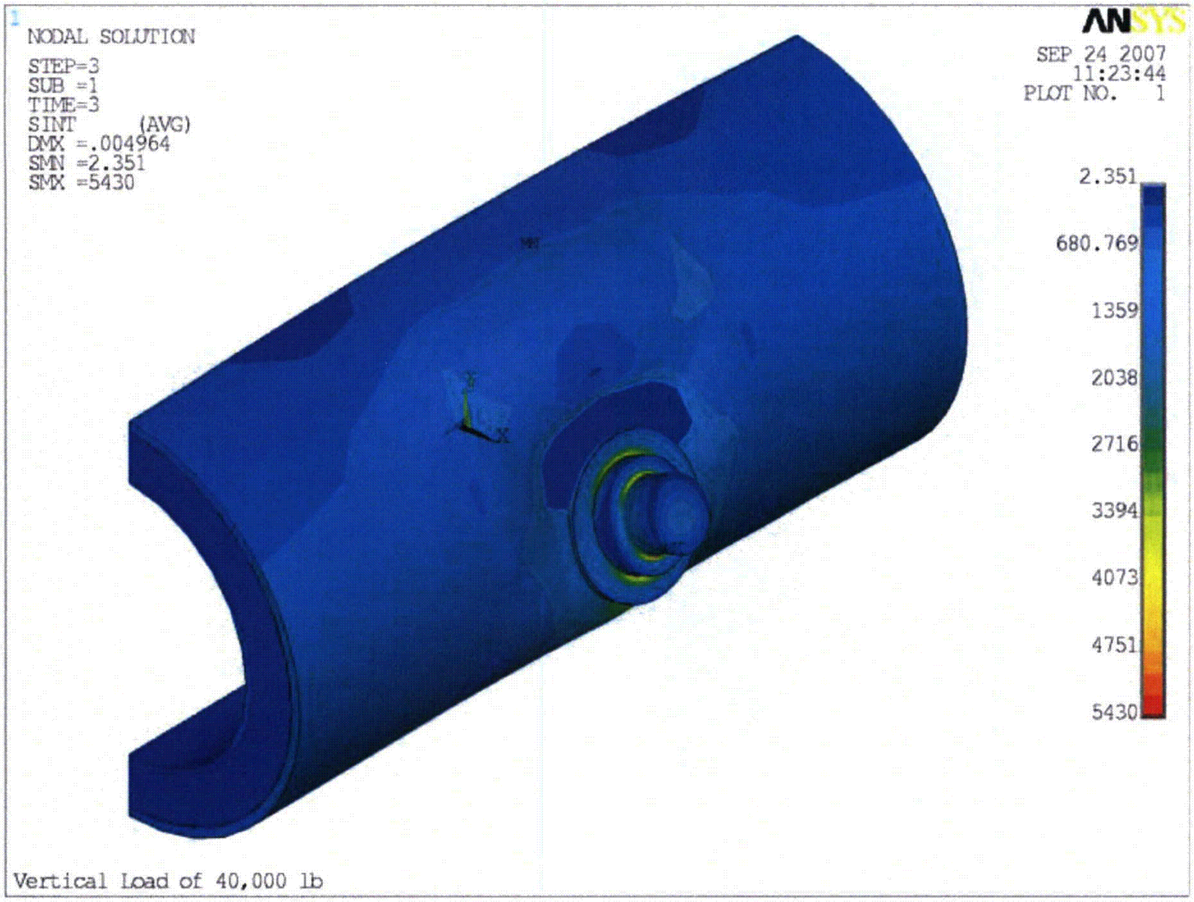


Figure 2-12 - Stress Intensity Plot – Lateral Loading

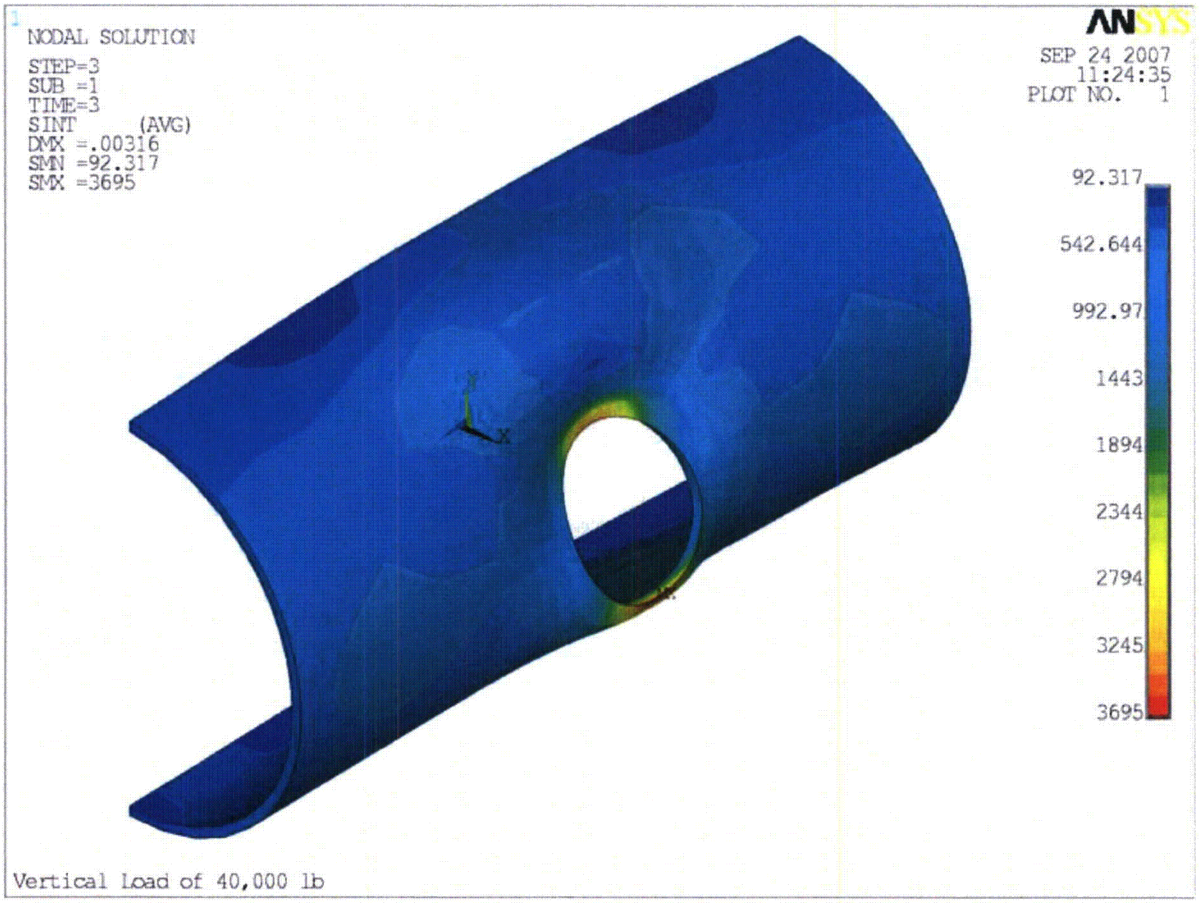


Figure 2-13 - Stress Intensity in the Shell – Lateral Loading

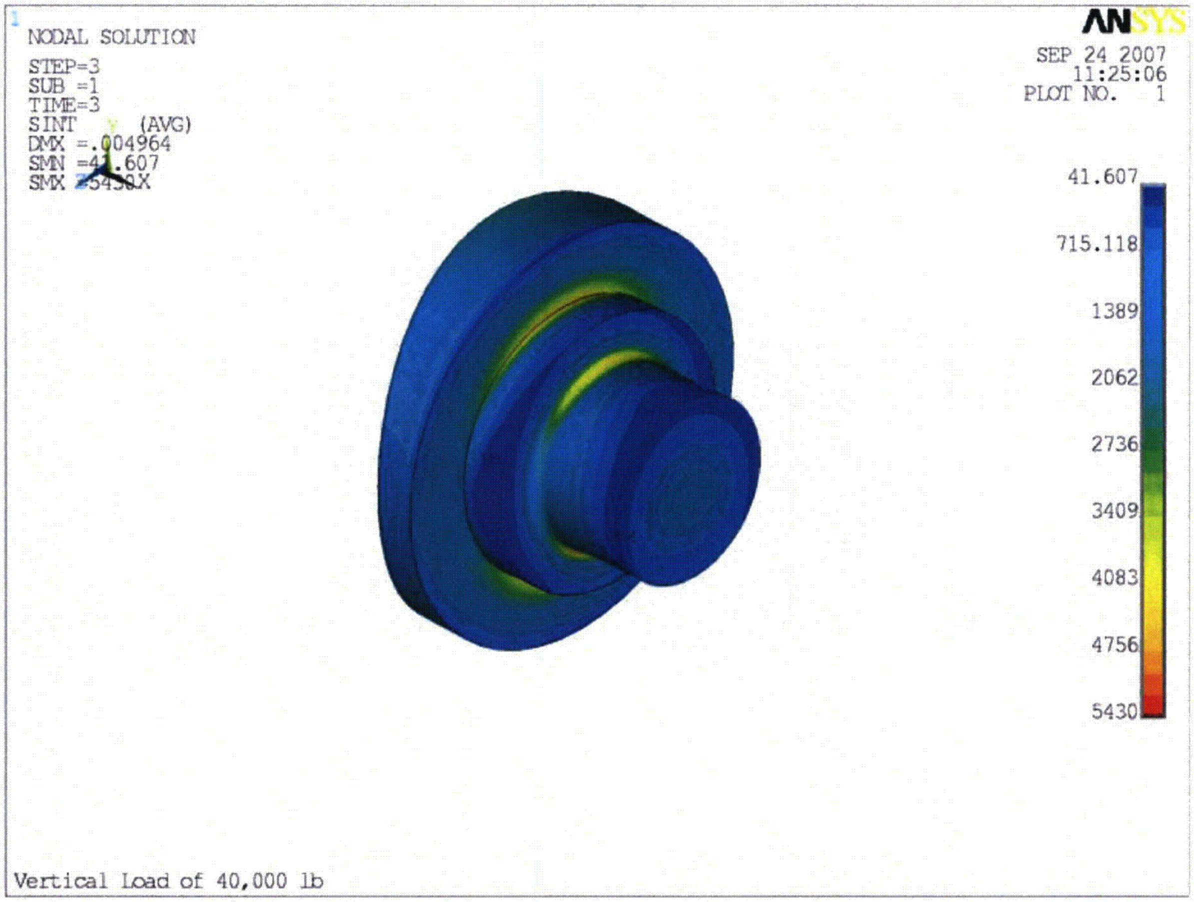


Figure 2-14 - Stress Intensity in the Trunnion – Lateral Loading

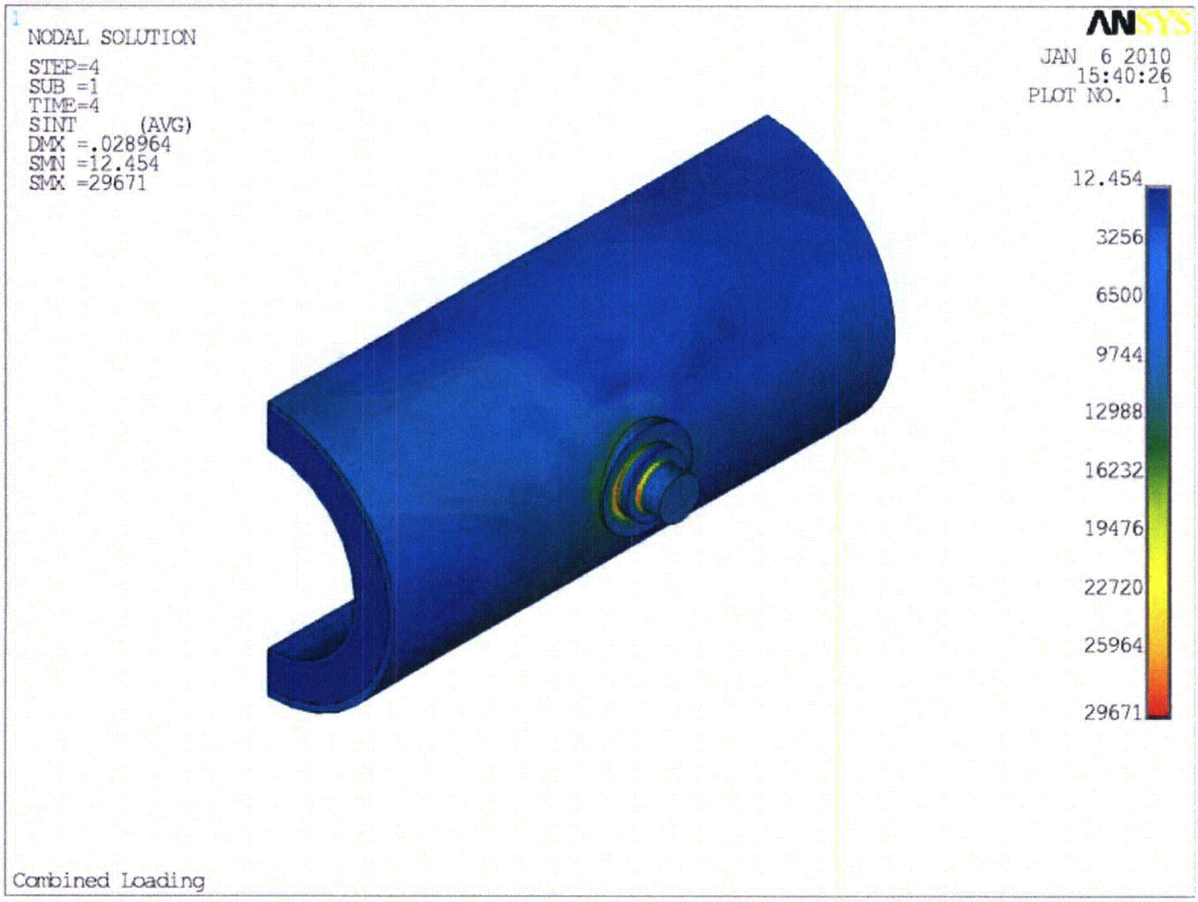


Figure 2-15 - Stress Intensity Plot – Combined Loading

Figure 2-16 - Stress Intensity in the Shell – Combined Loading

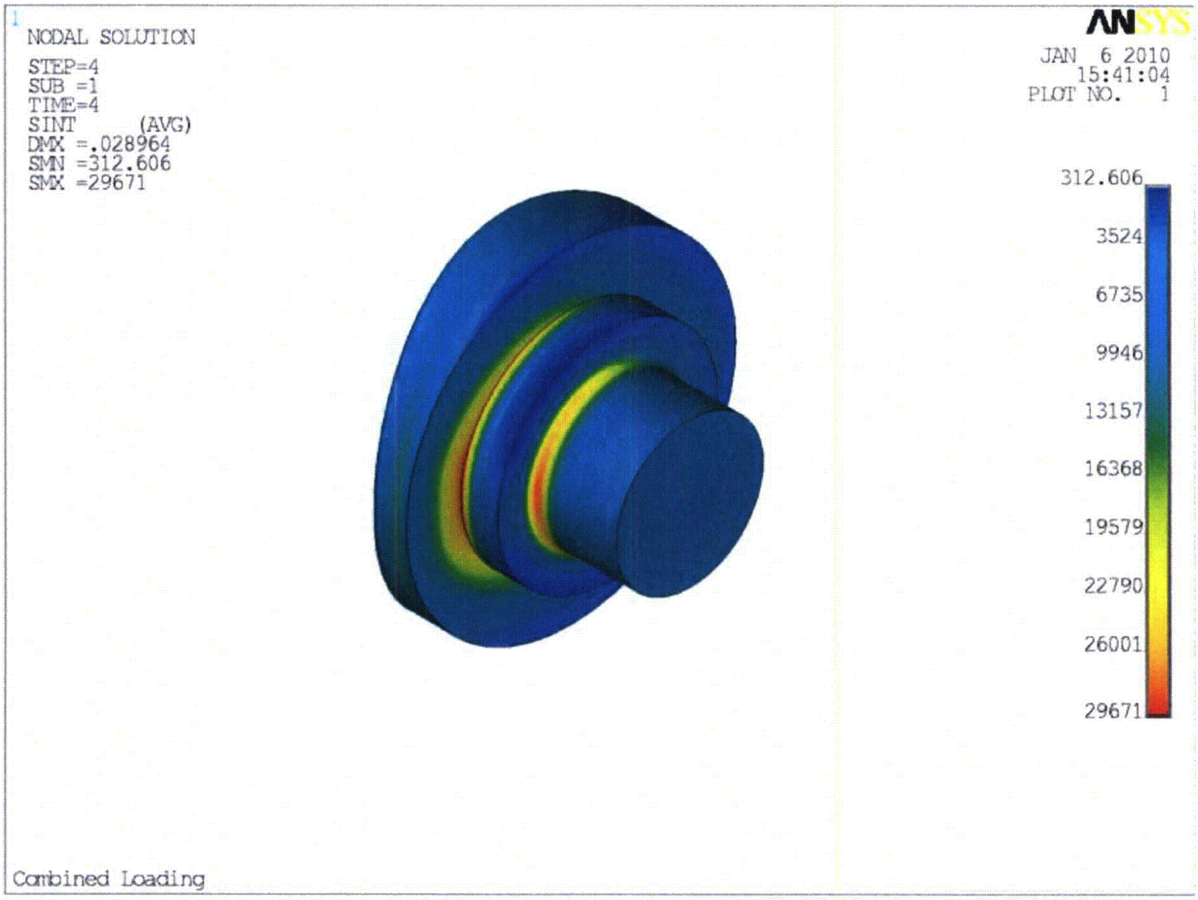


Figure 2-17 - Stress Intensity in the Trunnion – Combined Loading

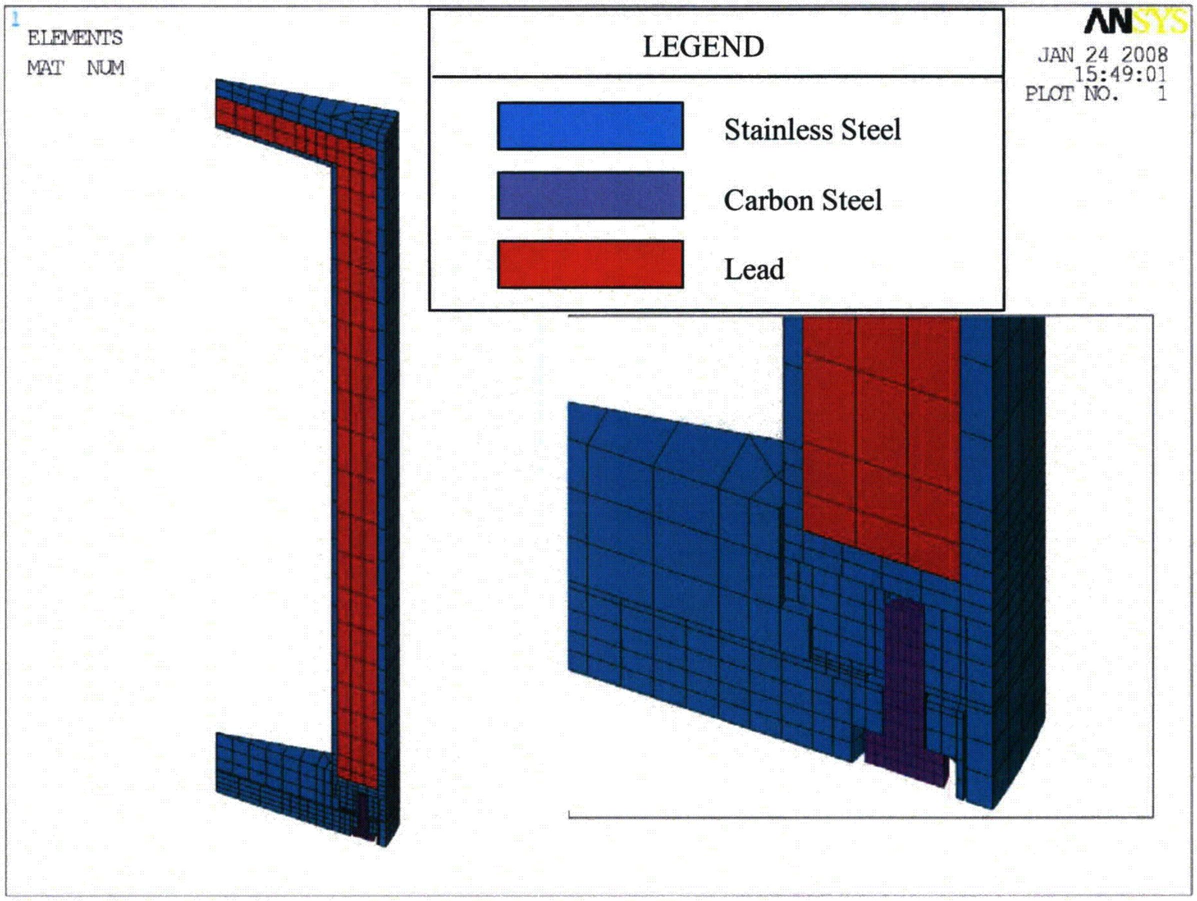


Figure 2-18 - Finite Element Model of the 3-60B Cask Identifying the Components by Material Numbers

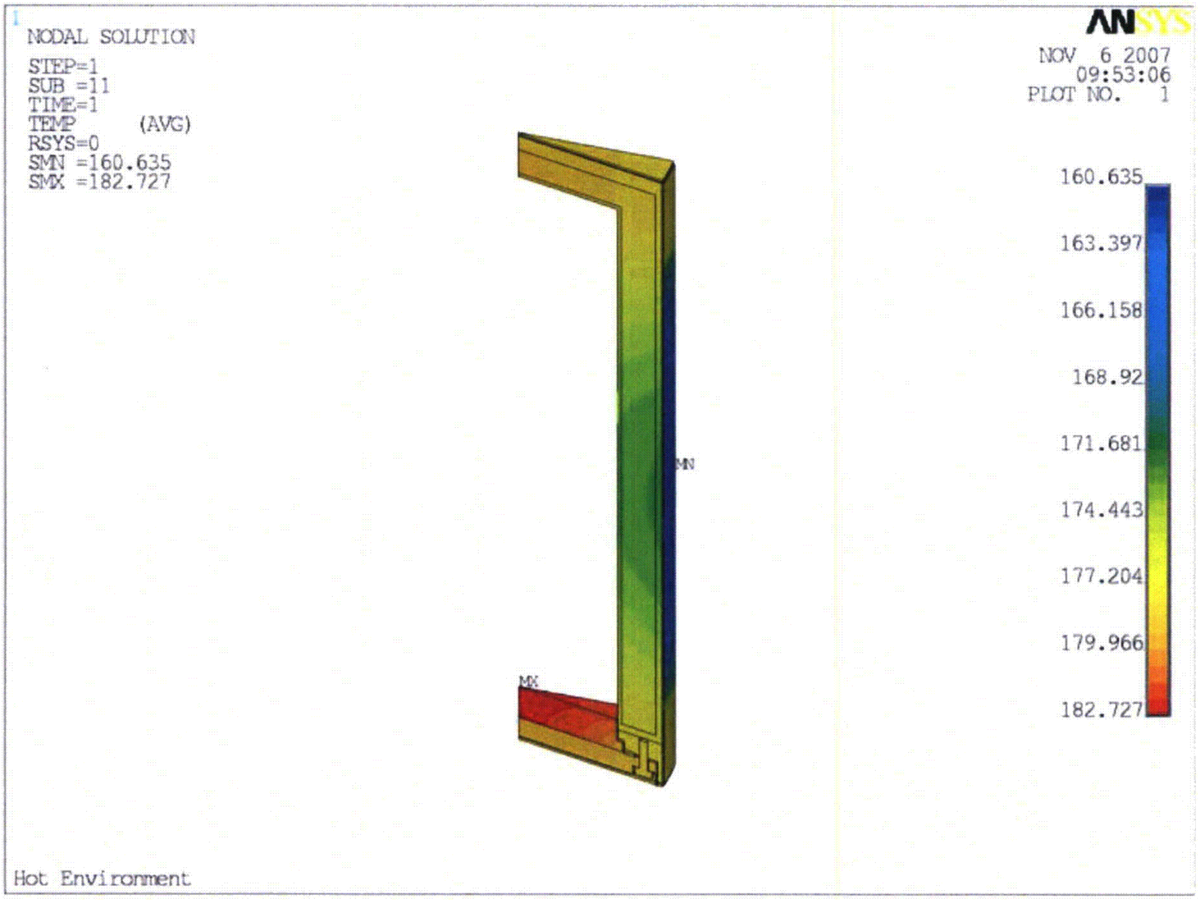


Figure 2-19 - Temperature Distribution in the Cask – Hot Environment

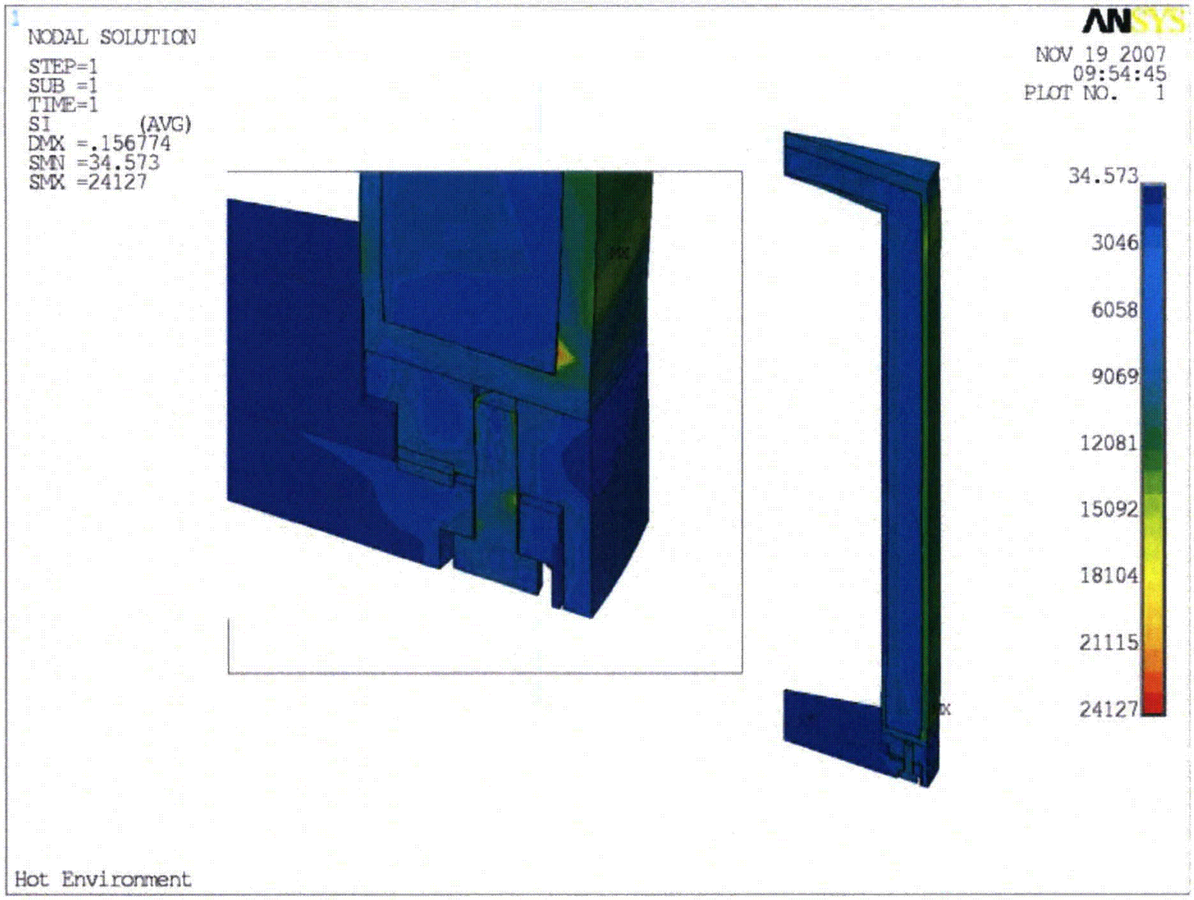


Figure 2-20 - Stress Intensity Contour Plot – Hot Environment

Figure 2-21 - Temperature Distribution in the Cask – Cold Environment

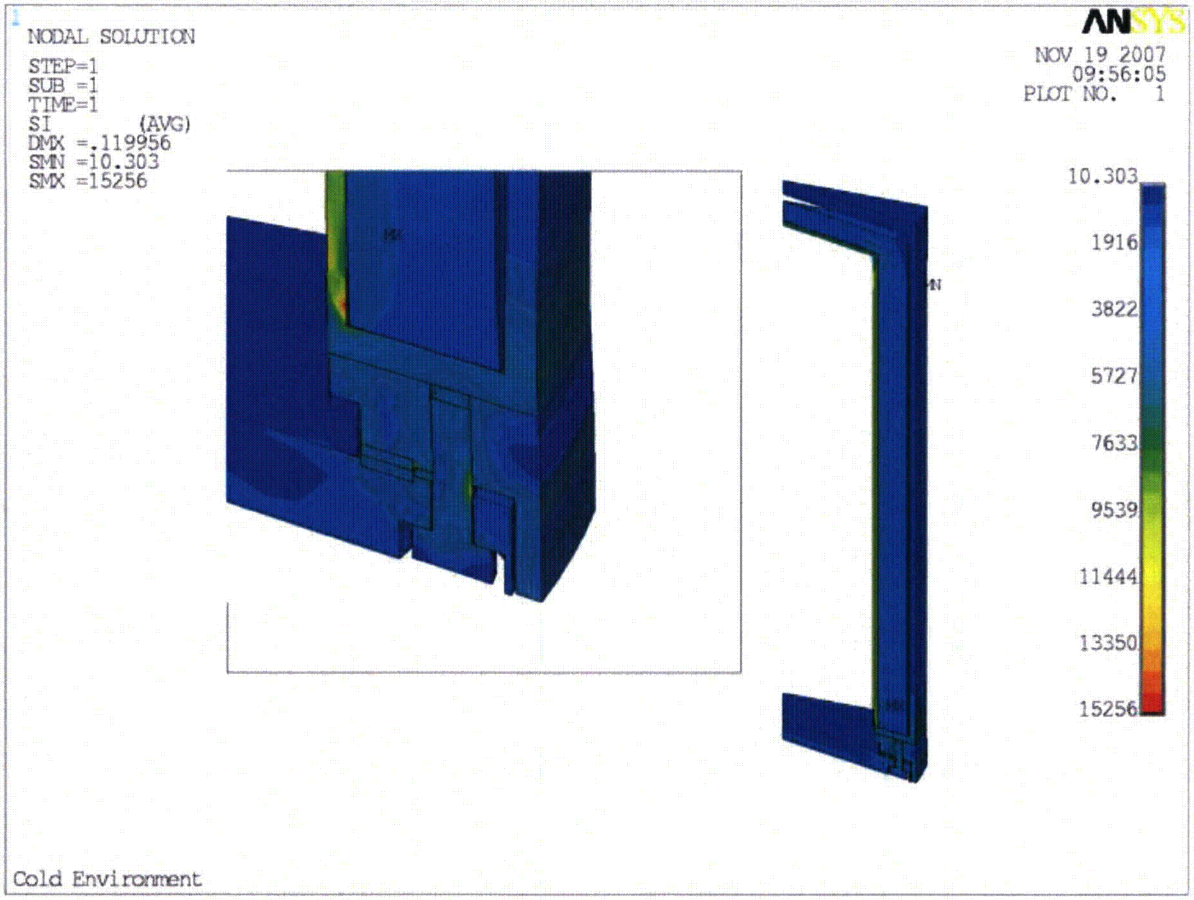


Figure 2-22 - Stress Intensity Contour Plot – Cold Environment

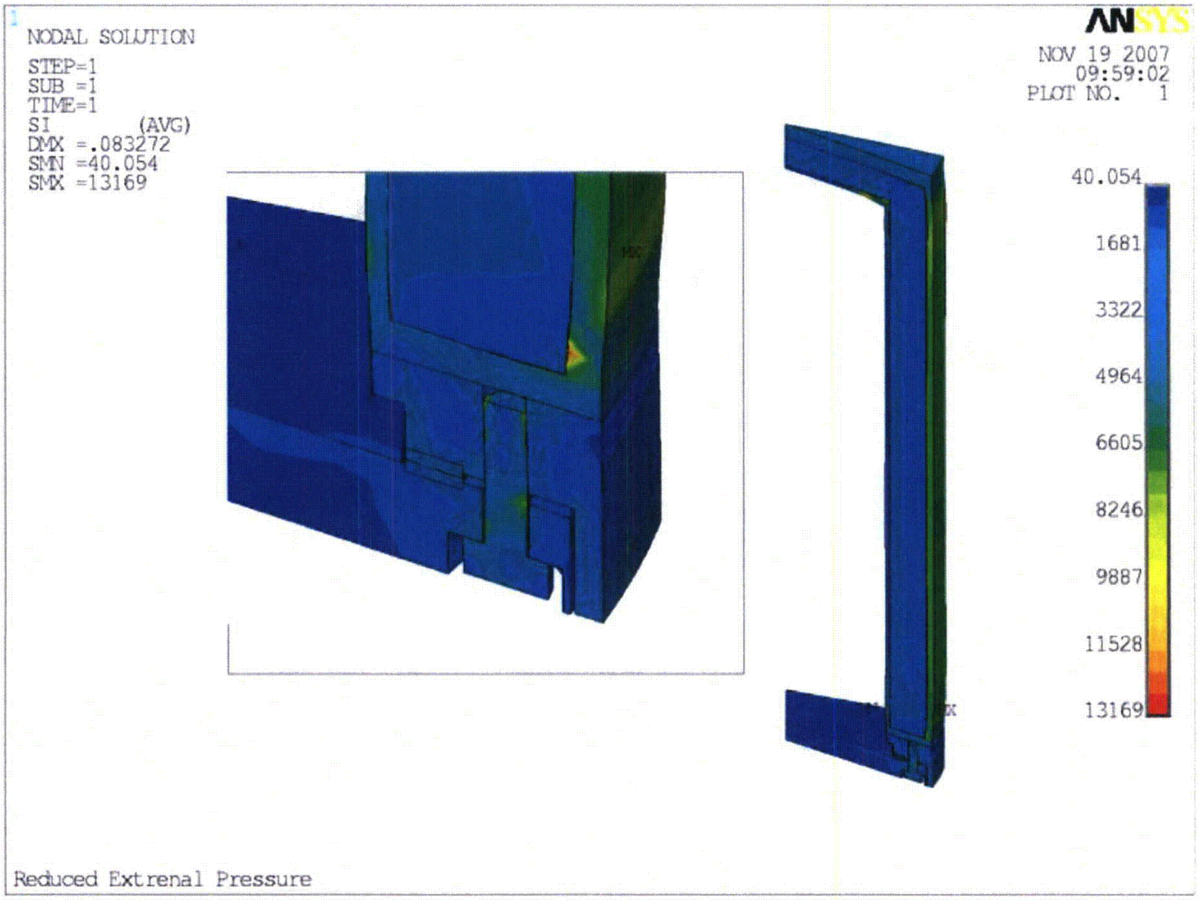


Figure 2-23 - Stress Intensity Contour Plot – Reduced External Pressure

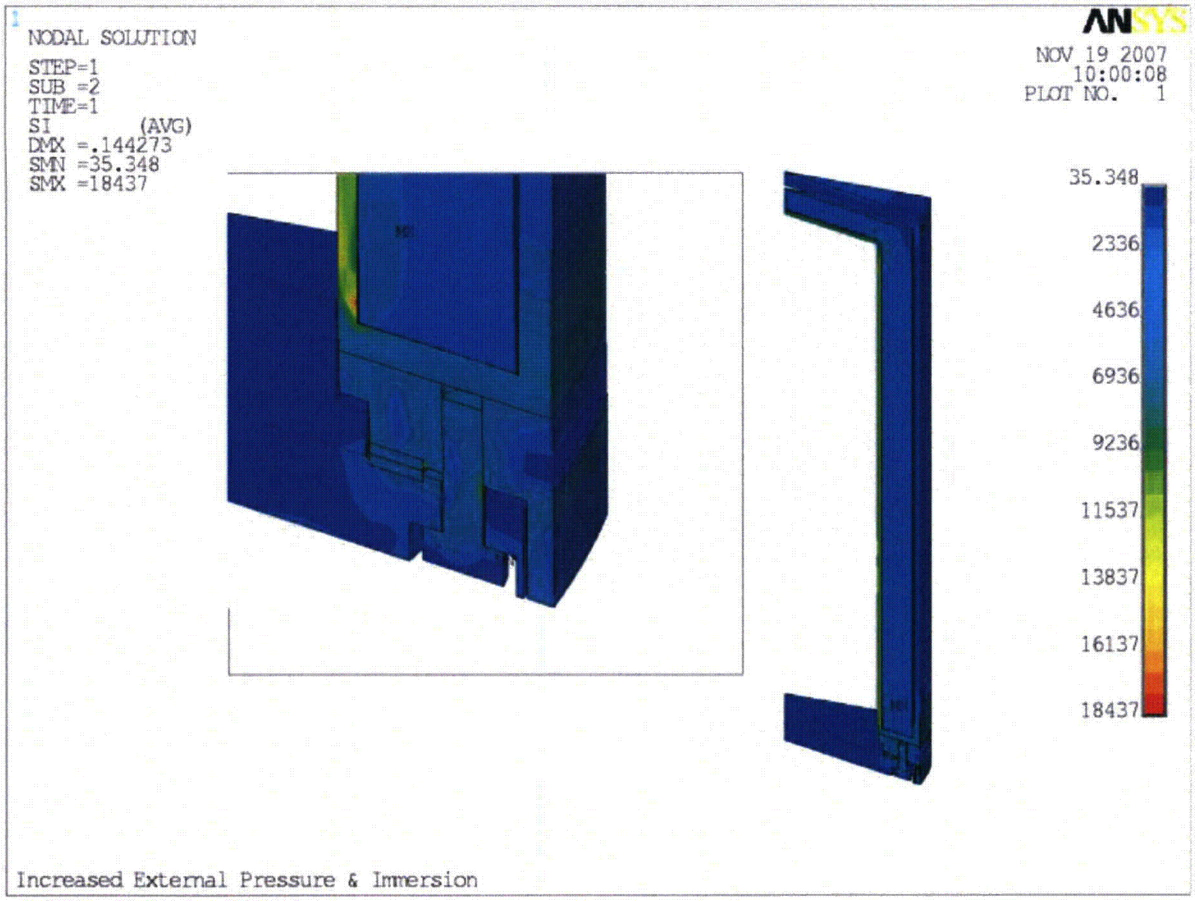


Figure 2-24 - Stress Intensity Contour Plot – Increased External Pressure

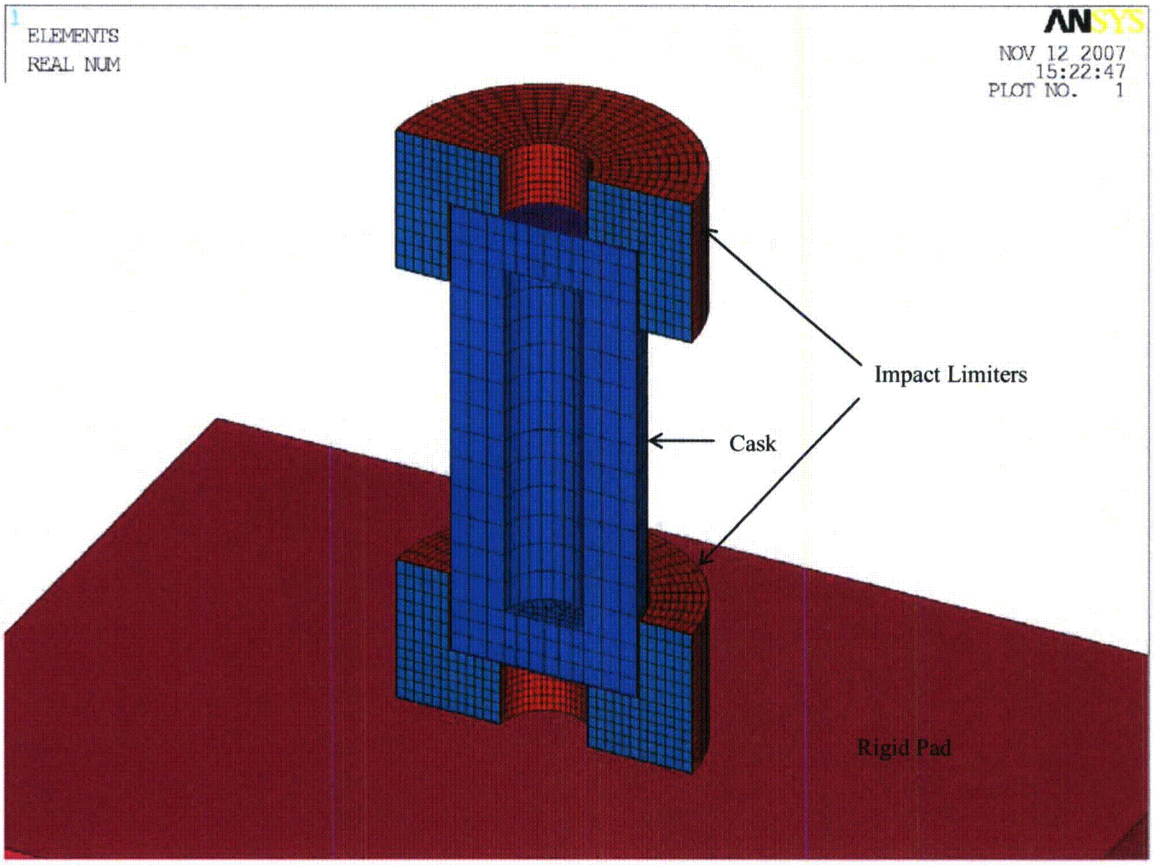


Figure 2-25 - LS-DYNA Model of the 3-60B Cask & Rigid Pad

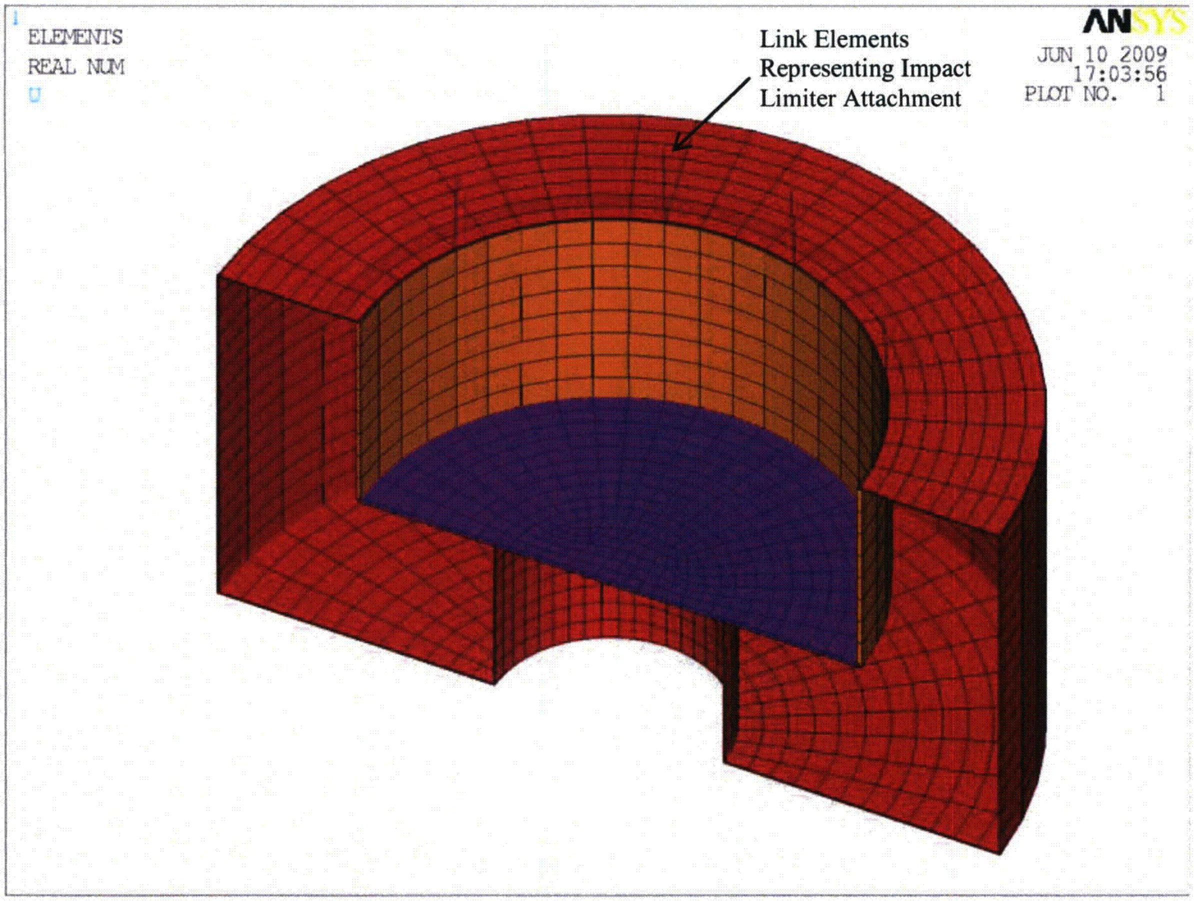


Figure 2-26 - Impact Limiter Shell and Attachment Model

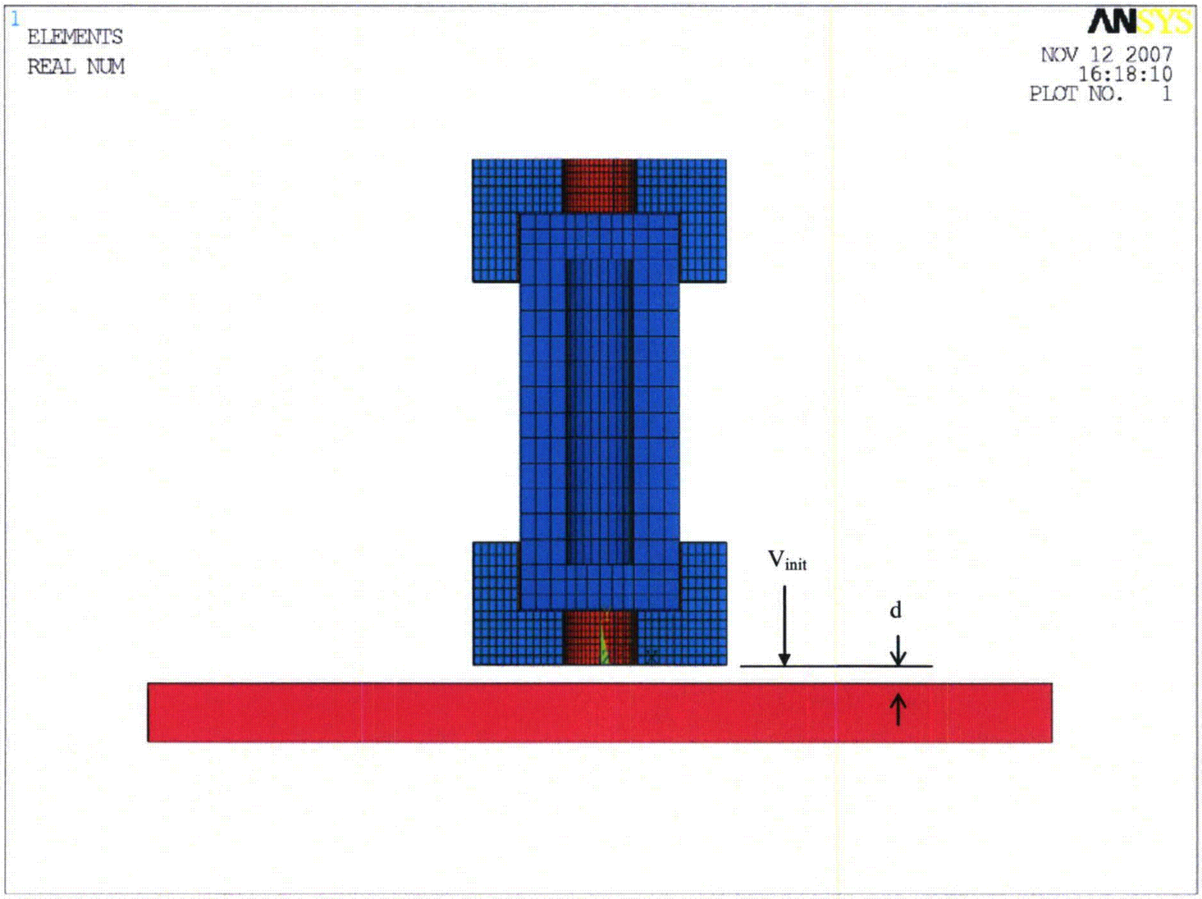


Figure 2-27 - End Drop Orientation

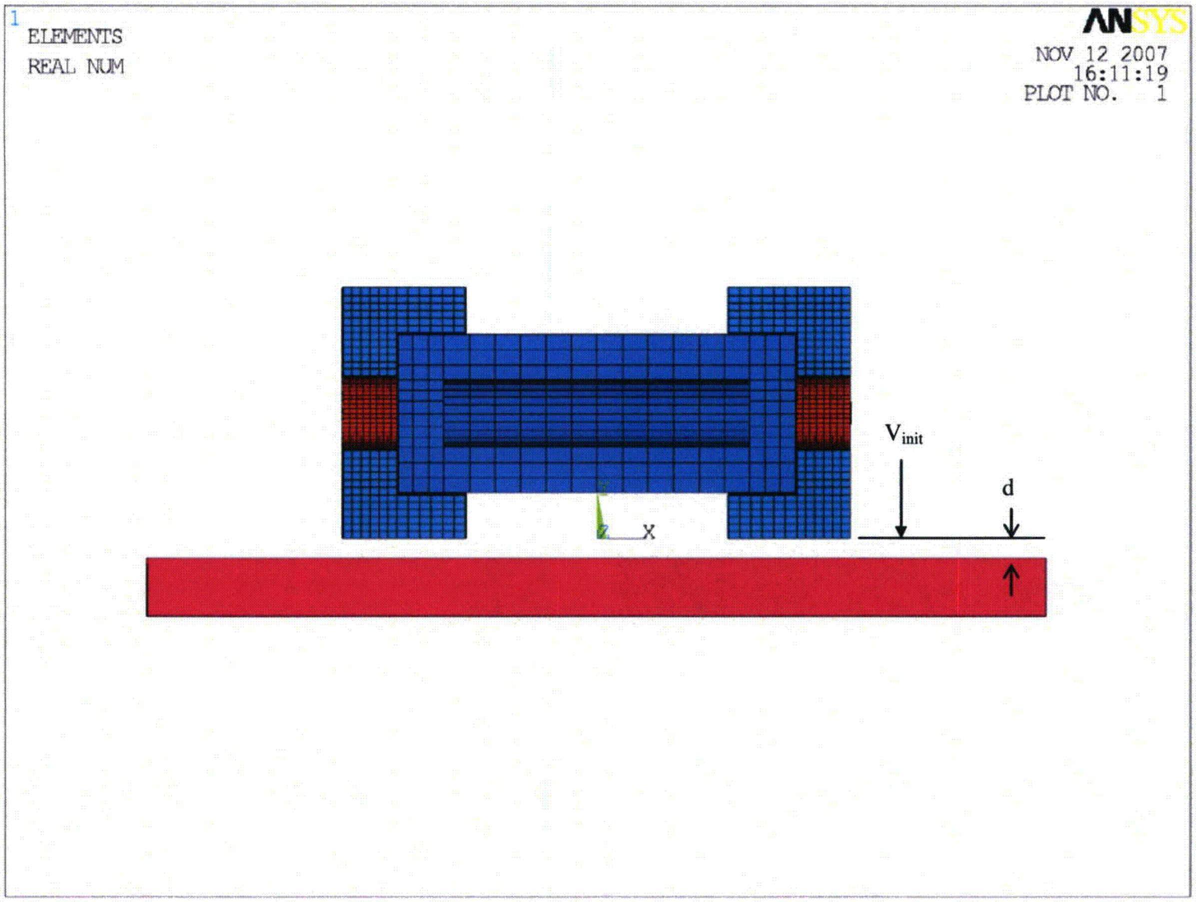


Figure 2-28 - Side Drop Orientation

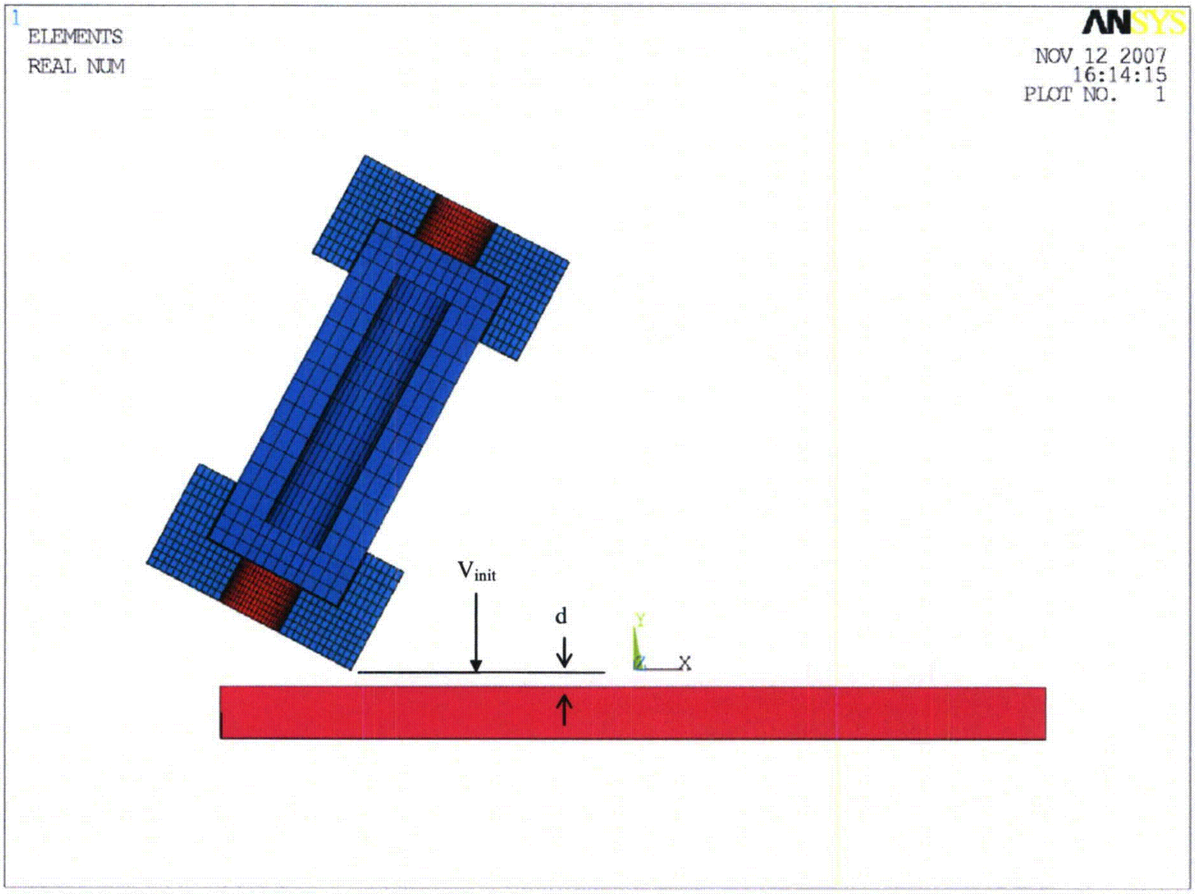


Figure 2-29 - Corner Drop Orientation

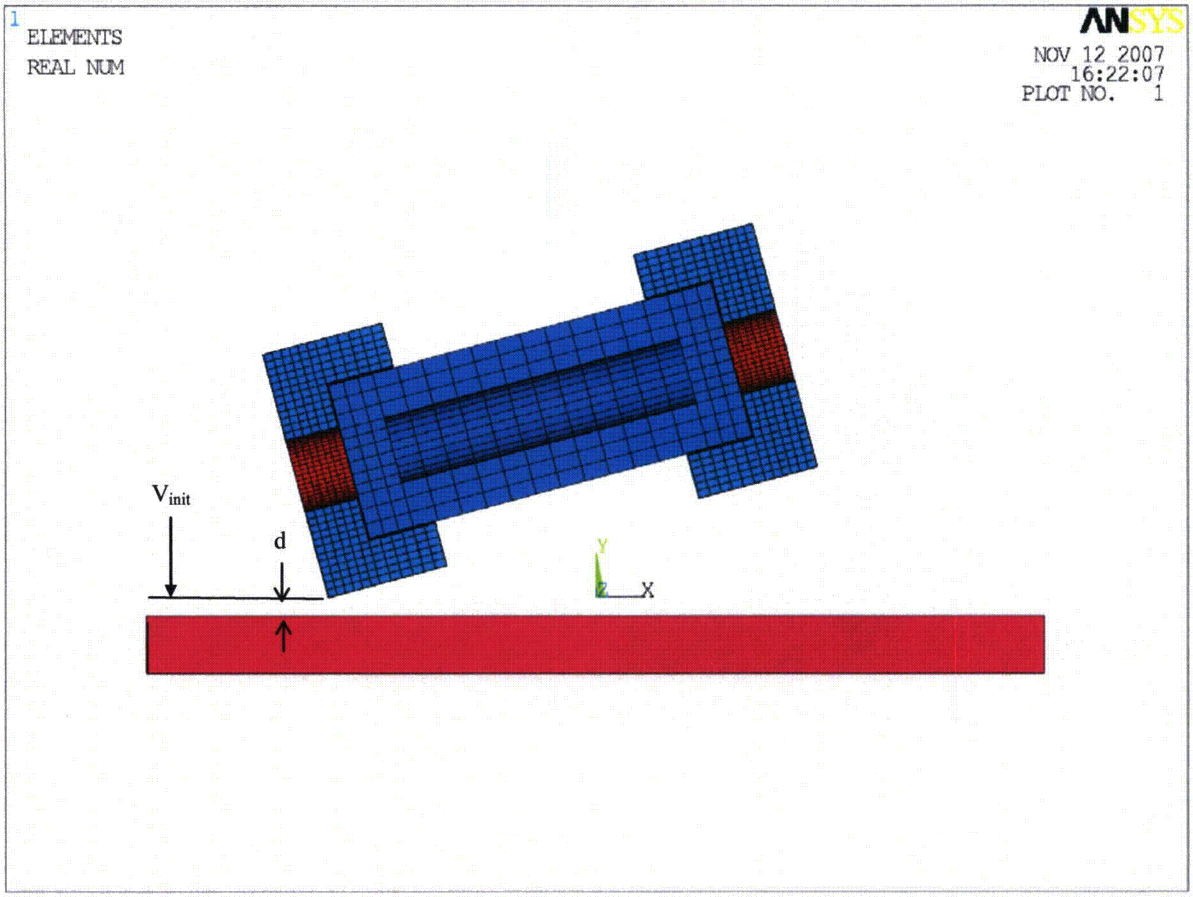


Figure 2-30 - Shallow Angle Drop Orientation

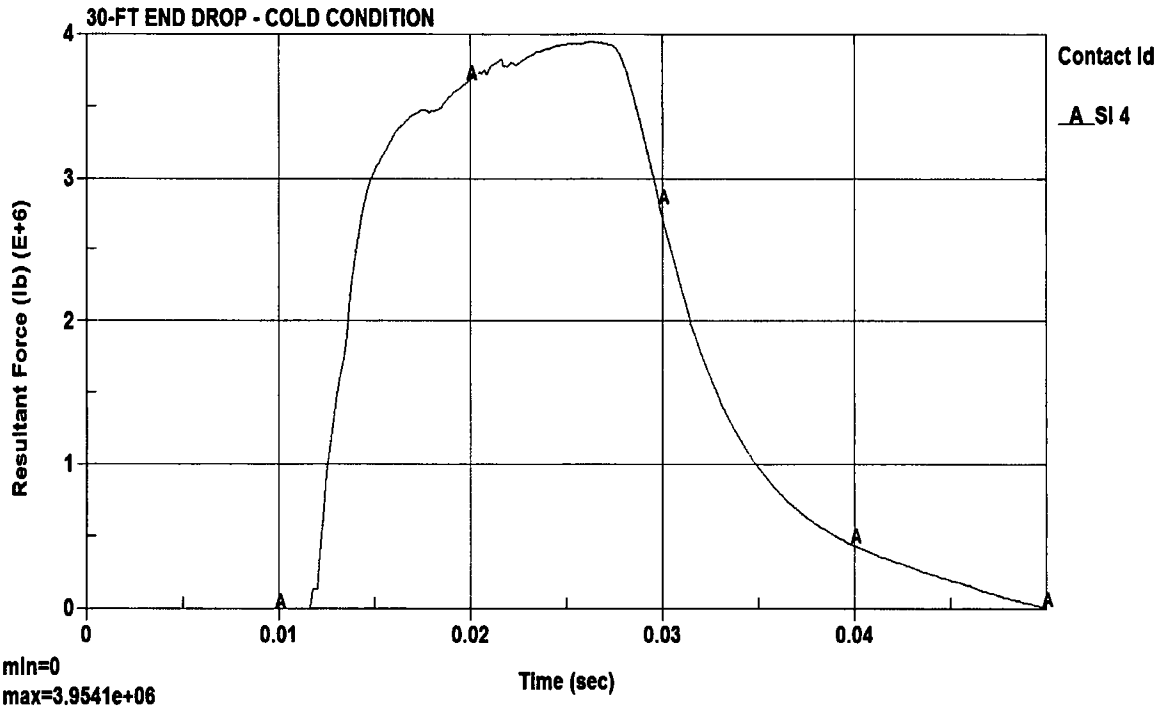


Figure 2-31 - Time-History Result, 30-Ft End Drop, Cold Condition (Resultant Force Plot)

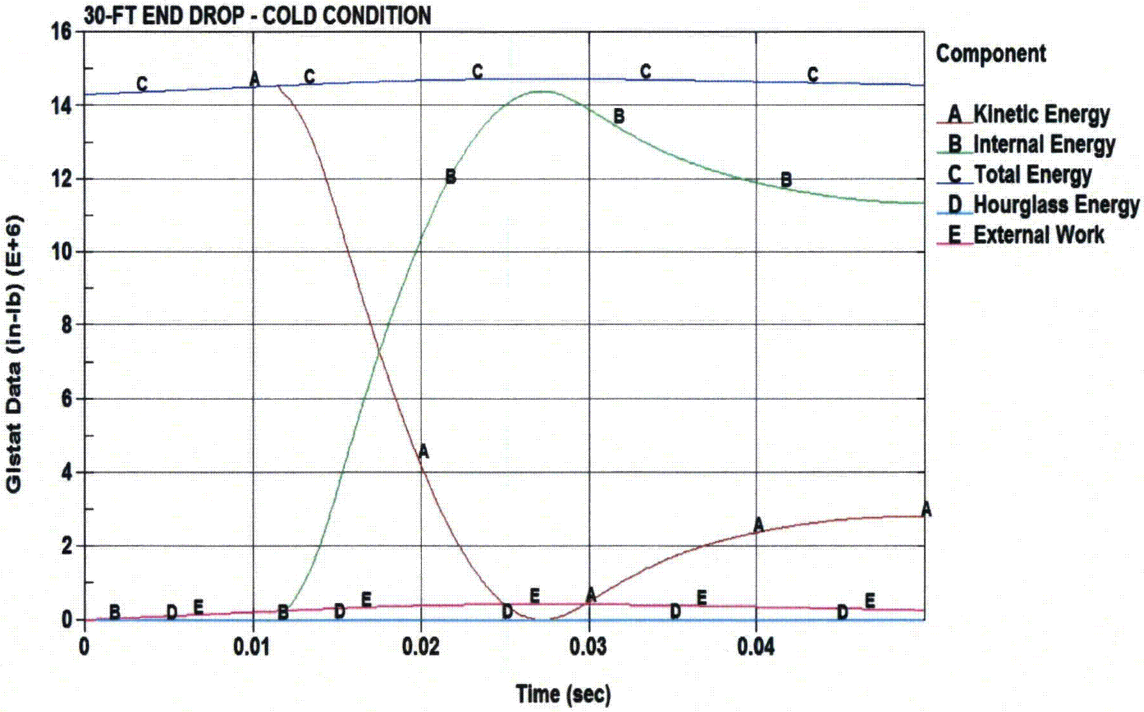


Figure 2-32 - Time-History Result, 30-Ft End Drop, Cold Condition (Energy Plots)

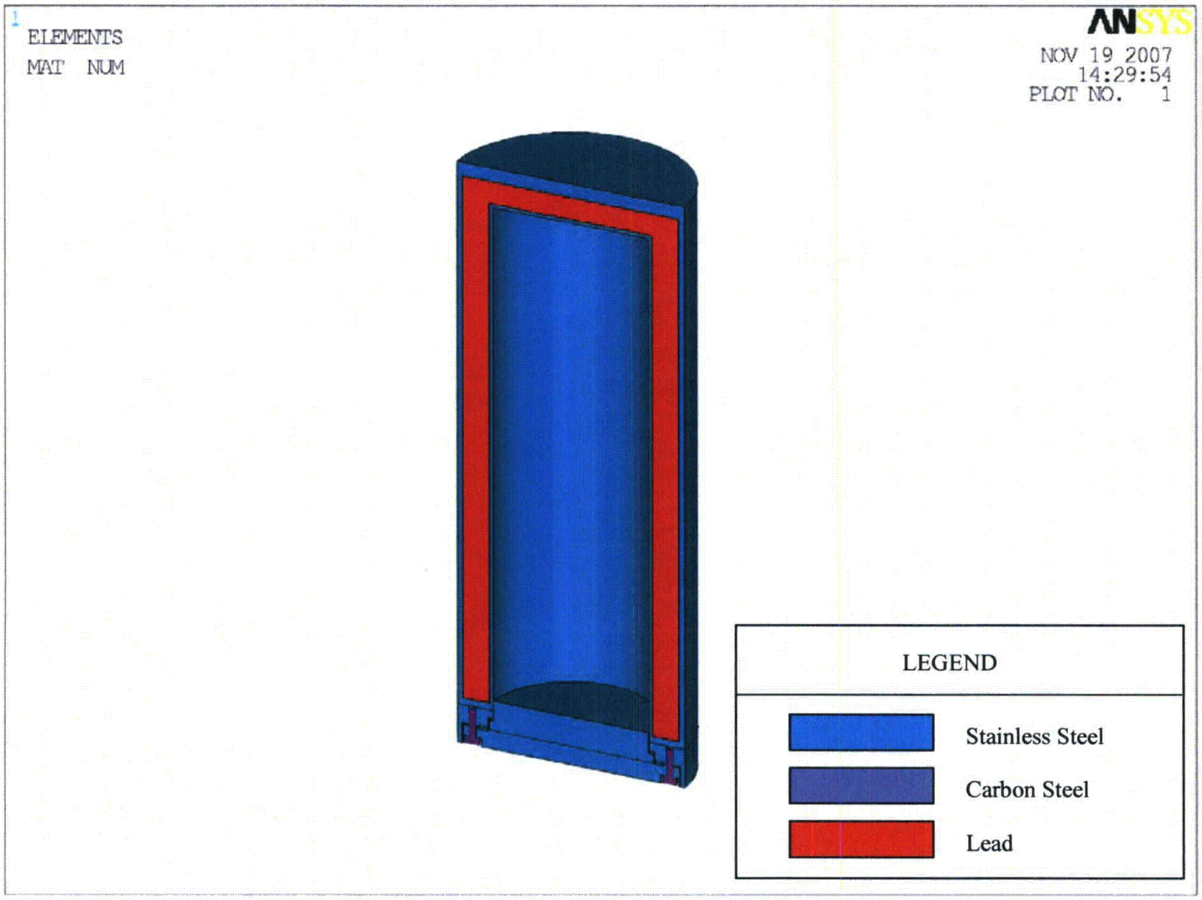


Figure 2-33 - Finite Element Model of the 3-60B Cask Identifying the Cask Components with Material Numbers

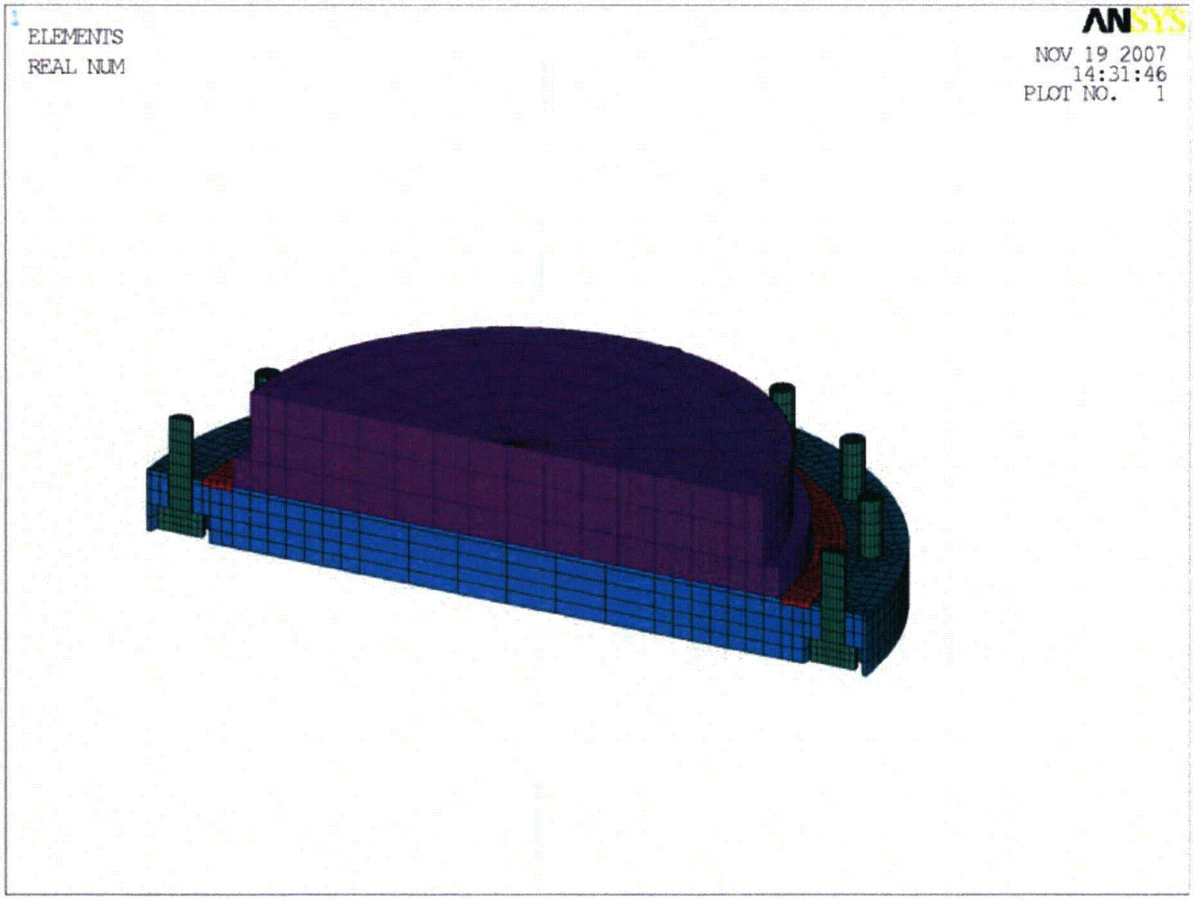


Figure 2-34 - Finite Element Model of the Lid, Seal Plate and Bolts

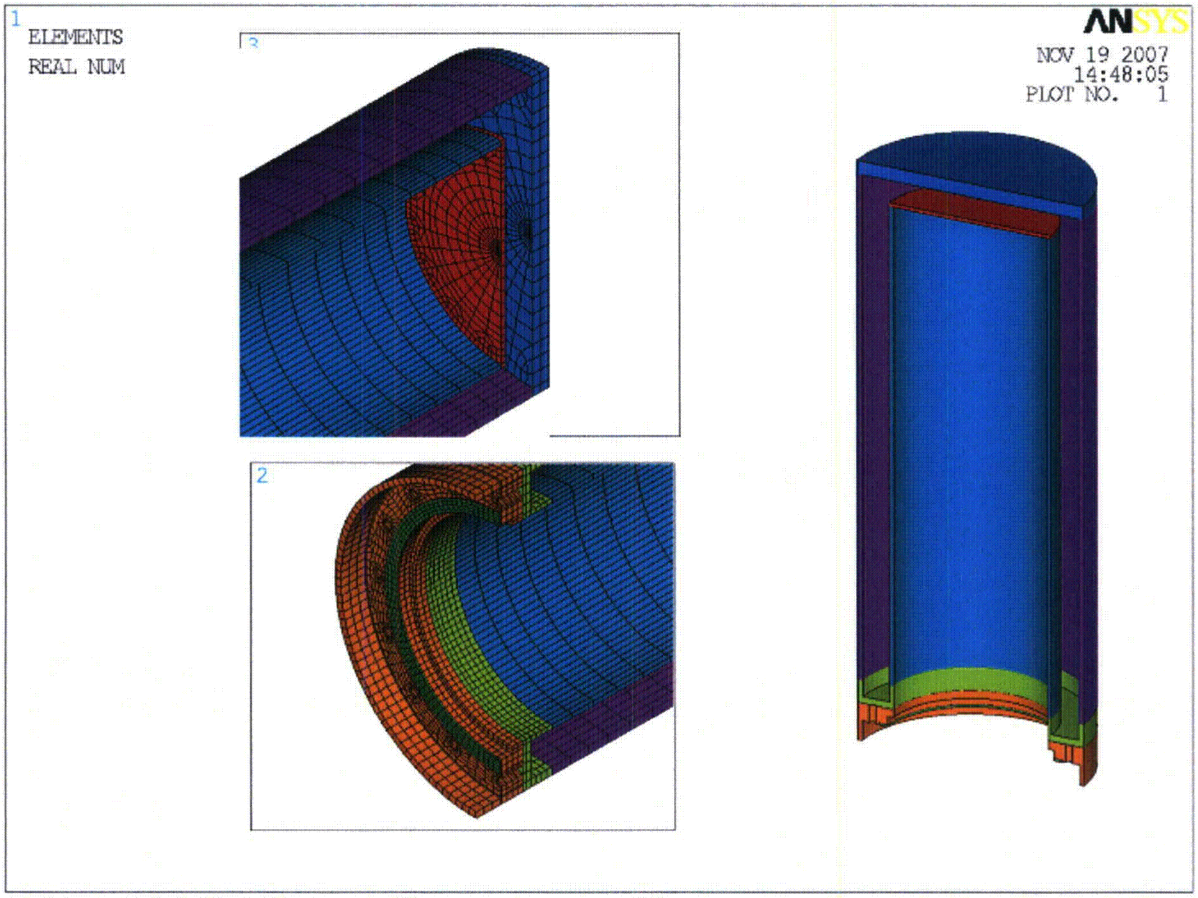


Figure 2-35 - Finite Element Model of the cask Body without the Lead

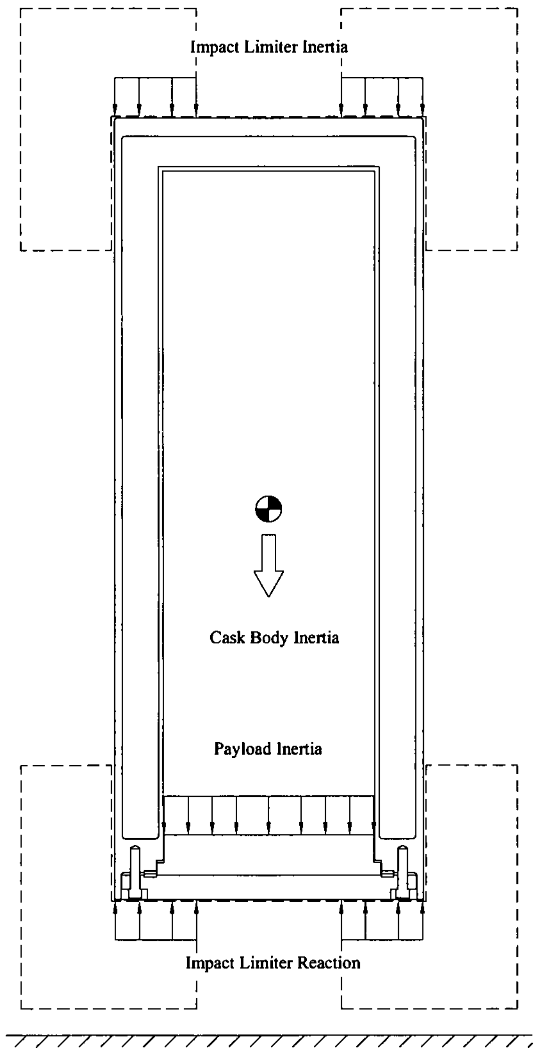


Figure 2-36 - Load Distribution on the Model during End Drop

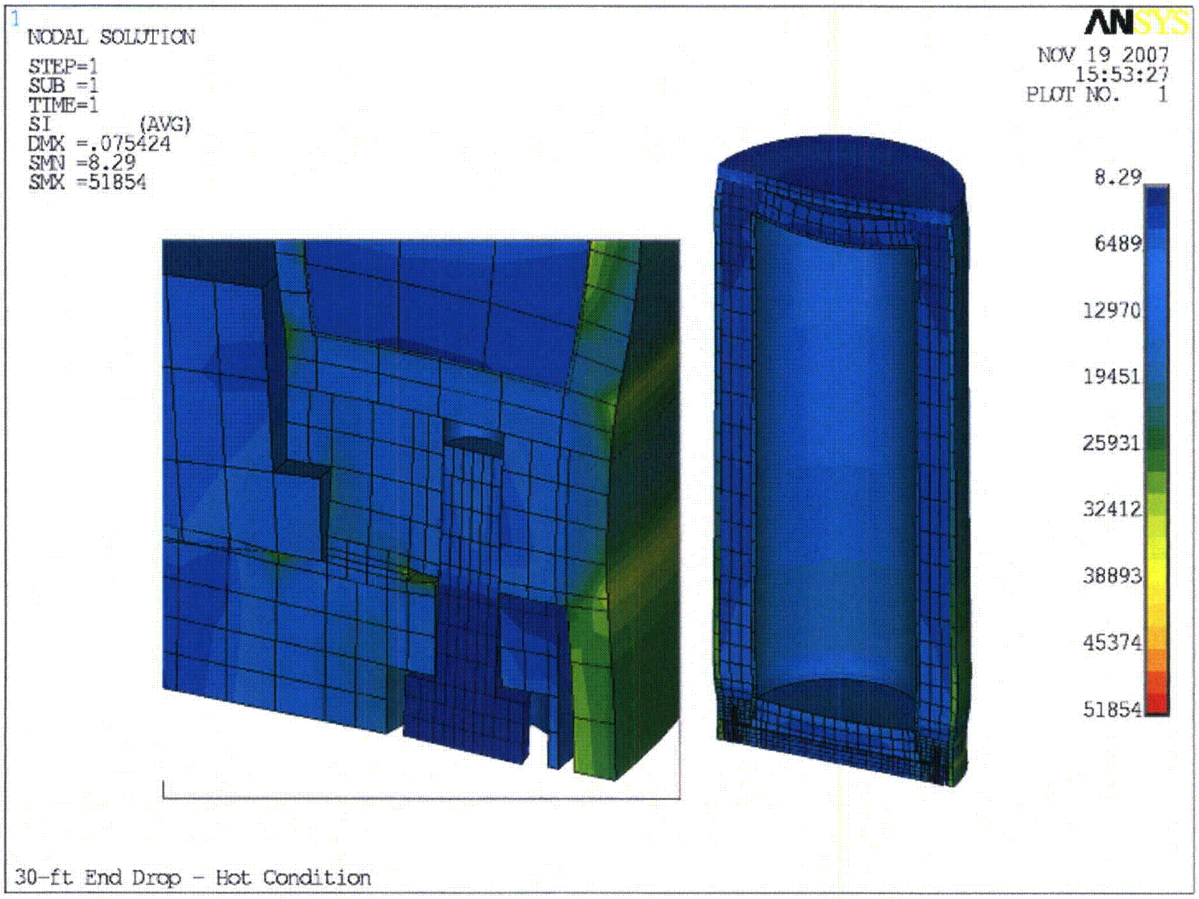


Figure 2-37 - Stress Intensity Plot – 30-ft End Drop – Hot Condition

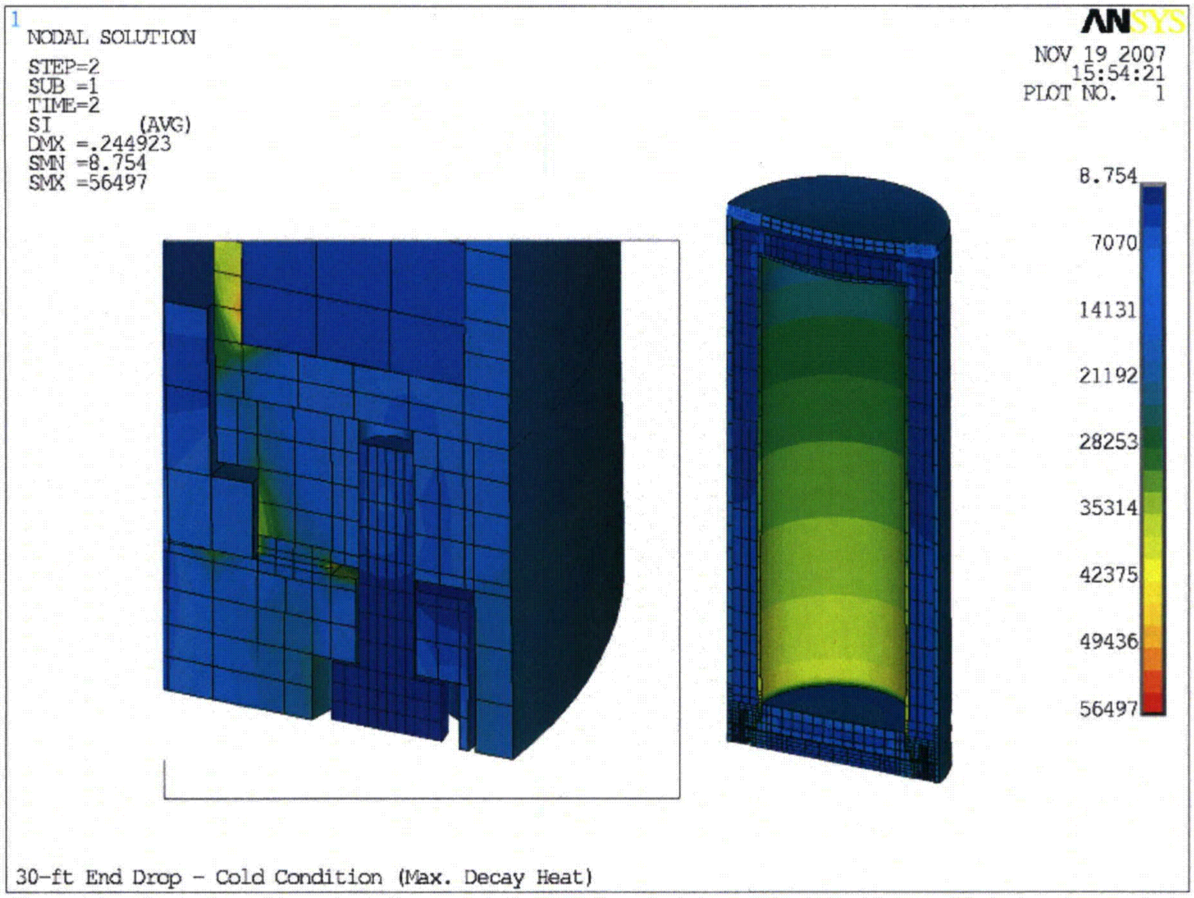


Figure 2-38 - Stress Intensity Plot – 30-ft End Drop – Cold Condition (Max. Decay Heat)

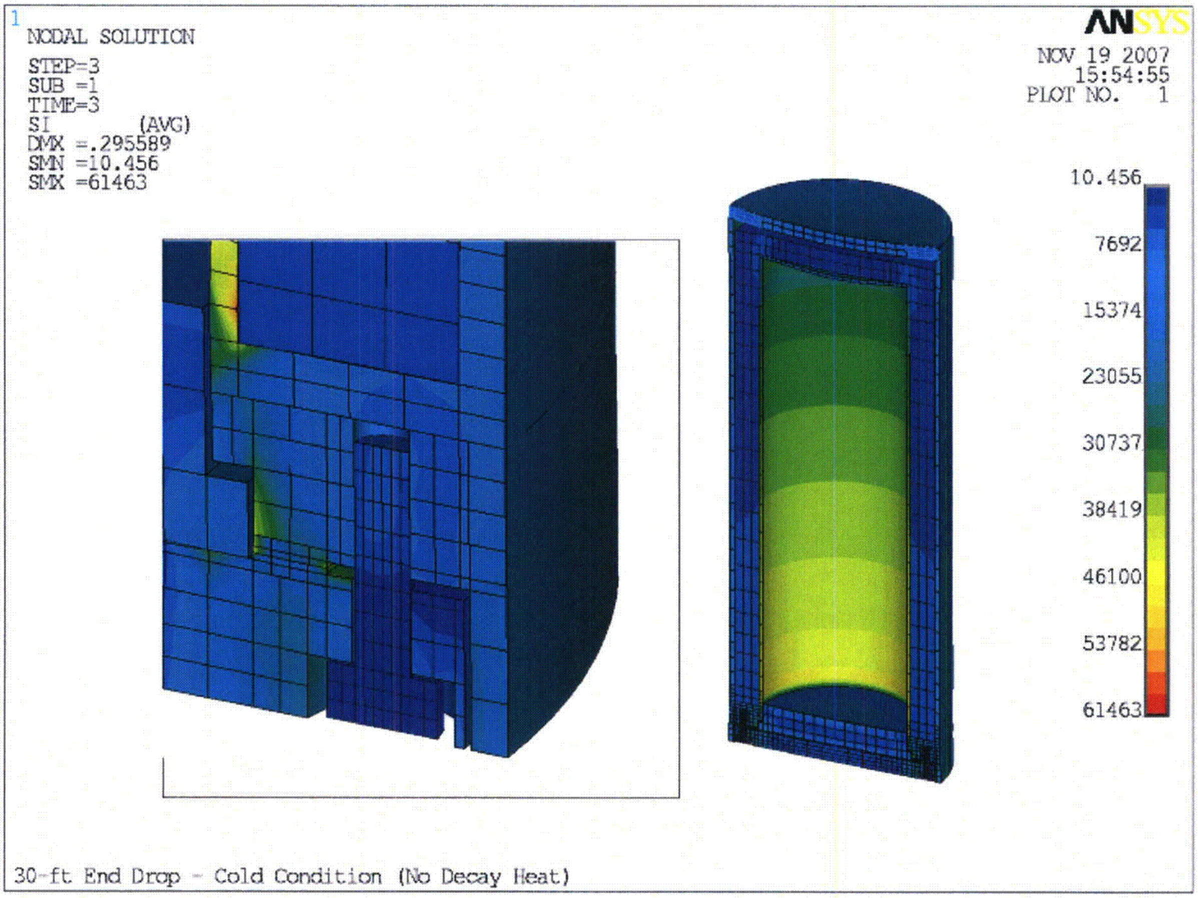


Figure 2-39 - Stress Intensity Plot – 30-ft End Drop – Cold Condition (No Decay Heat)

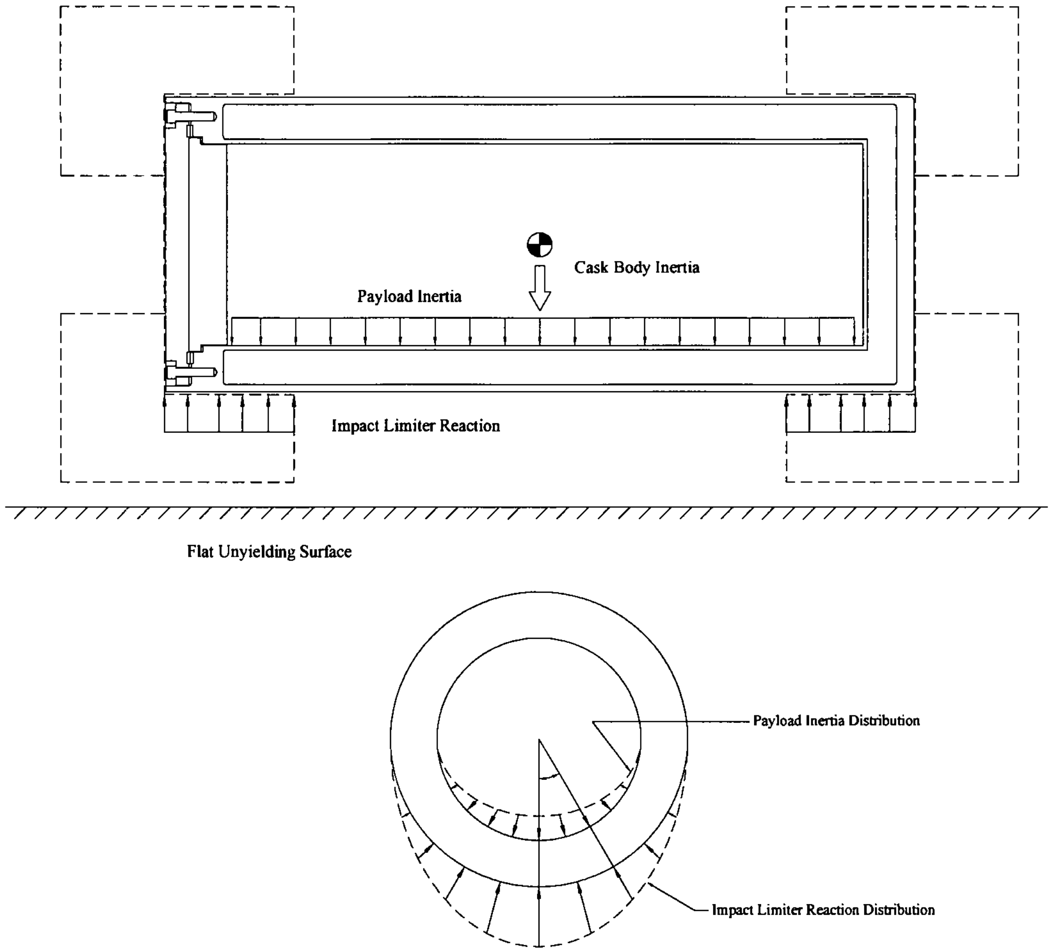


Figure 2-40 - Load Distribution on the Model during Side Drop

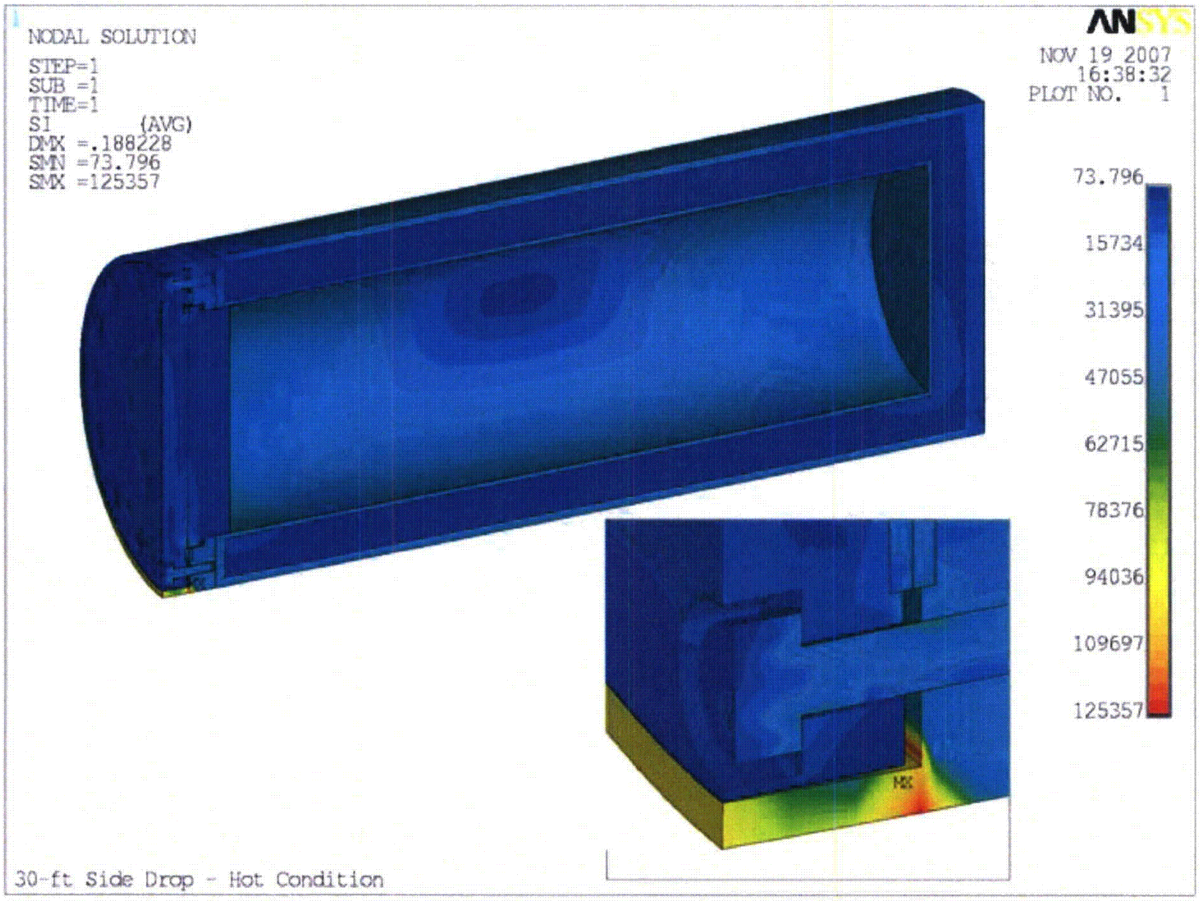


Figure 2-41 - Stress Intensity Plot – 30-ft Side Drop – Hot Condition

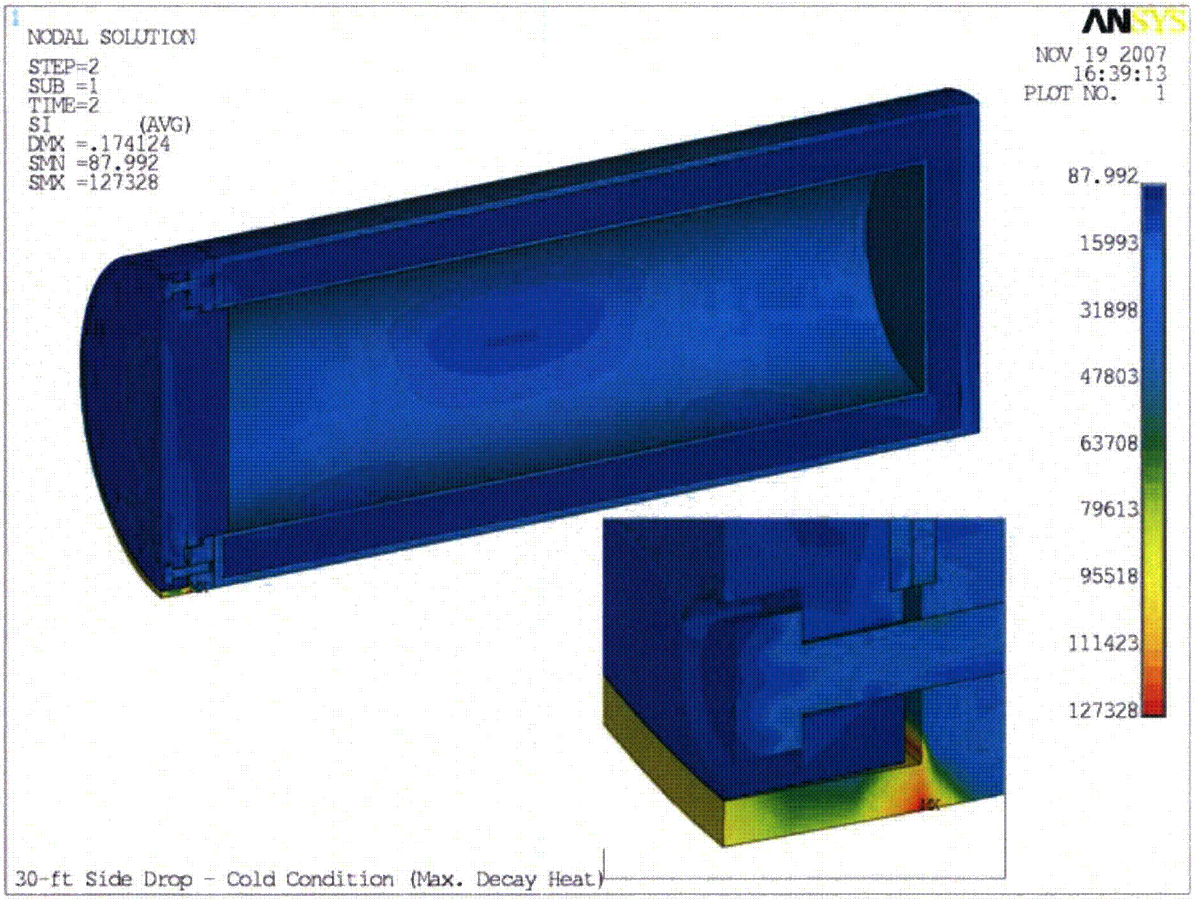


Figure 2-42 - Stress Intensity Plot – 30-ft Side Drop – Cold Condition (Max. Decay Heat)

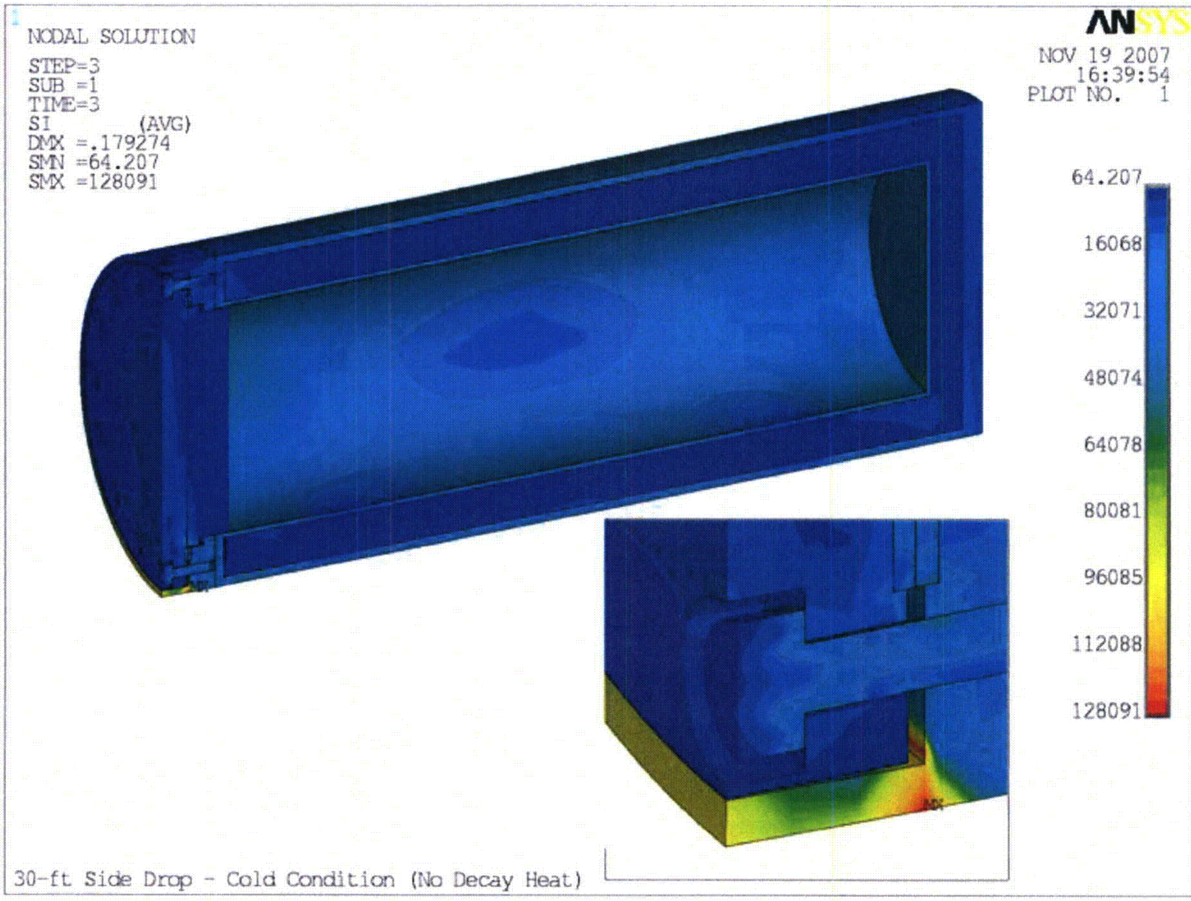


Figure 2-43 - Stress Intensity Plot – 30-ft Side Drop – Cold Condition (No Decay Heat)

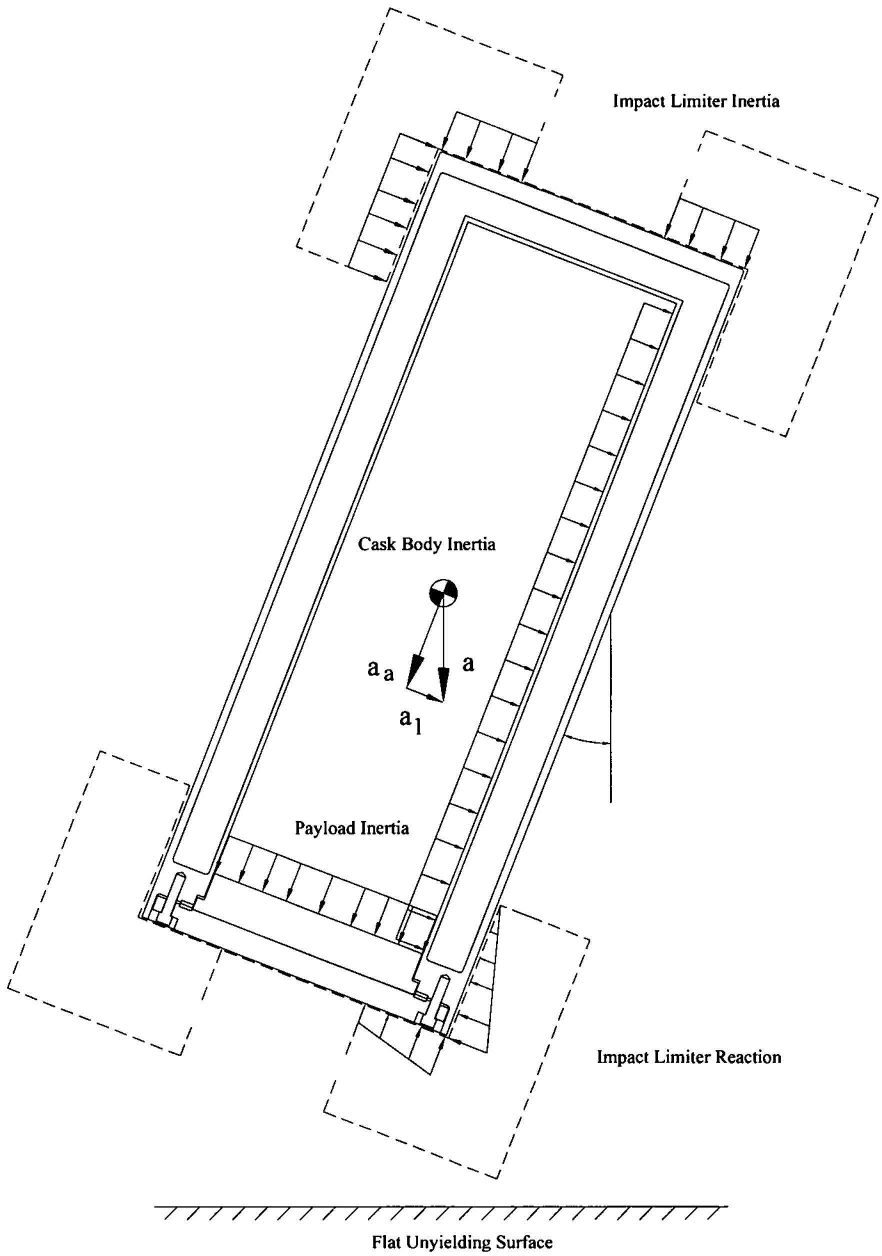


Figure 2-44 - Load Distribution on the Model during Corner Drop

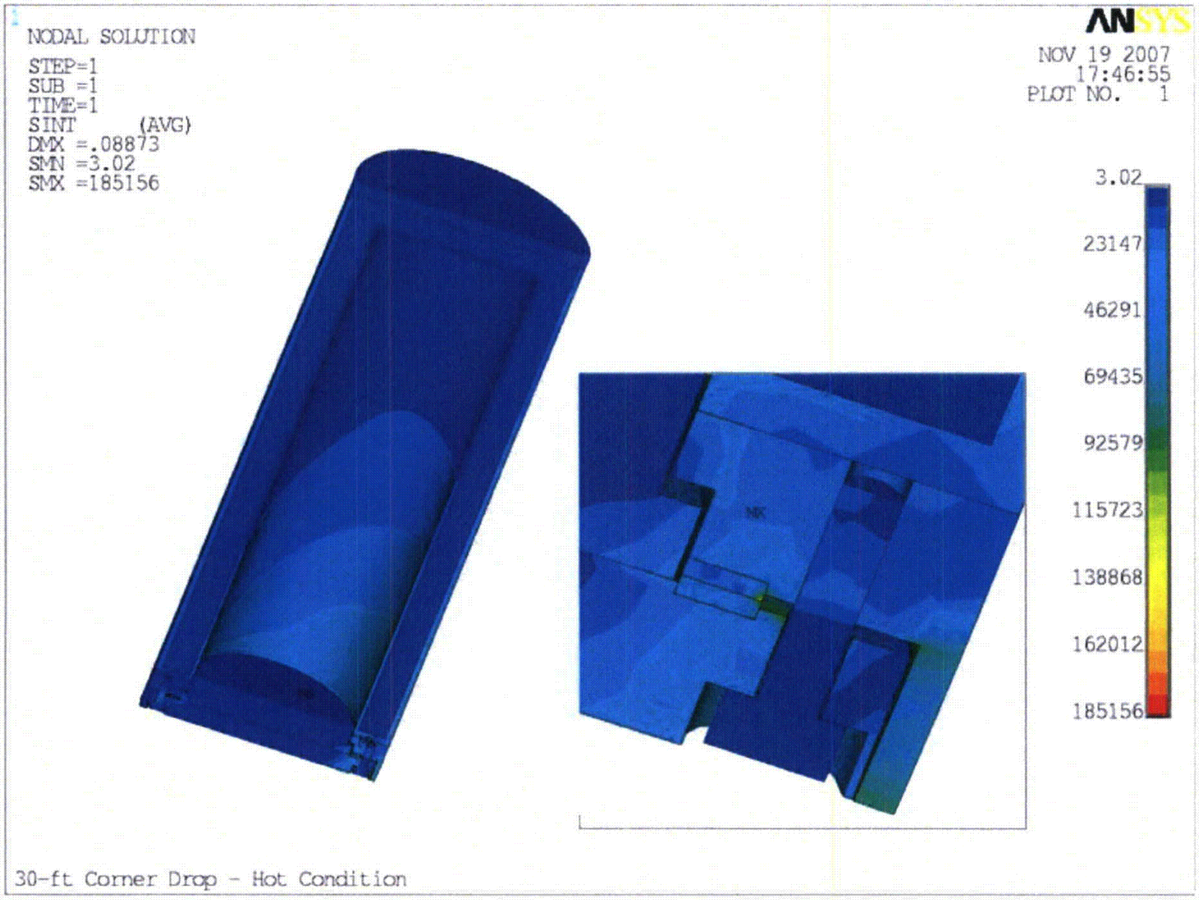


Figure 2-45 - Stress Intensity Plot – 30-ft Corner Drop – Hot Condition

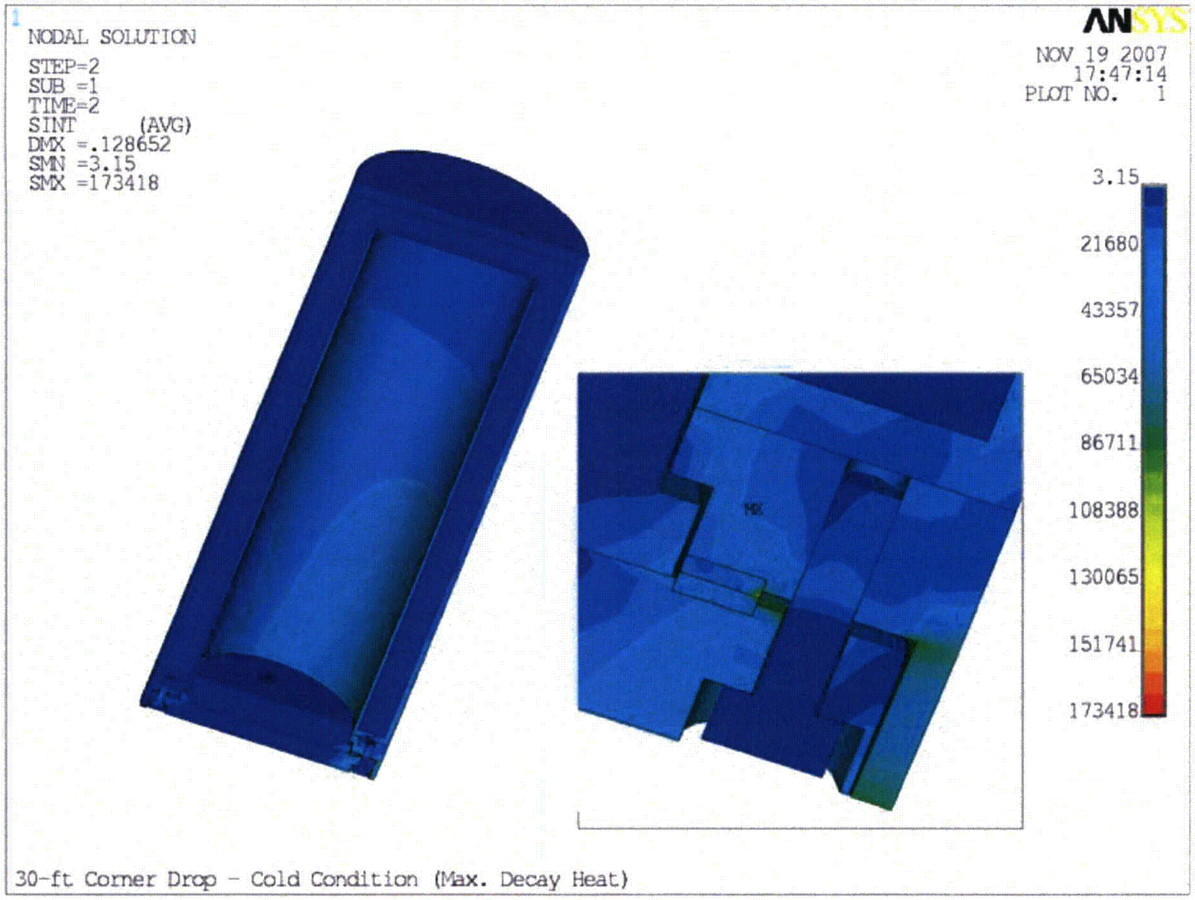


Figure 2-46 - Stress Intensity Plot – 30-ft Corner Drop – Cold Condition (Max. Decay Heat)

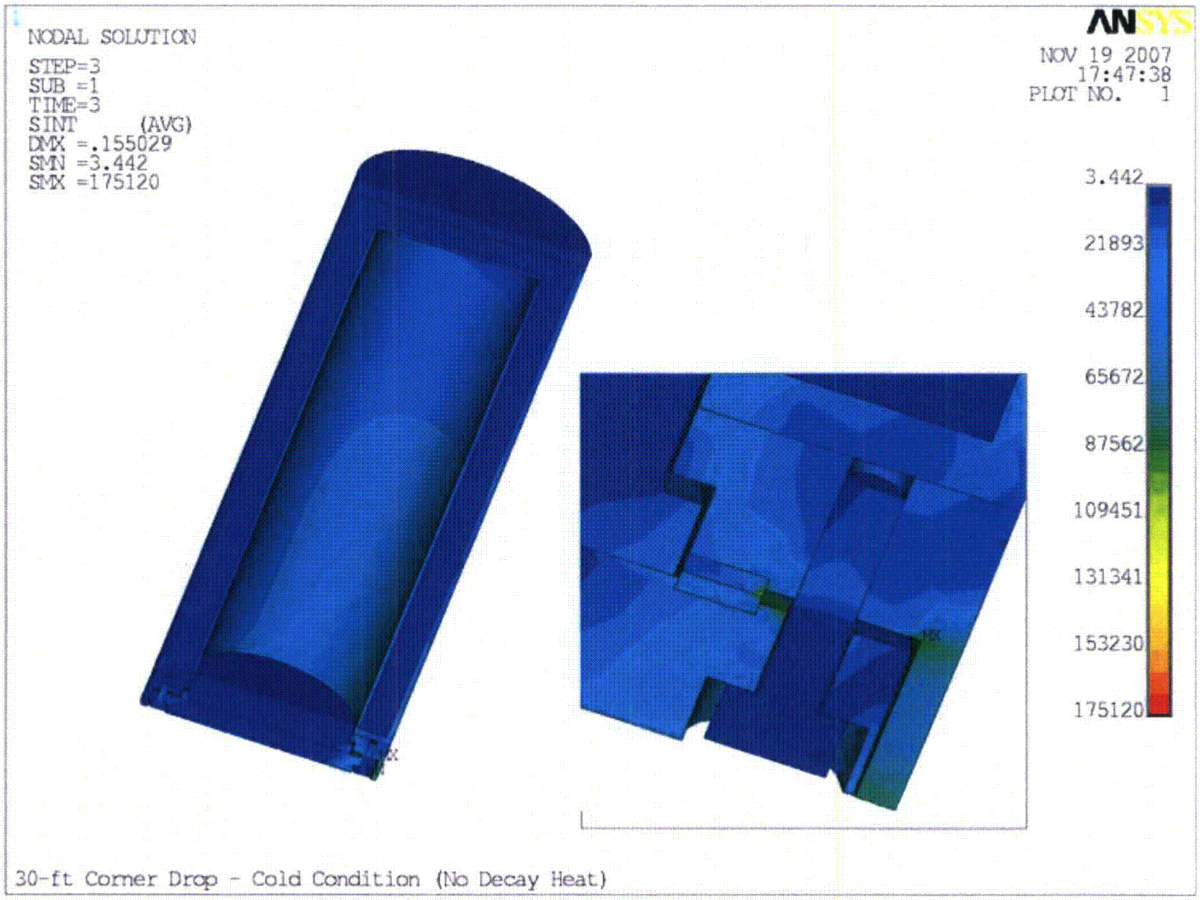


Figure 2-47 - Stress Intensity Plot – 30-ft Corner Drop – Cold Condition (No Decay Heat)

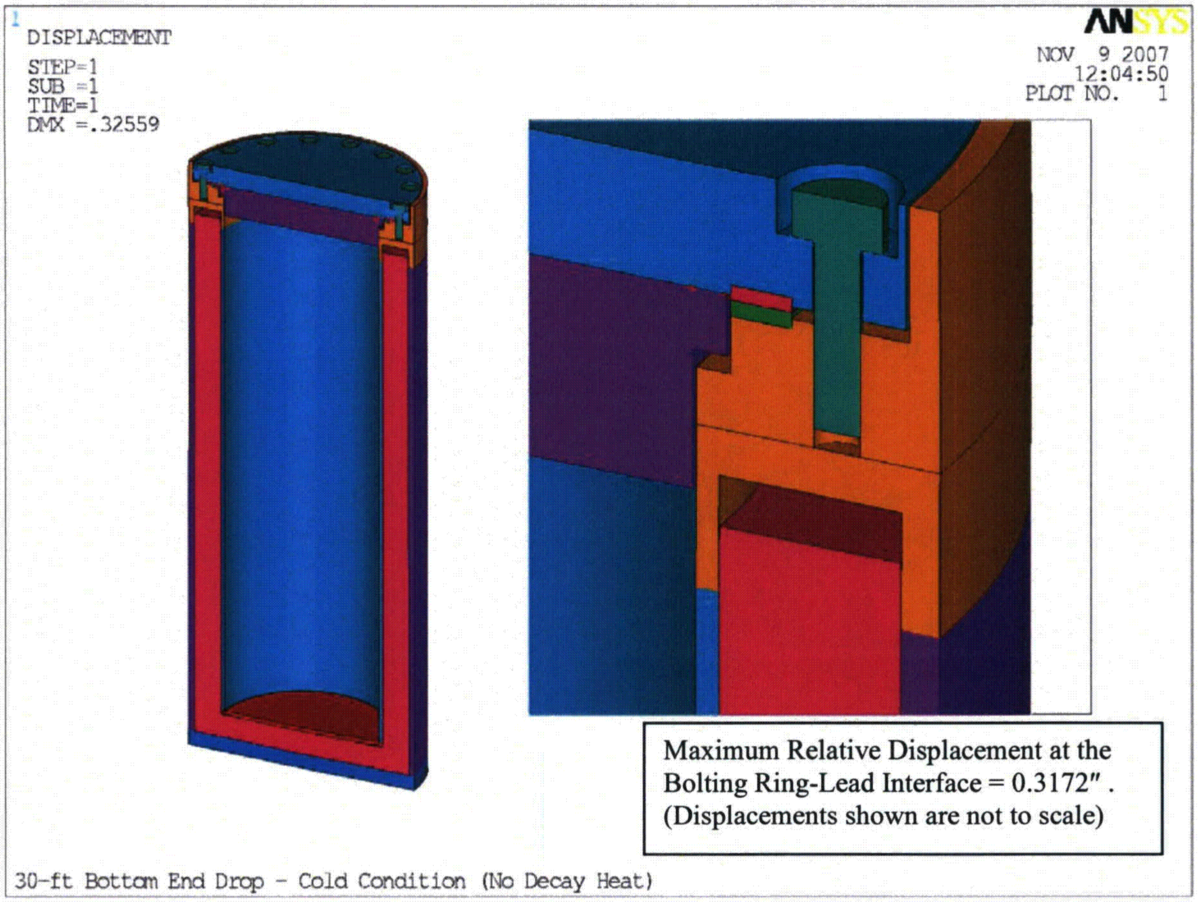


Figure 2-48 - 30-ft Bottom-End Down Drop - Displacement

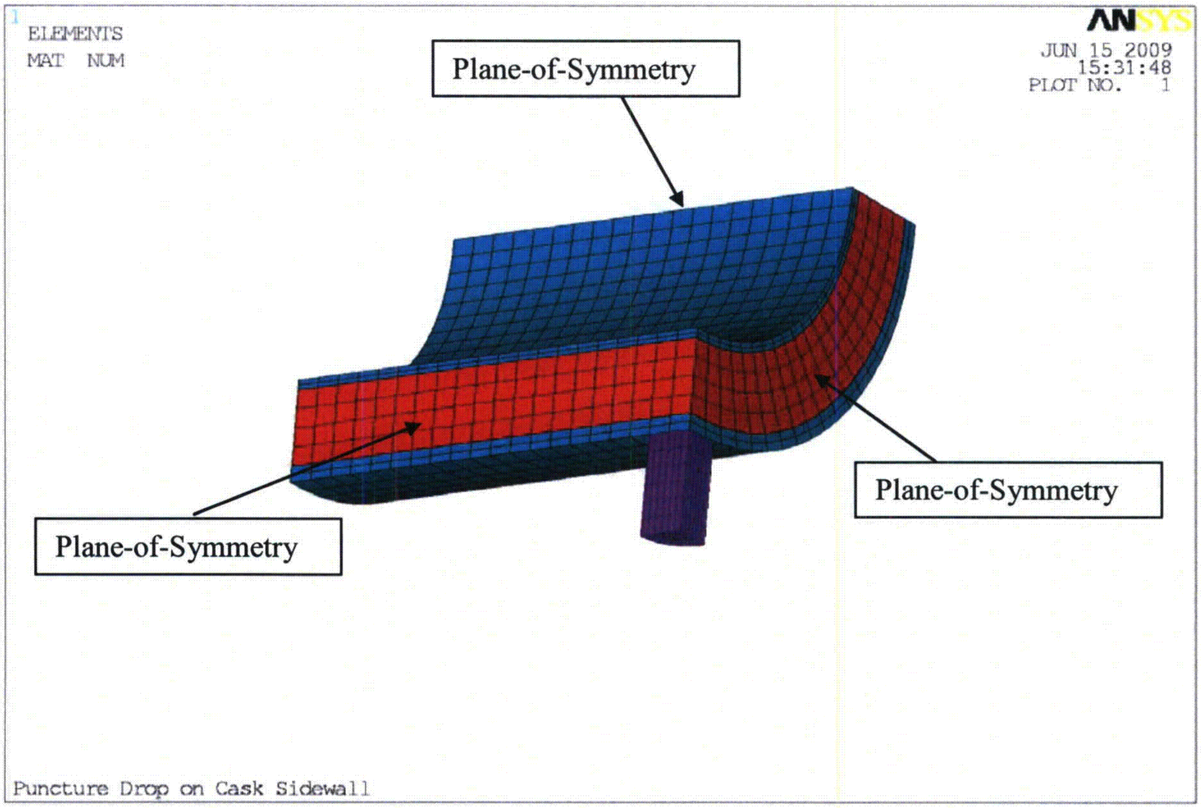


Figure 2-49 - Finite Element Model of the 3-60B Cask for Puncture Drop on the Sidewall Analysis

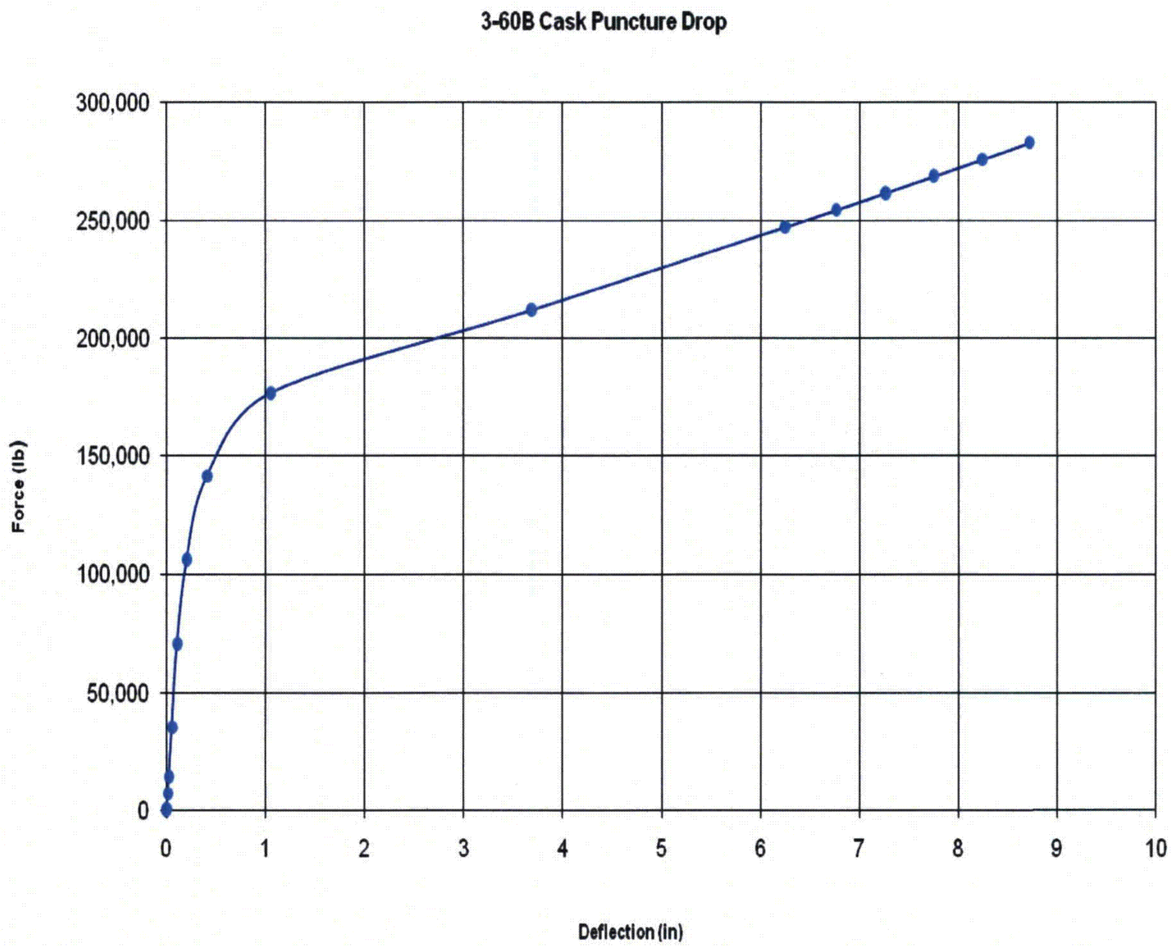


Figure 2-50 - Force-Deflection Plot at the Point of Impact

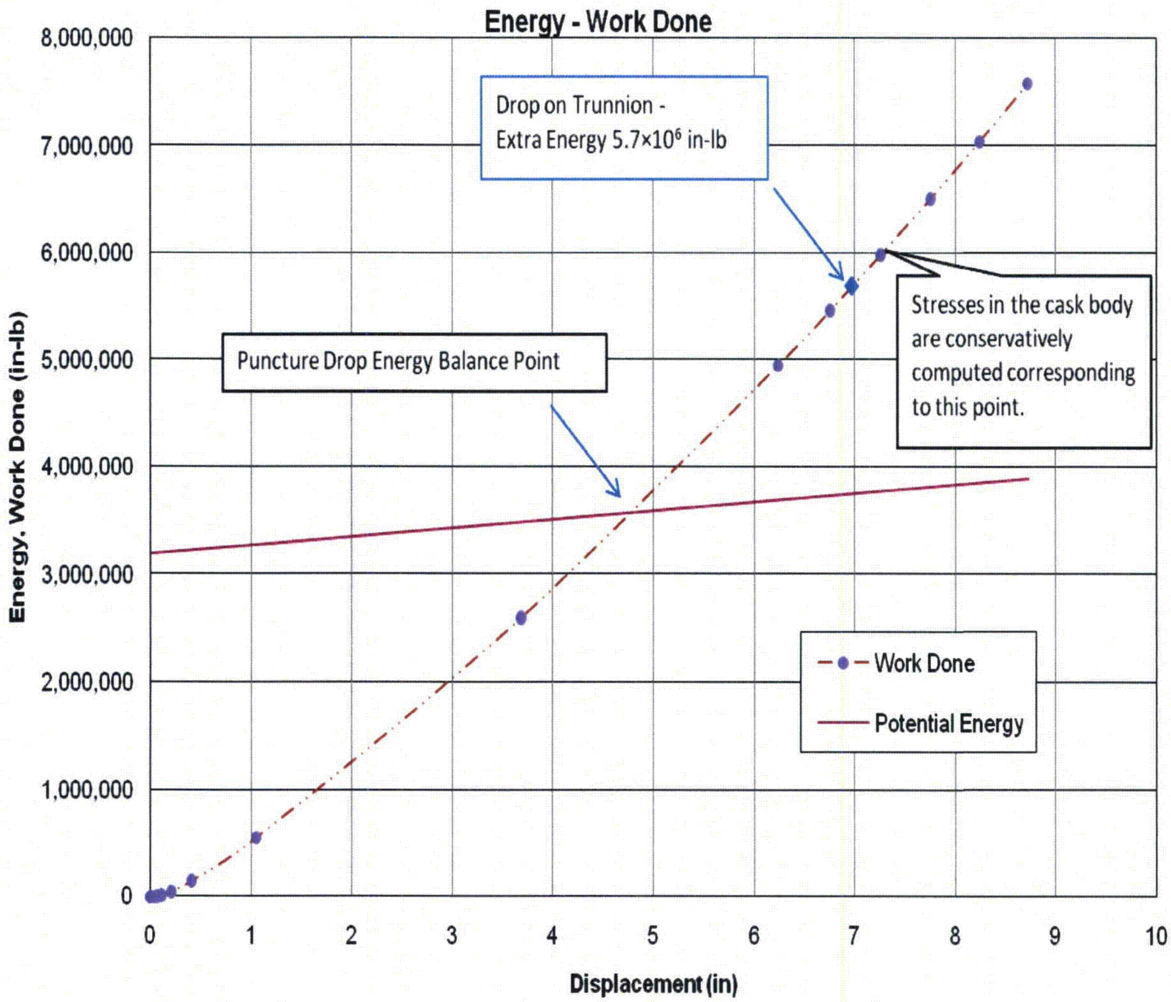


Figure 2-51 - Energy versus Deflection Plot

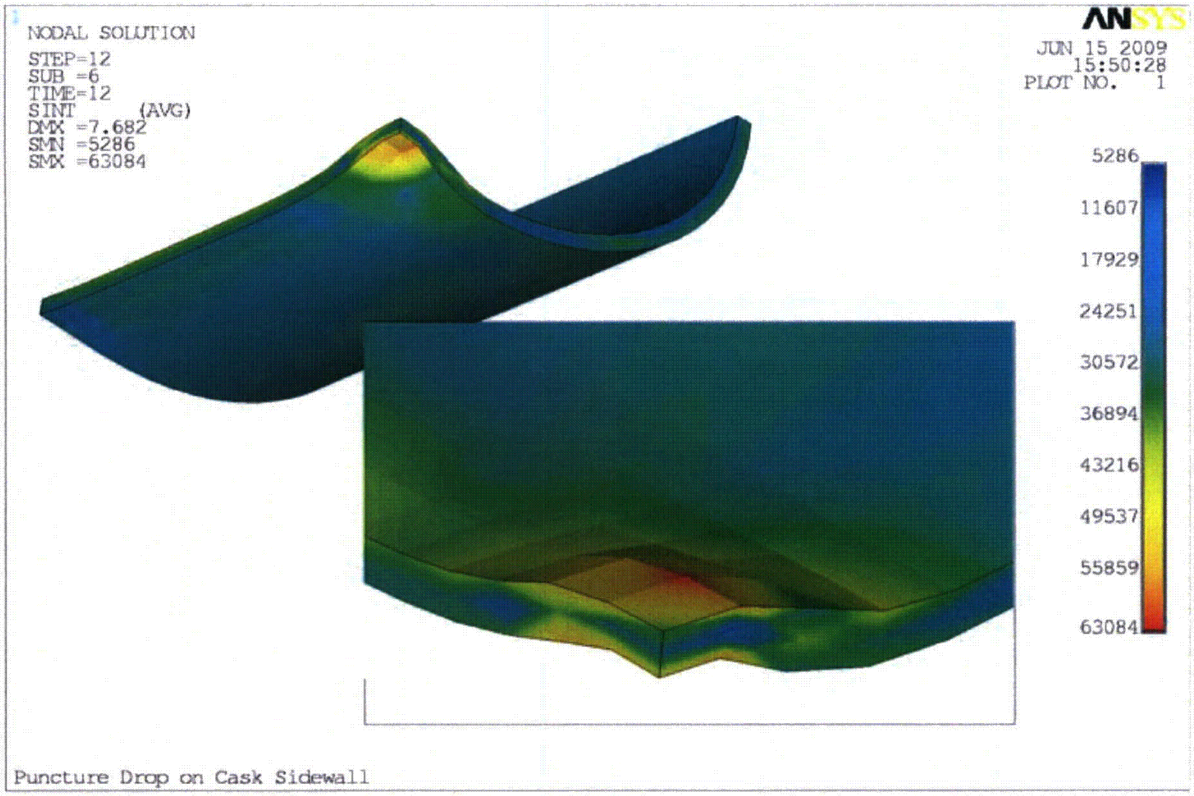


Figure 2-52 - Maximum Stress Intensity in the Outer Shells of the Cask under Puncture Drop

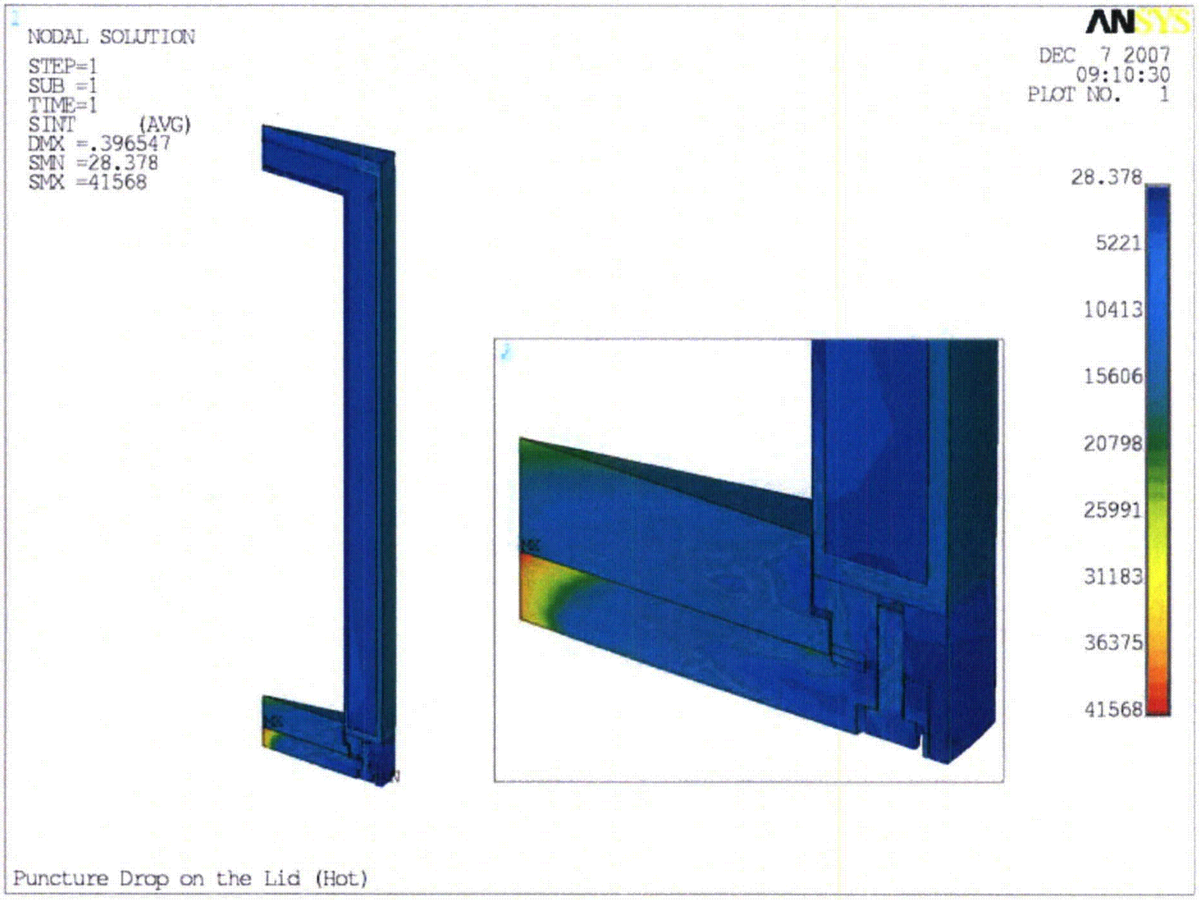


Figure 2-53 - Maximum Stress Intensity in the Cask under Puncture Drop on the Lid

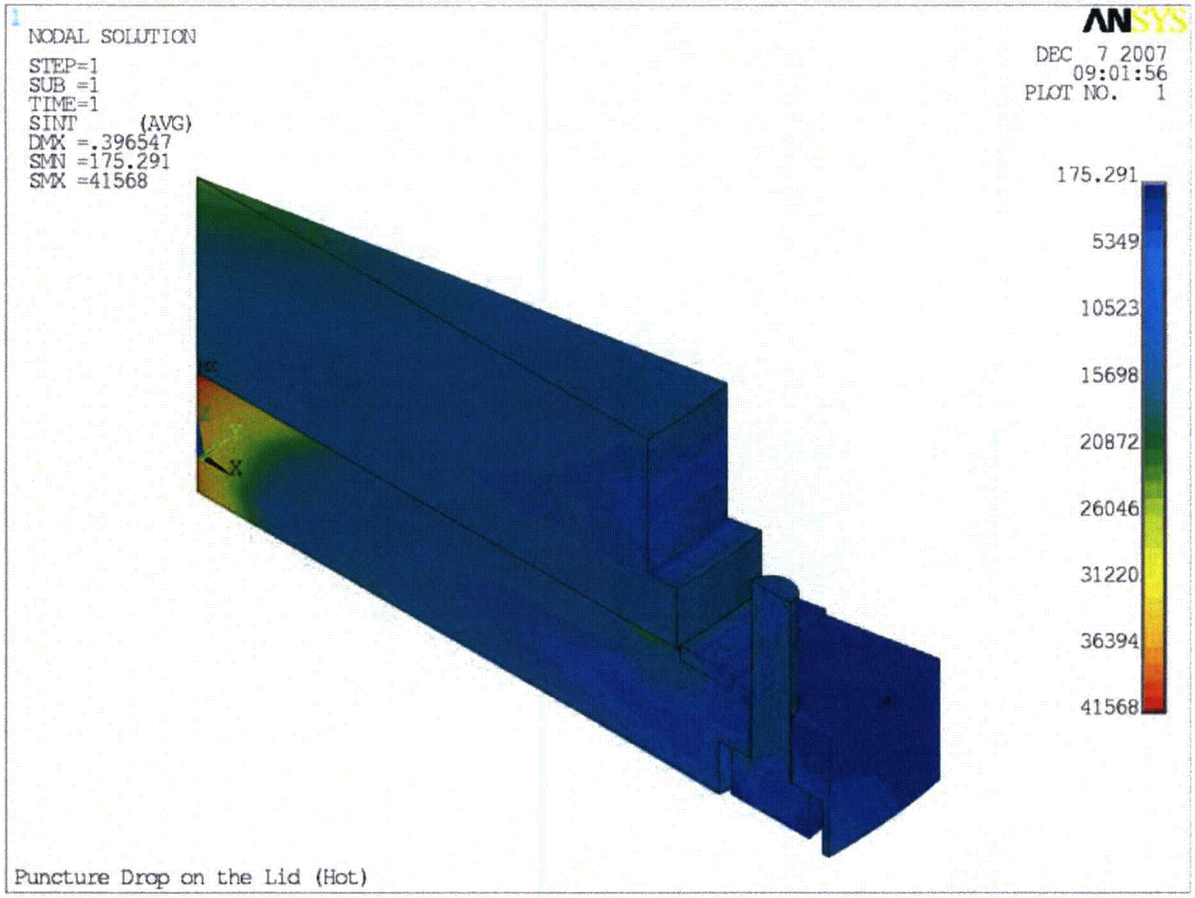


Figure 2-54 - Maximum Stress Intensity in the Lid under Puncture Drop (Hot Conditions)

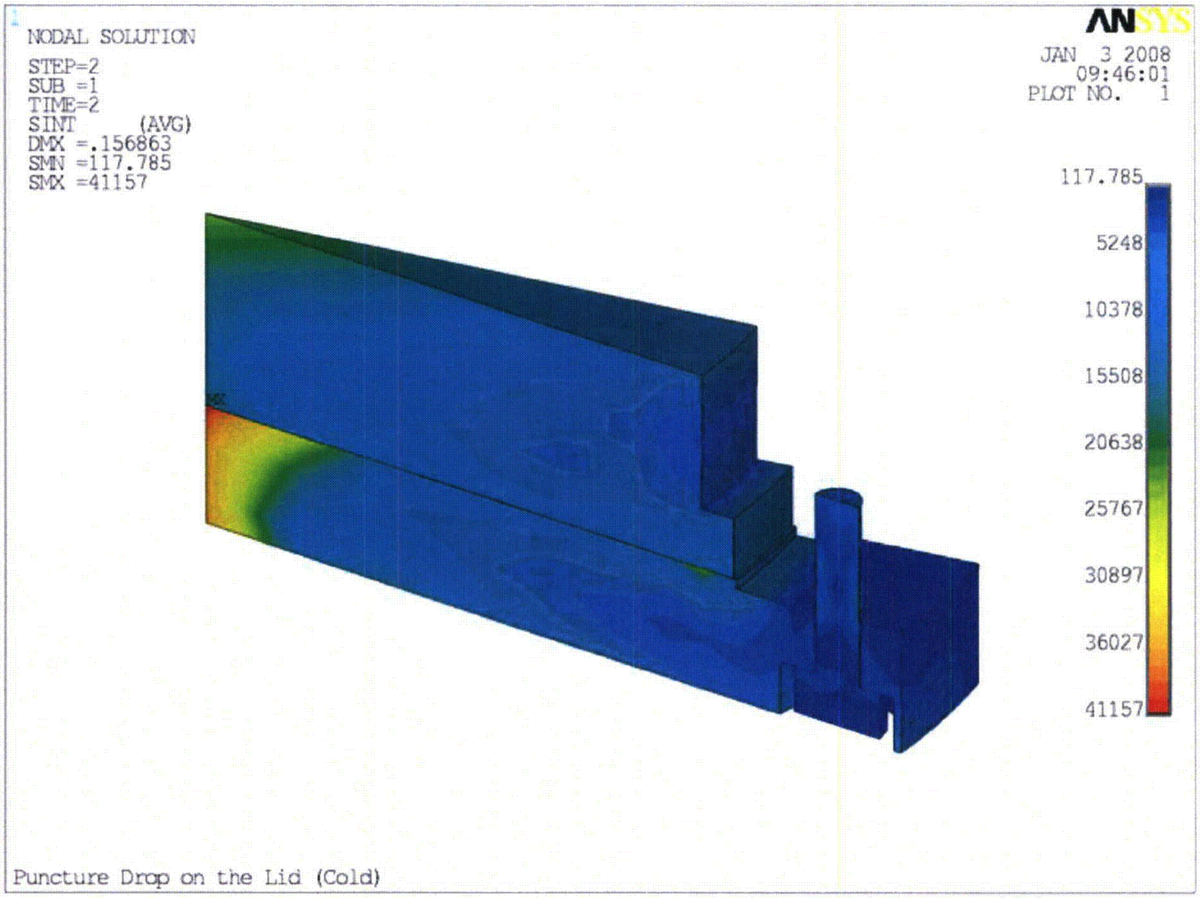


Figure 2-55 - Maximum Stress Intensity in the Lid under Puncture Drop (Cold Conditions)

This page intentionally blank.

3.0 THERMAL EVALUATION

This Section identifies, describes, discusses, and analyzes the principal thermal engineering design of the 3-60B package. Compliance with the performance requirements of 10 CFR 71 [3-1] is demonstrated.

3.1 **Description of thermal design**

Two components contribute to the thermal protection of the cask body. These components are the impact limiters which provide thermal protection to the ends of the cask and the fire shield which protects the side walls between the impact limiters.

3.1.1 Design Features

Figure 3-1 shows the design features of the components contributing to the thermal protection of the cask. These components are identified in the figure with solid red color.

The fire shield is made of 12 gage stainless steel sheet metal. In order to provide an air gap between the cask outer shell and the fire shield, 5/32″ diameter wires are helically wrapped around the cask outer shell. The fire shield is welded to the cask body at the two ends. Cut-outs are provided in the fire shield in order to wrap around the trunnions and the impact limiter attachment lugs.

The impact limiters are sheet metal enclosures filled with polyurethane foam which acts as insulation barrier to heat flow. The impact limiters are attached to the cask body through the arrangement as shown in Figure 3-1. In order to provide air gaps between the cask ends and the impact limiters, 5/32″ diameter wires are welded to the impact limiter inner plate. The impact limiters provide thermal insulation during the NCT events. However, during the HAC fire event it is assumed that the sheet metal enclosing the polyurethane foam would be damaged during the prior HAC drop and puncture tests (see Section 2.7.8). This will reduce the effectiveness of the foam to provide full thermal insulation. The impact limiters are shown to remain attached to the cask after the HAC tests (see Section 2.7.1.6). Consequently, only the metal casings, separated by the air gap, are the only thermal protection assumed during the HAC fire evaluation.

3.1.2 Content's Decay Heat

The maximum decay heat of the contents limited to 500 watts. No limit is placed on the minimum decay heat of the contents.

3.1.3 Summary Tables of Temperatures

The maximum temperatures in various important components of the cask during the NCT events are summarized in Table 3-1. Table 3-2 summarizes the maximum temperature in these components during the HAC fire test. The time at which these components achieve the maximum temperature is also identified in Table 3-2. Table 3-3 provides the temperature in cask cavity and the contents of the cask during NCT and HAC fire test.

The results summarized in Table 3-1 and Table 3-2 are discussed in detail in Sections 3.3 and 3.4.

3.1.4 Summary Table of Maximum Pressures

The summary of maximum pressures during the NCT and HAC fire test are provided in Table 3-4. The details of these pressure calculations are provided in Sections 3.3.2 and 3.4.3 for NCT and HAC fire test, respectively.

3.2 **Material Properties and Component Specifications**

3.2.1 Material Properties

The material properties of the cask components used in the analysis of the 3-60B package are provided in Table 3-5 through Table 3-7. Table 3-5 provides the temperature independent properties of the steel and lead components. Table 3-6 provides the temperature dependent specific heat and thermal conductivity of stainless steel, carbon steel and lead. Table 3-7 provides the temperature dependent density, specific heat and conductivity of air. Material properties have been obtained from standard references ([3-2] through [3-6]) and are identified in Table 3-5 through Table 3-7.

3.2.2 Component Specifications

The metallic components that are important for the thermal performance of the package are made of 304L stainless steel. The non-metallic components are specified as follows:

- The material used for the lid containment O-ring seals, vent port plug containment O-ring seals, drain port plug fastener seal, and test port plug fastener seal must be an elastomer, having a normal service temperature range of -40°F to 250°F and a maximum short-term (1-hour) temperature limit that is ≥350°F.

- Lead is specified to be ASTM B-29 commercial grade. The melting temperature is 622°F.

- Polyurethane foam used in the impact limiters are specified by ES-M-172 [8-1]. All the pertinent thermal properties are included in this specification.

3.3 **Thermal Evaluation for Normal Conditions of Transport**

The thermal analyses of the 3-60B package under various loading conditions have been performed using finite element modeling techniques. ANSYS finite element analysis code [3-7] has been employed to perform the analyses. Since the lid of the cask is attached to the body using 16 bolts, the cask geometry has a cyclic symmetry every 11.25° of the circumference. Therefore, an 11.25° model of the cask is employed. Figure 3-2 shows the finite element model used in various thermal load analyses. Figure 3-3 shows the material property modeling of various components of the cask.

The finite element model is representative of, and applicable to, both cask Configuration A and cask Configuration B. Although the finite element model geometry is specifically based on cask Configuration A, the results obtained from the model are bounding for cask Configuration B. The primary difference between the two configurations, with respect to the finite element model used for the thermal evaluation, is the lid seal ring design. Configuration A incorporates a separate seal ring in the lid assembly, but Configuration B includes a seal ring that is integral to the lid outer plate, as shown on the general arrangement drawing in Section 1.3. Although the finite element model used for the thermal evaluation includes the separate seal ring of Configuration A, complete thermal connectivity is modeled between the seal ring and the lid outer plate. Since no credit is taken for thermal resistance between the seal ring and the lid outer plate, the temperature results for the lid seals are bounding for both cask configurations.

The internal heat load has been modeled in the FEM in two different ways - implicitly and explicitly. In the implicit model the heat load is applied as a uniform flux over the cavity of the cask. This results in a conservative cask body temperature. However, the cavity temperature predicted is not conservative. To get a conservative prediction of the cask cavity temperature, the internal contents of the cask is explicitly modeled. The cask body structural evaluation has been performed with the implicit model results and the cask cavity temperature needed for the calculation of internal pressure has been obtained from the explicit model.

For the NCT conditions the impact limiters are assumed to provide total heat insulation around them. Therefore, only the exposed portion of the fire shield is used for the heat rejection to the ambient.

The details of the analyses, including the assumptions, modeling details, boundary conditions, and input and output data are included in Energy*Solutions* document TH-022 [3-8].

3.3.1 Heat and Cold

The finite element model described in Section 3.3 is analyzed for the following loading conditions:

- Hot Environment – This load case is based on the requirements of 10 CFR 71.71 (c) (1). The loading includes a 100°F ambient temperature, solar insolation, and maximum internal heat load. This loading is used as one of the extreme initial conditions for NCT and HAC test evaluation. The temperature distribution in the cask body under this loading condition is shown in Figure 3-4.
- Cold Environment – This load case is based on the requirements of 10 CFR 71.71 (c) (2). The loading includes a -40°F ambient temperature, no solar insolation, and maximum internal heat load. This loading is used as one of the extreme initial conditions for NCT and HAC test evaluation. The temperature distribution in the cask body under this loading condition is shown in Figure 3-5.
- Normal Hot - This load case is based on the requirements of 10 CFR 71.71 (b). The loading includes a 100°F ambient temperature, no solar insolation, and maximum internal heat load. The temperature distribution in the cask body under this loading condition is shown in Figure 3-6.

- Normal Cold - This load case is based on the requirements of 10 CFR 71.71 (b). The loading includes a -20°F ambient temperature, no solar insolation, and maximum internal heat load. The temperature distribution in the cask body under this loading condition is shown in Figure 3-7.

The thermal analysis shows that under the NCT there is no reduction in packaging effectiveness. The heat transfer capability of the components is not reduced under NCT, nor are there changes in material properties that affect structural performance, containment, or shielding.

3.3.2 Maximum Normal Operating Pressure

Gas Generation

The potential mechanisms of gas generation in the 3-60B cask are: radiolysis, chemical reactions, thermal degradation, and biological activity. The contents of the 3-60B are restricted to solid inorganic materials and explosives, pyrophorics, and corrosives (pH less than 2 or greater than 12.5), are prohibited (see Chapter 1). The restriction of the contents to inorganic materials eliminates the potential for gas generation due to thermal degradation or biological activity. The operating procedures of Chapter 7 require an assurance of chemical compatibility using EPA's Chemical Compatibility Chart, EPA-600/2-80-076 prior to loading. The content restrictions and material compatibility requirements preclude chemical reactions that might produce gases.

The remaining mechanism for gas generation is radiolysis. As noted in [3-9], solid inorganic materials have a G value of zero, i.e., solid inorganic materials do not generate hydrogen or other gases through radiolysis. Solidified or dewatered material may contain some water and if the cask is loaded underwater, a small of amount of water may remain in the cavity after draining. The radiolytic generation of gases is limited to the radiolysis of this residual water. Hydrogen and oxygen may be produced in the cask by radiolytic decomposition of residual water in the cask contents. The amount of hydrogen must be limited to prevent the formation of a flammable mixture. The hydrogen concentration can be limited to 5% by limiting the decay heat for contents that include water.

The hydrogen and oxygen generation rate is determined using the methodology developed by DOE for evaluation of TRU wastes [3-9] with a number of additional assumptions. The radioactive constituents may include byproduct, source, or SNM. These radionuclides may produce alpha, beta, and/or gamma radiation. In the 3-60B gas generation methodology, only the bounding G-value for water is used in the calculation of hydrogen generation. The bounding G value, 1.6 molecules per 100 eV absorbed, is independent of radiation type. Since the 3-60B will primarily transport gamma or mixed sources that are predominately gamma, use of the bounding G value is very conservative (the G value for gamma is ~0.4). Also, the total decay energy is conservatively assumed to be absorbed by the contents, i.e., all gamma and beta decay energy is assumed to be absorbed by the contents. Thus, the type of radiation does not affect the calculated amount of hydrogen generated.

The 3-60B gas generation methodology is not specific to a particular material type. Since all the decay energy is assumed to be absorbed and the radiation invariant bounding G value is used, the

gas generation rate is unchanged for all the allowed content forms, e.g., powdered solids, solidified material, resins, or activated components.

The 3-60B gas generation methodology calculates the amount of decay energy expressed as decay heat that will result in a hydrogen concentration of 5%. This amount of energy is defined as the decay heat limit and depends on only two variables, 1) the amount of water expressed as a fraction of the mass of the contents, and 2) the size of the void in which hydrogen may collect, expressed as a fraction of the volume of the cask cavity. The method for determining the decay heat limit is given below.

The gas generation rate, n_g (moles/sec), is determined by:

$n_g = W \times \sum_i(F_i \times G_i) \times C$ (see [3-9] page 2.1-6) .... Eq. 3.1

where,

W = the total decay heat (watts)

F_i = fraction of energy emitted of type i and absorbed by the material

G_i = number of gas molecules generated per 100 ev of ionizing radiation absorbed by the contents (potential gas producing material)

C = conversion factor based on units of measurement

The effective G value is determined from the following equation : see [3-9], page 2.2-3

$G_{eff} = \sum_i(F_i \times G_i) \times F_p$ .... Eq. 3.2

where,

F_i = weight fraction of material I in the contents

Gi = bounding G value for material i

Fp = fraction of energy emitted by the radioactive materials absorbed by the waste

As discussed in Appendix 2.5 of [3-9], the effective G value can be substituted into Eq. 1 resulting in:

$n_g = W \times G_{eff} \times C$ .... Eq. 3.3

where,

W = the total decay heat (watts)

G_{eff} = the effective G value for the contents in number of gas molecules generated per 100 ev of ionizing radiation absorbed by the contents (potential gas producing material)

C = conversion factor based on units of measurement.

For the units used for G, C = 1.04E-7 (g-mole)(100 eV) / (molecule)(W-s)

Hydrogen Concentration:

The hydrogen concentration, C_H, in liters of hydrogen per liters of void, at the end of the shipping period is determined by the following:

$C_H = n_g \times T \times cf \times V_{void}^{-1}$ .... Eq. 3.4

where,

n_g = gas generation rate, in moles/sec

T = time since the cask was sealed, which equals the shipping period, in seconds

cf = conversion factor; 22.4 liter/mole at STP

V_{void}= void volume in which gas can accumulate, in liters

Combining equations 3.3 & 3.4 gives:

$C_H = W \times \sum_i(F_i \times G_i) \times F_p \times C \times T \times cf \times V_{void}^{-1}$ .... Eq. 3.5

Rearranging gives:

$W = C_H \times V_{void} / (\sum_i(F_i \times G_i) \times F_p \times C \times T \times cf)$ .... Eq. 3.6

Assumptions:

C_H = 5% by volume; regulatory limit

F_p = 1; conservatively assumes all the decay energy is absorbed by the waste.

i = water; the cask contents are limited to inorganic materials, typically metal, that are usually loaded underwater; recognizing that draining the cask and dewatering the contents (as applicable) will leave some water, hydrogen can be generated by radiolysis from this residual water

G_{H2O}= bounding G value for water; 1.6 molecules/100 eV ; includes all types of radiation; see [3-9]

F_{H2O}= weight fraction of water in the contents

T = 60 days = 5.184E+6 seconds; see Attachment 3A to Chapter 3

F_V = void fraction, which is defined as the smallest void volume in which hydrogen could collect (Vvoid) divided by the cask cavity volume (V_{cavity});

F_V = V_{void} / V_{cavity}, thus,

V_{void}= $F_V \times V_{cavity}$

V_{cavity} = volume of the cask cavity; = 1724 liters (from cask dimensions)

C = 1.04E-7 (g-mole)(100 eV) / (molecule)(W-s); as previously defined

cf = conversion factor; 22.4 l/mole at STP; as previously defined

Substituting the above into Eq. 3.6 gives:

$W = 0.05 \times F_V \times 1724 / (F_{H2O} \times 1.6 \times 1 \times 1.04E\text{-}7 \times 5.184E\text{+}6 \times 22.4)$ Eq.3.7

thus,

$W = 4.46 \times F_V / F_{H2O}$ watts Eq.3.8

With the decay heat limited to W, the flammable gas (hydrogen) concentration is limited to less than 5%. The requirement for determining a decay heat limit and the calculational process are included in the operating procedures of Chapter 7 along with several examples of the calculation of the maximum decay heat for various contents and configurations.

Cask Internal Pressure

The maximum internal pressure of the cask is calculated assuming that the gas within the cask, a mixture of air, water vapor, oxygen, and hydrogen, behaves as an ideal gas. To determine the maximum internal pressure under NCT in the cask (MNOP) the temperature of the gas mixture within the cask was evaluated. The maximum pressure is the sum of three components: 1) the pressure due to addition of gas due to radiolysis, 2) the pressure due to the increased temperature of the gas in the cavity (the maximum temperature under NCT is 227.3°F, see Table 3-3), and 3) the pressure due to water in the cask (vapor pressure of water).

1. The cask on loading has an internal pressure equal to ambient, assumed to be 14.7 psi at 70°F. Radiolysis will produce hydrogen and oxygen that will add to the pressure in the cavity. By limiting the amount of water and decay heat as discussed above, the maximum amount (in volume percent) of gases produced by radiolysis of water (based on the decay heat, the effective G value and a 60-day shipping period) will be 5% hydrogen and, correspondingly, 2.5% for oxygen. The addition of hydrogen and oxygen to the sealed cask cavity result in an increased cask pressure (at 70°F) of:

   $P_1 = 14.7 + (14.7 \times (5\%+2.5\%)) = 15.8$ psi

2. The pressure in the cask, at 70°F (T_1), which includes the additional pressure from the radiolytic generation of hydrogen and oxygen, is 15.8 psi, as shown above. The pressure in the cask at 227.3°F (T_2, the maximum temperature under NCT), P_2, may be calculated by the ideal gas relationship:

$P_2 = \frac{T_2}{T_1} \times P_1$, where T is in degrees absolute

$P_2 = 20.5$ psi

3. Since the cask cavity is assumed to also contain water, the vapor pressure of water must be added to the pressure in the cavity. The vapor pressure contributed by water in the cavity at 227.3°F (108.65°C) is 19.8 psia (interpolated from the table Vapor Pressure of Water from 0 to 370°C , page 6-15, from [3-4], a copy of the table is attached as Attachment 3B).

Therefore, the calculated maximum normal operating pressure (in gage pressure) is,

MNOP = 20.5 + 19.8 – 14.7 = 25.6 psig

The value used for MNOP is conservatively set at 35.0 psig.

3.3.3 Thermal Stresses

The structural evaluation of the package under NCT loading is performed in Section 2.6.1 of this SAR. All the stresses are within the design allowable values established for 3-60B package.

3.4 **Hypothetical Accident Thermal Evaluation**

The thermal analyses of the 3-60B package under HAC fire conditions have been performed using finite element model, described in Section 3.3. A nonlinear thermal transient analysis is performed to obtain the time-history of the temperature in package.

Similar to the NCT analyses, the HAC fire analyses have performed with two different ways, by implicitly and explicitly modeling the internal heat loading. The results from the implicit heat modeling have been used for performing the structural evaluation of the 3-60B Cask under HAC fire. The maximum temperature of the cavity predicted by the explicit heat modeling during the entire transient has been used for calculating the cask pressure during the HAC fire.

For the HAC fire the foam of the impact limiters is conservatively assumed not to provide any thermal insulation. In the structural analyses of the HAC drop and puncture drop conditions, it has been shown that after these tests, the casing of the impact limiter will be intact and remain attached to the cask body. Therefore, it is assumed that the fire directly hits the two ends of the cask through the ½-inch thick plate that form the casing of the impact limiters, in addition to the entire length of the fire-shield.

Analyses have also been performed to evaluate the conditions in which the fire-shield is damaged during the puncture drop test. The fire is assumed to hit the area directly where the puncture bar damages the fire shield. It has been shown that under these conditions the cask experiences locally high temperatures but they are within the acceptable limit for the materials. See [3-10] for the details of this analysis.

The details of the analyses, including the assumptions, modeling details, boundary conditions, and input and output data are included in Energy*Solutions* document TH-023 [3-10].

3.4.1 Initial Conditions

The initial temperature condition, used for the HAC fire test analysis is obtained by running the finite element model with the following boundary conditions:

- Internal heat load – 500 W
- Solar insolation - no
- Heat Transfer to the ambient by radiation – yes
- Heat transfer to the ambient by natural convection – yes
- Ambient air temperature - 100°F

3.4.2 Fire Test Conditions

The fire transient is run with the body temperature resulting from the above initial conditions. The fire transient is run for 30 minutes (1,800 sec) with the following boundary conditions:

- Internal heat load – 500 W
- Solar insolation - no
- Heat Transfer to the ambient by radiation – yes
- Heat transfer to the ambient by forced convection – yes
- Ambient air temperature - 1475°F

The end of fire analysis of the model is performed with the body temperature resulting from the above fire transient to 1801 sec with the following boundary conditions:

- Internal heat load – 500 W
- Solar insolation - no
- Heat Transfer to the ambient by radiation – yes
- Heat transfer to the ambient by natural convection – yes
- Ambient air temperature - 100°F

The cool-down analysis of the model is performed with the body temperature resulting from the above fire transient to 14,000 sec with the following boundary conditions:

- Internal heat load – 500 W

- Solar insolation - yes
- Heat Transfer to the ambient by radiation – yes
- Heat transfer to the ambient by natural convection – yes
- Ambient air temperature - 100°F

Figure 3-8 shows the boundary conditions used during the fire transient analysis.

3.4.3 Maximum Temperatures and Pressure

From the analyses of the finite element model, a time-history data of the temperature in various components of the cask is obtained. The fire shield, outer shell, inner shell, lead, and seal were considered as the critical components of the cask. The temperatures at representative locations in these components are monitored during the entire fire and cool down transient analysis. The nodes that are monitored at these critical components are shown in Figure 3-9.

Figure 3-10 gives the plot of the time-history data at the representative nodes of the cask components. Figure 3-11 gives the same data in cask components that are not directly exposed to the fire. The maximum temperature of various components of the cask during the entire transient analysis is presented in Table 3-2. The temperature profile in the cask during the cool-down period is shown in Figure 3-12.

The maximum internal pressure of the cask is calculated assuming that the gas within the cask, a mixture of air, water vapor, oxygen, and hydrogen, behaves as an ideal gas.

The temperature of the gas mixture within the cask is evaluated (see Table 3-3). The average gas temperature in the cask under HAC is conservatively set at 320°F. Assuming 15.8 psia (see Section 3.3.2) exists inside the cask at 70°F, the pressure in the cask at 320°F, P_2, may be calculated by the ideal gas relationship:

$$P_2 = \frac{T_2}{T_1} \cdot P_1 \text{, where T is in degrees absolute}$$

$$P_2 = 23.26 \text{ psia}$$

The vapor pressure contributed by water in the cavity at 320°F is 89.71 psia [3-4].

Therefore, the maximum pressure during the HAC fire,

$$P_{max} = 23.26 + 89.71 - 14.7 = 98.27 \text{ psig}$$

The value used for P_{max} is conservatively set at 100 psig.

3.4.4 Maximum Thermal Stresses

The structural evaluation of the package under the HAC fire test conditions is performed in Section 2.7.4 of this SAR. The maximum thermal stresses in the package with the corresponding allowable stresses are compared in Table 2-23. All the stresses are within the design limits established for the 3-60B package.

3.4.5 Accident Conditions for Fissile Packages for Air Transport

Not applicable.

3.5 Appendix

3.5.1 References

[3-1] Code of Federal Regulations, Title 10, Part 71, Packaging and Transportation of Radioactive Material, January 2007.

[3-2] Heat Transfer, J.P. Holman, McGraw Hill Book Company, New York, Fifth Edition, 1981.

[3-3] Cask Designers Guide, L.B. Shappert, et. al, Oak Ridge National Laboratory, February 1970, ORNL-NSIC-68.

[3-4] CRC Handbook of Chemistry and Physics, Robert C. Weast and Melvin J. Astel, eds., CRC Press, Inc., Boca Raton, Florida, 62nd ed., 1981.

[3-5] ASME Boiler & Pressure Vessel Code, 2001, Section II, Part D, Materials, The American Society of Mechanical Engineers, New York, NY, 2005.

[3-6] Rohsenow and Hartnett, Handbook of Heat Transfer, McGraw Hill Publication, 1973.

[3-7] ANSYS, Rev. 11.0, Computer Software, ANSYS Inc., Canonsburg, PA, 2007.

[3-8] Energy*Solutions* Document No. TH-022, Rev.1, Steady State Thermal Analyses of the 3-60B Cask Using a 3-D Finite Element Model.

[3-9] RH TRU Payload Appendices Rev. 0, June 2006 U.S. Department of Energy.

[3-10] Energy*Solutions* Document No. TH-023, Rev.3, Hypothetical Fire Accident Thermal Analyses of the 3-60B Cask.

3.5.2 Attachments

Attachment 3A
SHIPPING PERIOD

1.0 INTRODUCTION

This Attachment presents the basis for the shipping period for 3-60B shipments from the time of cask closure until cask opening. This shipping period is used in the analysis of the gas generation in the 3-60B cask.

The 3-60B cask is expected to be used to ship high-activity waste from nuclear power plant sites to a disposal site on a rental basis. Given the daily rental rate, there is a large financial incentive for the cask user to minimize the shipping time.

2.0 EXPECTED SHIPPING PERIOD

The expected shipping period is the amount of time from the sealing of the cask at the loading facility until the opening of the cask at the unloading facility. It consists of: the time from cask sealing to the release of the transport unit from the loading facility, the expected transit time, and the time from arrival at the unloading facility until the cask is opened. For assessing the expected shipping period, it will be assumed that there are no delays.

2.1 Loading

The loading process from cask sealing to unit release includes health physics surveys, installing the impact limiters, and vehicle inspections. The time from cask sealing until the unit is released for travel is expected to be accomplished in less than two days. A full two day (48 hour) duration will be assumed.

2.2 Transit

Access to disposal sites for this type of waste is currently uncertain. A conservatively long but possible route is from the Turkey Point Plant in Florida to the Hanford, Washington disposal site, approximately 3200 miles. Assuming an average speed of 45 mph, which includes time for vehicle inspections, fueling, meals, and driver relief, the duration of a 2800 mile trip is expected to be 71 hours. Again, to be conservative, the transit duration will be assumed to be three days (72 hours).

2.3 Unloading

The unloading process includes receipt survey, positioning of the trailer in the waste unloading area, and removal of the lid. This process should be accomplished in less than eight (8) hours. Again, to be conservative, the unloading duration will be assumed to be one day (24 hours).

2.4 Total

The total expected shipping period, with no delays, is less than 75 hours. For the purpose of this analysis, a conservative period of 5 days (120 hours) will be assumed.

3.0 SHIPPING DELAYS

The maximum shipping time will be assumed to be the sum of the expected shipping time and the time for delays which could extend the shipping time. These delays are: loading delays; transit delays due to weather or road closures, shipping vehicle accidents, mechanical delays, or driver illness; and unloading delays. Each of these delays are assessed below.

3.1 Loading Delays

There are a number of situations that could extend the time between cask sealing and truck release. These include: loading preceding a holiday weekend, problems with a leak test, and handling equipment failure. Both the leak test problem and the handling equipment failure should be resolvable by replacing or obtaining temporary equipment. Each of these situations is unlikely to cause more than a two day delay. The holiday weekend could cause a delay of three days, i.e., from Friday afternoon until Tuesday. It is very unlikely that more than two of the three loading delays could occur on the same shipment, so a total of five days seems a reasonably conservative assessment for a loading delay.

3.2 Transit Delays

Transit delays due to weather, e.g., a road closed due to snow, are unlikely to cause a delay of more than five days. A road closure due to a vehicle accident or a roadway or bridge failure would result in re-routing which could add up to two days to the transit time. A transit time delay due to weather or road closure will be assumed to be five days.

Transit delays due to an accident with the truck could cause a lengthy delay. Response time for notification and to take immediate corrective action is assumed to be one day. Accident mitigation may require transferring the cask to a different trailer using cranes and other heavy equipment. Mitigation is assumed to take five days for a total accident delay of six days.

Mechanical problems with the truck or trailer could also cause multi-day delays. Significant failures may require a replacement tractor or trailer. An appropriate response to a mechanical failure is assumed to take four days.

Driver illness could also cause transit delays. If a driver it too ill to continue, a replacement driver will be brought in. A two day delay is assessed for bringing in a replacement driver.

3.3 Unloading Delay

An unloading delay will occur if the truck arrives just before a holiday weekend. This could result in a four day delay. Additionally, a delay due to unloading equipment failure could occur. Repair of such equipment should not require more than four days. The unloading delay will be conservatively assumed to be five days. If an unanticipated situation occurs that would result in a much longer delay, the cask can be vented.

3.4 Total Delay

The total delay, i.e., the sum of the delay times for each of the delay types, is 27 days. This assumes that each type of delay occurs on the same shipment.

4.0 Maximum Shipping Period

The maximum shipping period, as the sum of the expected shipping period and the total delay, is 32 days. This period assumes that each of the possible shipping delays occurs on the same shipment, a very unlikely occurrence. For additional conservatism, the assumed maximum will be set at 60 days. Thus, a 60 day shipping period will be used in analysis of gas generation in the sealed cask.

Attachment 3B

Vapor Pressure of Water

VAPOR PRESSURE OF WATER FROM 0 TO 370° C

This table gives the vapor pressure of water at intervals of 1° C from the melting point to the critical point.

T/°C	P/kPa	T/°C	P/kPa	T/°C	P/kPa	T/°C	P/kPa
0	0.61129	55	15.752	110	143.24	165	700.29
1	0.65716	56	16.522	111	148.12	166	717.83
2	0.70605	57	17.324	112	153.13	167	735.70
3	0.75813	58	18.159	113	158.29	168	753.94
4	0.81359	59	19.028	114	163.58	169	772.52
5	0.87260	60	19.932	115	169.02	170	791.47
6	0.93537	61	20.873	116	174.61	171	810.78
7	1.0021	62	21.851	117	180.34	172	830.47
8	1.0730	63	22.868	118	186.23	173	850.53
9	1.1482	64	23.925	119	192.28	174	870.98
10	1.2281	65	25.022	120	198.48	175	891.80
11	1.3129	66	26.163	121	204.85	176	913.03
12	1.4027	67	27.347	122	211.38	177	934.64
13	1.4979	68	28.576	123	218.09	178	956.66
14	1.5988	69	29.852	124	224.96	179	979.09
15	1.7056	70	31.176	125	232.01	180	1001.9
16	1.8185	71	32.549	126	239.24	181	1025.2
17	1.9380	72	33.972	127	246.66	182	1048.9
18	2.0644	73	35.448	128	254.25	183	1073.0
19	2.1978	74	36.978	129	262.04	184	1097.5
20	2.3388	75	38.563	130	270.02	185	1122.5
21	2.4877	76	40.205	131	278.20	186	1147.9
22	2.6447	77	41.905	132	286.57	187	1173.8
23	2.8104	78	43.665	133	295.15	188	1200.1
24	2.9850	79	45.487	134	303.93	189	1226.9
25	3.1690	80	47.373	135	312.93	190	1254.2
26	3.3629	81	49.324	136	322.14	191	1281.9
27	3.5670	82	51.342	137	331.57	192	1310.1
28	3.7818	83	53.428	138	341.22	193	1338.8
29	4.0078	84	55.585	139	351.09	194	1368.0
30	4.2455	85	57.815	140	361.19	195	1397.6
31	4.4953	86	60.119	141	371.53	196	1427.8
32	4.7578	87	62.499	142	382.11	197	1458.5
33	5.0335	88	64.958	143	392.92	198	1489.7
34	5.3229	89	67.496	144	403.98	199	1521.4
35	5.6267	90	70.117	145	415.29	200	1553.6
36	5.9453	91	72.823	146	426.85	201	1586.4
37	6.2795	92	75.614	147	438.67	202	1619.7
38	6.6298	93	78.494	148	450.75	203	1653.6
39	6.9969	94	81.465	149	463.10	204	1688.0
40	7.3814	95	84.529	150	475.72	205	1722.9
41	7.7840	96	87.688	151	488.61	206	1758.4
42	8.2054	97	90.945	152	501.78	207	1794.5
43	8.6463	98	94.301	153	515.23	208	1831.1
44	9.1075	99	97.759	154	528.96	209	1868.4
45	9.5898	100	101.32	155	542.99	210	1906.2
46	10.094	101	104.99	156	557.32	211	1944.6
47	10.620	102	108.77	157	571.94	212	1983.6
48	11.171	103	112.66	158	586.87	213	2023.2
49	11.745	104	116.67	159	602.11	214	2063.4
50	12.344	105	120.79	160	617.66	215	2104.2
51	12.970	106	125.03	161	633.53	216	
52	13.623	107	129.39	162	649.73	217	
53	14.303	108	133.88	163	666.25	218	
54	15.012	109	138.50	164	683.10	219	

6-15

Table 3-1 - Summary of Maximum NCT Temperatures

Component	Maximum Calculated Temp.		Maximum Allowable Temperature (°F)
	Location (Node Nos.)	Value (°F)	
Fire Shield	2268	177.7	185[1]
Outer Shell	2028	177.6	[2]
Inner Shell	1800	177.8	[2]
Lead	2718	178.9	622
Seals	249	178.6	250

NOTES:

(1) Based on the requirements of 10CFR71.45(g).

(2) Set by stress conditions.

Table 3-2 - Summary of Maximum HAC Fire Temperatures

Component	Maximum Calculated Temp.			Maximum Allowable Temperature (°F)
	Location (Node Nos.)	Time (Sec.)	Value (°F)	
Fire Shield	3600	1,800	1331	N.A
Outer Shell	1897	1,806	353.5	800
Inner Shell	1790	3,984	284.1	800
Lead	2366	2,051	301.6	622
Seals	288	4,838	295.7	350

Table 3-3 - Summary of Cask Cavity Temperatures during NCT and HAC Fire Test

Quantity	NCT (°F)	HAC (°F)
Maximum Cavity Temperature	227.3	329.3
Maximum Average Cavity Temperature	186.0	273.2
Maximum Waste Container Temperature	227.5	294.0

Table 3-4 - Summary of Maximum Pressures during NCT and HAC Fire Test

Condition	Maximum Pressure (psig)	Reference
NCT	35.0	Section 3.3.2
HAC Fire Test	100.0	Section 3.4.3

Table 3-5 - Temperature-Independent Metal Thermal Properties

Material	Property	Reference: Page	Value
Steel	Density	3-2: 536	0.2824 lb/in^3
	ε (Outside)	3-1: 648	0.8
	ε (Inside)	3-3:133	0.15
Lead	Density	3-2: 535	0.4109 lb/in^3
	Spec. Heat	3-2: 535	0.0311 Btu/lb-°F
	Melting Point	3-4: B-29	621.5 °F

Table 3-6 - Temperature-Dependent Metal Thermal Properties

Temp. (°F)	Stainless Steel [3-5]		Carbon Steel [3-5]		Lead [3-6]
	Sp. Heat Btu/lb-°F	Conductivity $\times 10^{-3}$ Btu/sec-in-°F	Sp. Heat Btu/lb-°F	Conductivity $\times 10^{-3}$ Btu/sec-in-°F	Conductivity $\times 10^{-3}$ Btu/sec-in-°F
70	0.117	0.199	0.104	0.813	0.465
100	0.117	0.201	0.106	0.803	0.461
150	0.120	0.208	0.109	0.789	0.455
200	0.122	0.215	0.113	0.778	0.448
250	0.125	0.222	0.115	0.762	0.441
300	0.126	0.227	0.118	0.748	0.435
350	0.128	0.234	0.122	0.731	0.428
400	0.129	0.241	0.124	0.715	0.422
450	0.130	0.245	0.126	0.701	0.415
500	0.131	0.252	0.128	0.683	0.409
550	0.132	0.257	0.131	0.667	0.402
600	0.133	0.262	0.133	0.648	0.395
650	0.134	0.269	0.135	0.632	0.389
700	0.135	0.273	0.139	0.616	0.389
750	0.136	0.278	0.142	0.600	0.389
800	0.136	0.282	0.146	0.583	0.389
900	0.138	0.294	0.154	0.551	0.389
1,000	0.139	0.306	0.163	0.519	0.389
1,100	0.141	0.315	0.172	0.484	0.389
1,200	0.141	0.324	0.184	0.451	0.389
1,300	0.143	0.336	0.205	0.417	0.389
1,400	0.144	0.345	0.411	0.380	0.389
1,500	0.145	0.354	0.199	0.363	0.389

Table 3-7 - Temperature-Dependent Air Thermal Properties

Temp. (°F)	Air [3-2]		
	Density $\times 10^{-5}$ lb/in^3	Sp. Heat Btu/lb-°F	Conductivity $\times 10^{-7}$ Btu/sec-in-°F
70	4.3507	0.2402	3.4491
100	4.1117	0.2404	3.5787
150	3.7517	0.2408	3.9028
200	3.4676	0.2414	4.1759
250	3.2361	0.2421	4.4468
300	3.0307	0.2429	4.7037
350	2.8310	0.2438	4.9560
400	2.6730	0.2450	5.2037
450	2.5220	0.2461	5.4491
500	2.3964	0.2474	5.6875
550	2.2778	0.2490	5.9213
600	2.1684	0.2511	6.1435
650	2.0706	0.2527	6.3634
700	1.9803	0.2538	6.5810
750	1.8981	0.2552	6.7894
800	1.8177	0.2568	6.9954
900	1.6898	0.2596	7.4097
1,000	1.5712	0.2628	7.8032
1,100	1.4722	0.2659	8.1759
1,200	1.3848	0.2689	8.5440
1,300	1.3044	0.2717	8.8981
1,400	1.2350	0.2742	9.2847
1,500	1.1707	0.2766	9.7060

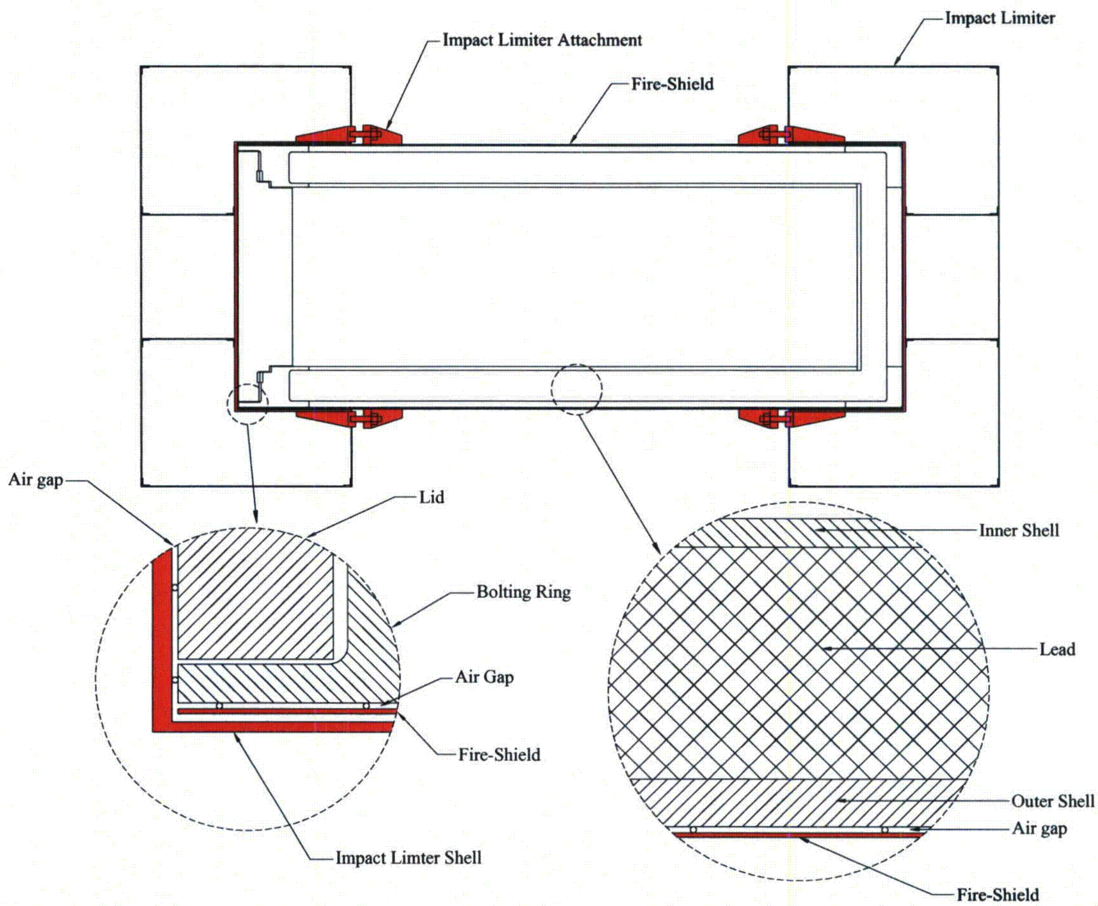


Figure 3-1 - 3-60B Cask Design Features Important to Thermal Performance

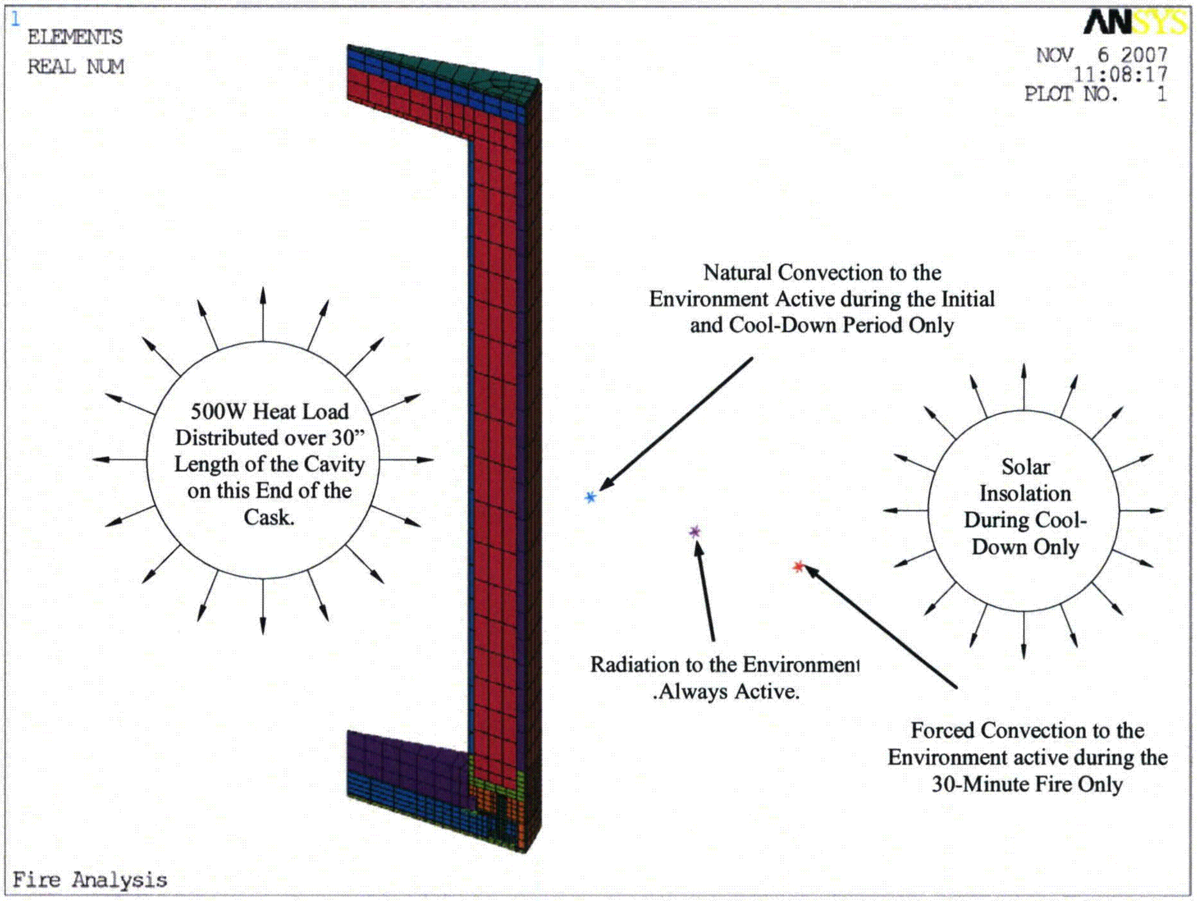


Figure 3-2 - Finite Element Model of the 3-60B Cask Used for the Thermal Analyses

(Please Refer to [3-8] & [3-10] for Detailed Model Description and Figures)

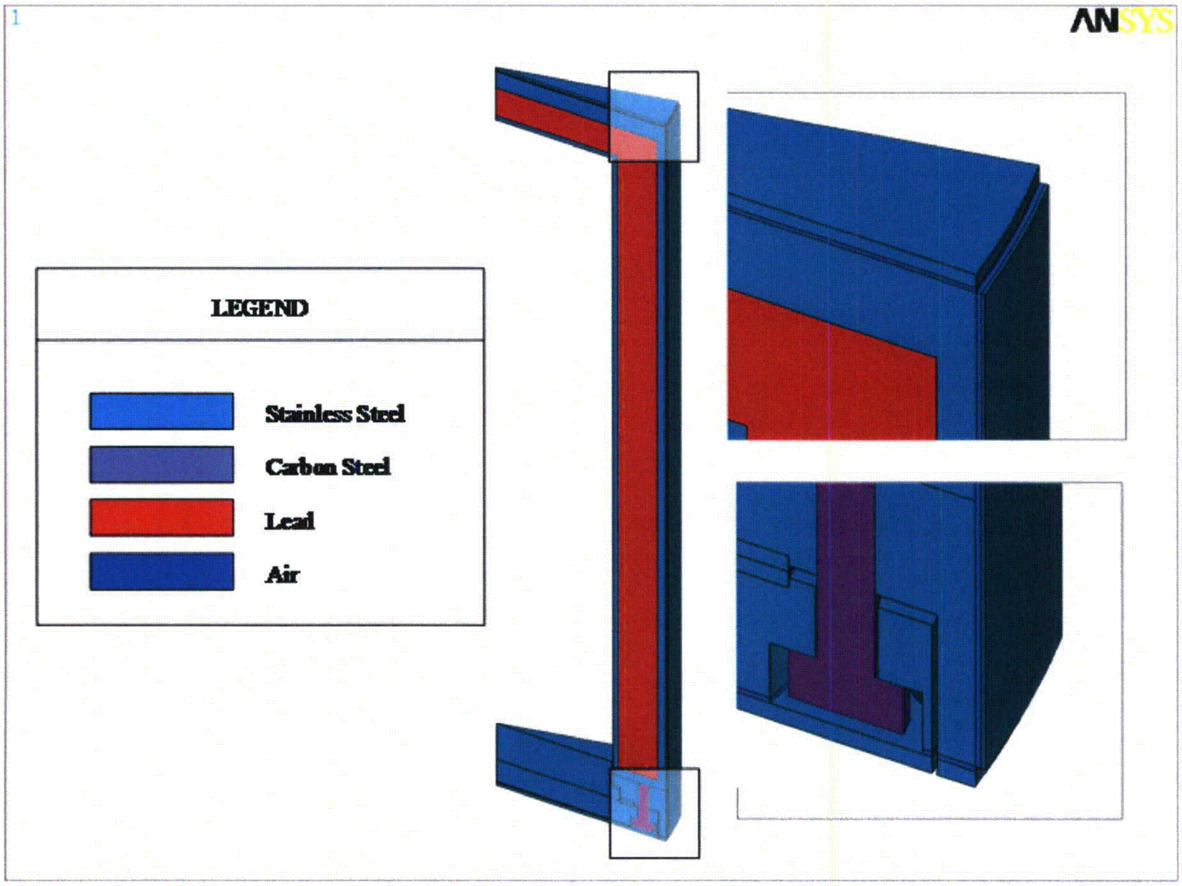


Figure 3-3 - Materials Used in the Finite Element Model

Figure 3-4 - Temperature Distribution – Hot Environment

Figure 3-5 - Temperature Distribution – Cold Environment

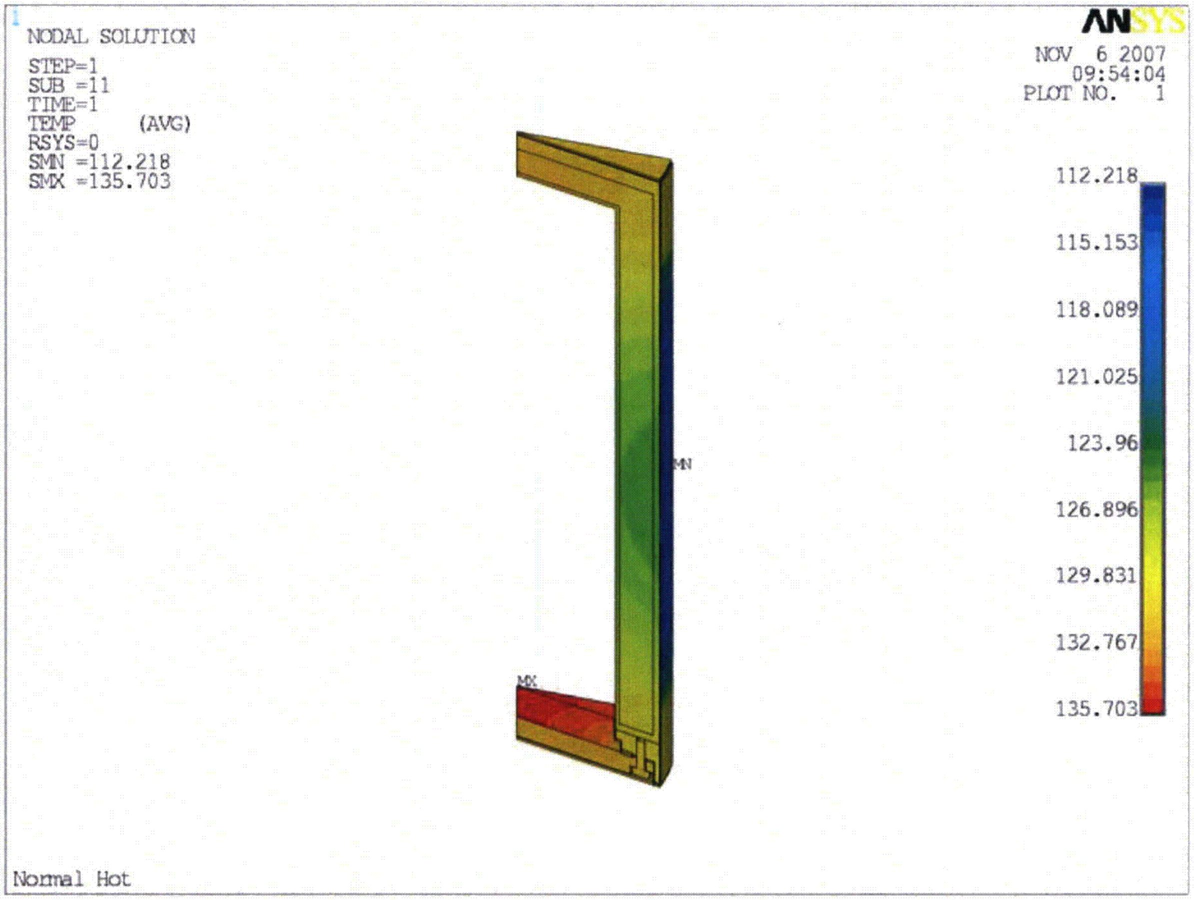


Figure 3-6 - Temperature Distribution – Normal Hot

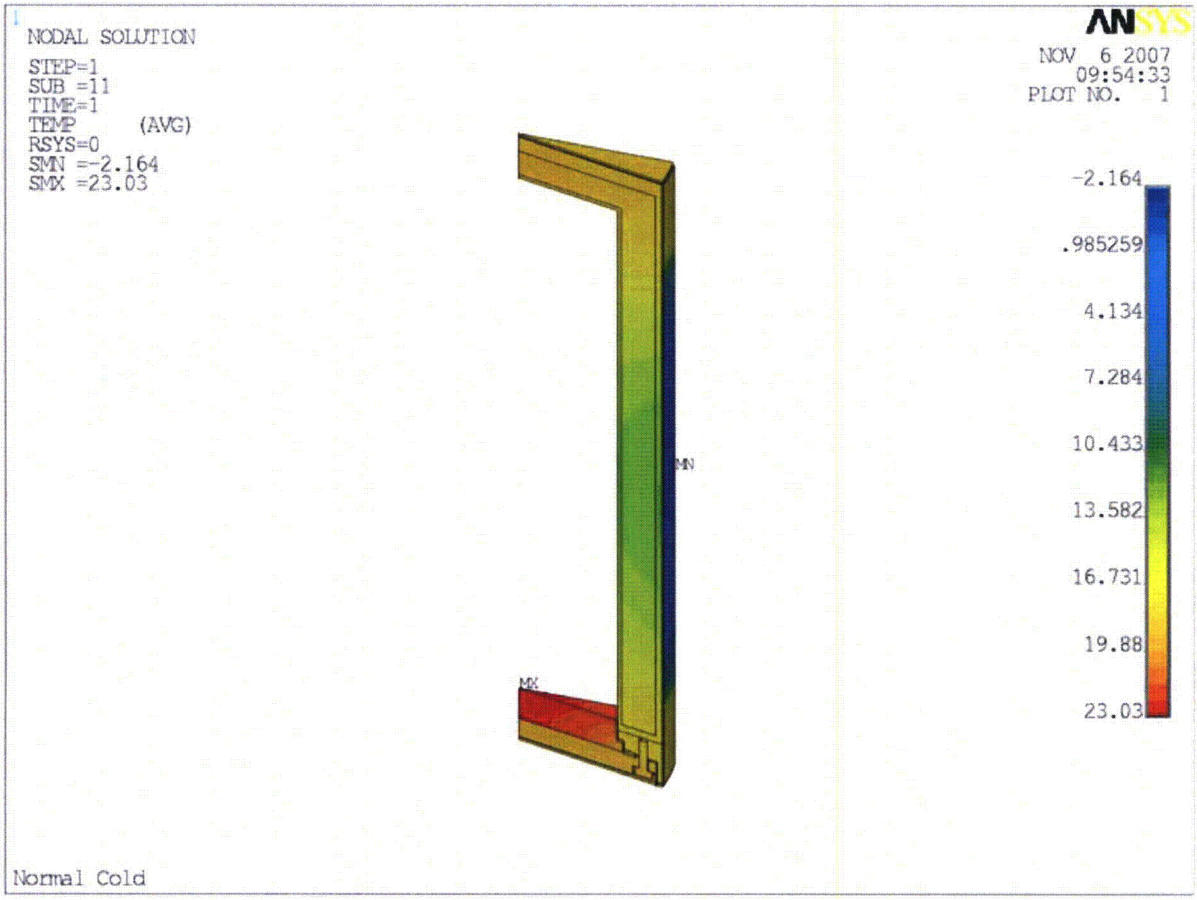


Figure 3-7 - Temperature Distribution – Normal Cold

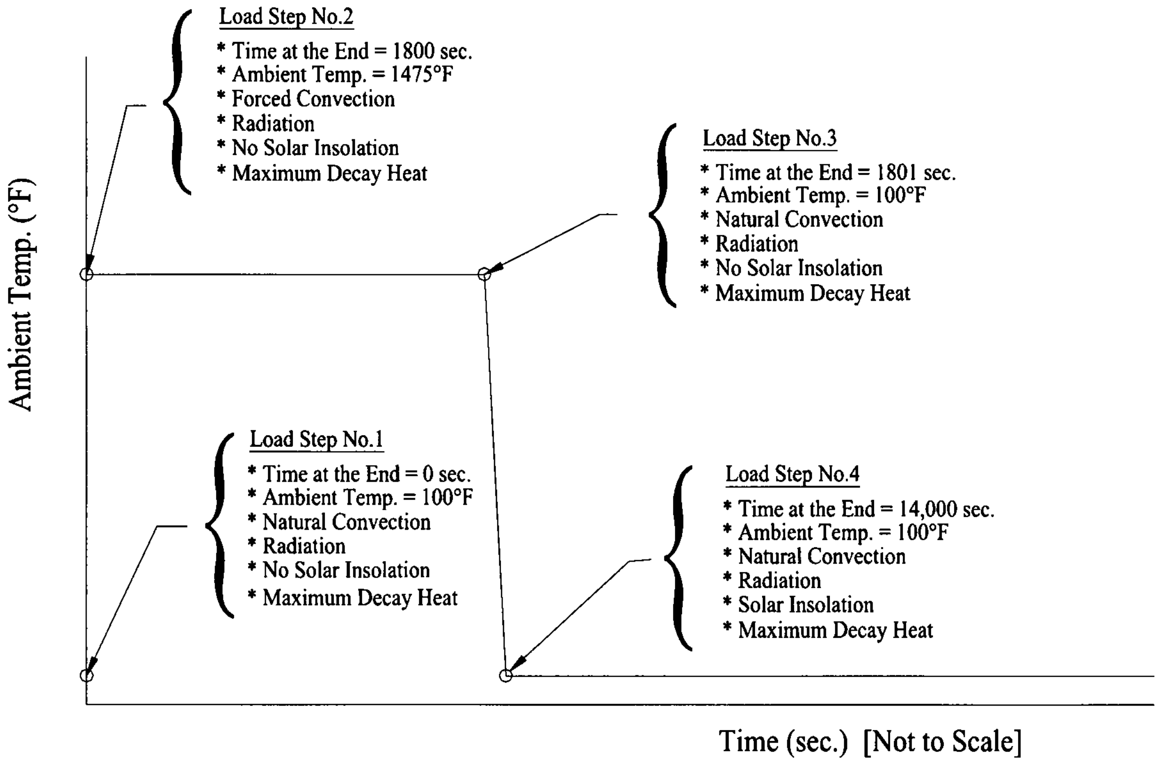


Figure 3-8 - HAC Fire Analysis Load Steps and Boundary Conditions

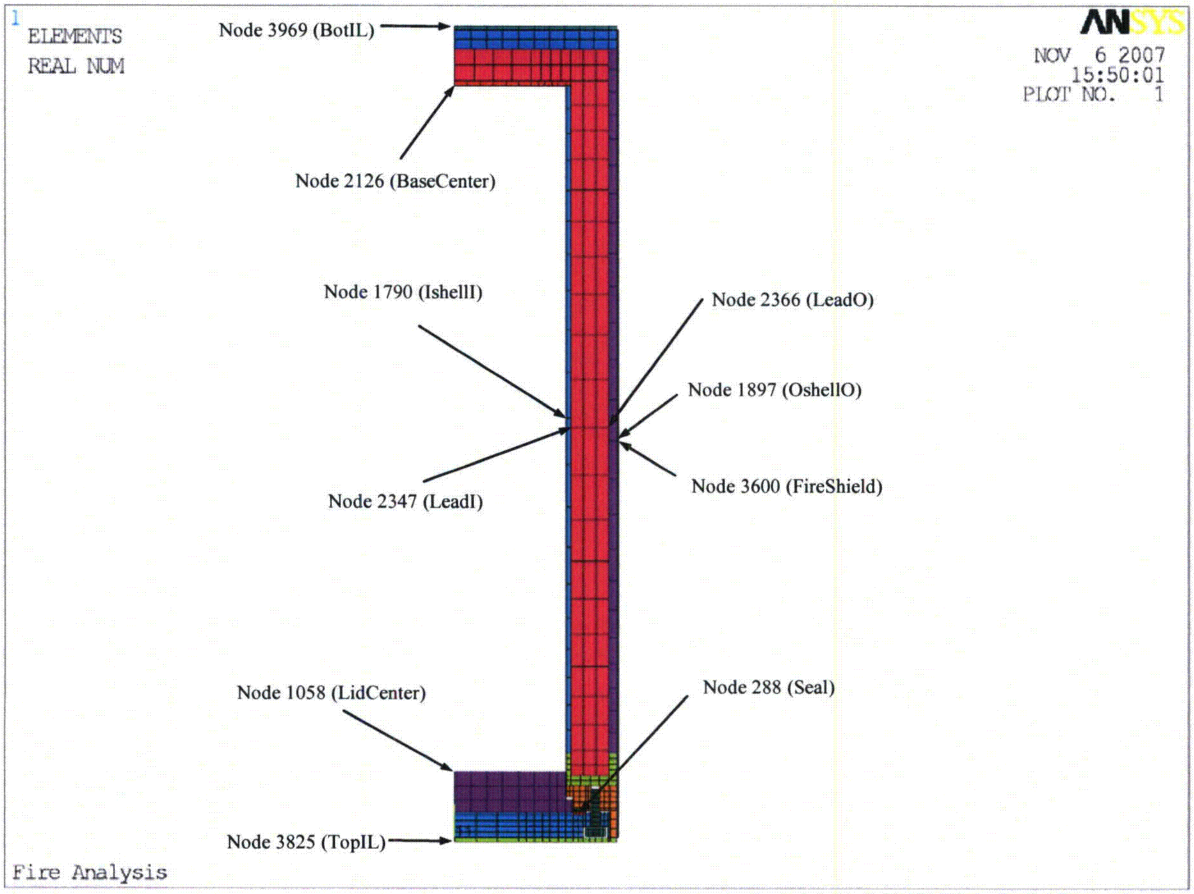


Figure 3-9 - Identification of the Nodes where Time-History is Monitored

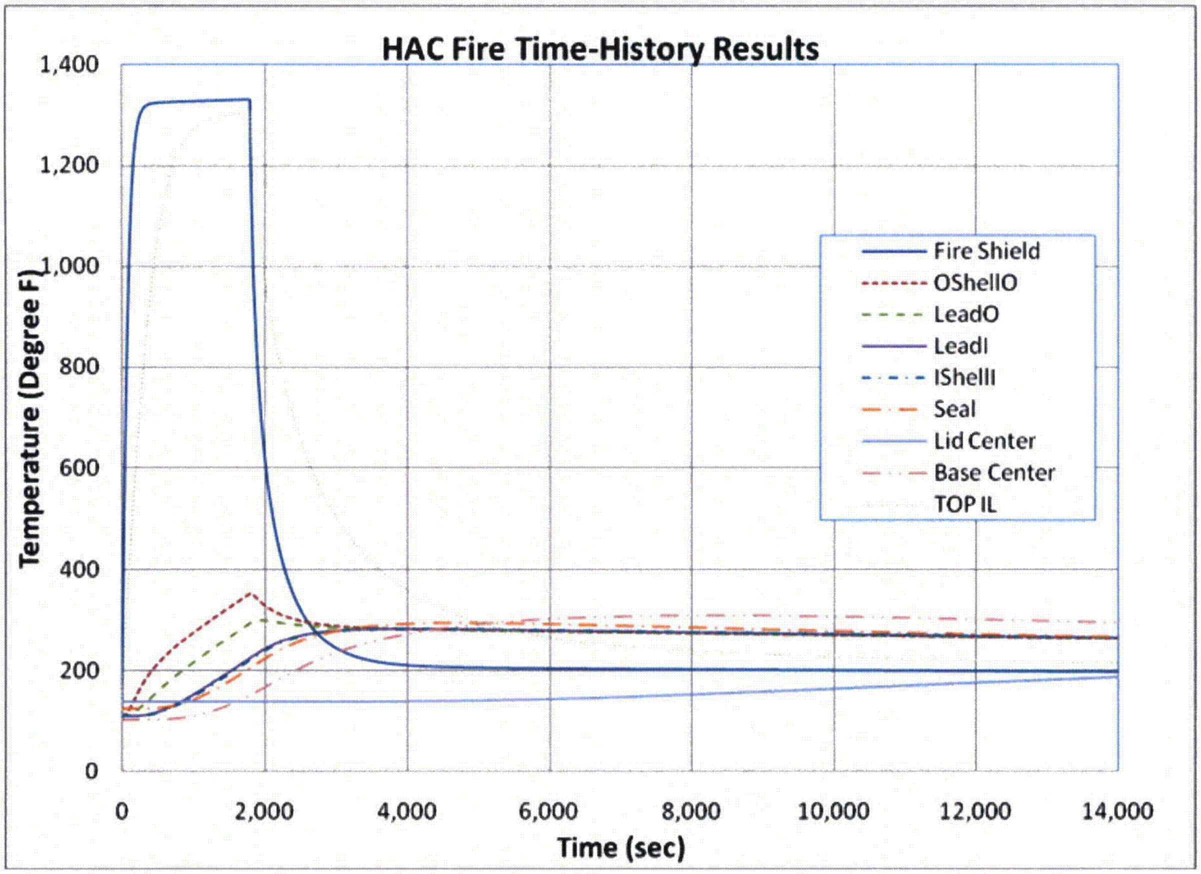


Figure 3-10 - Temperature Time-History Plot in Various Components of the Cask

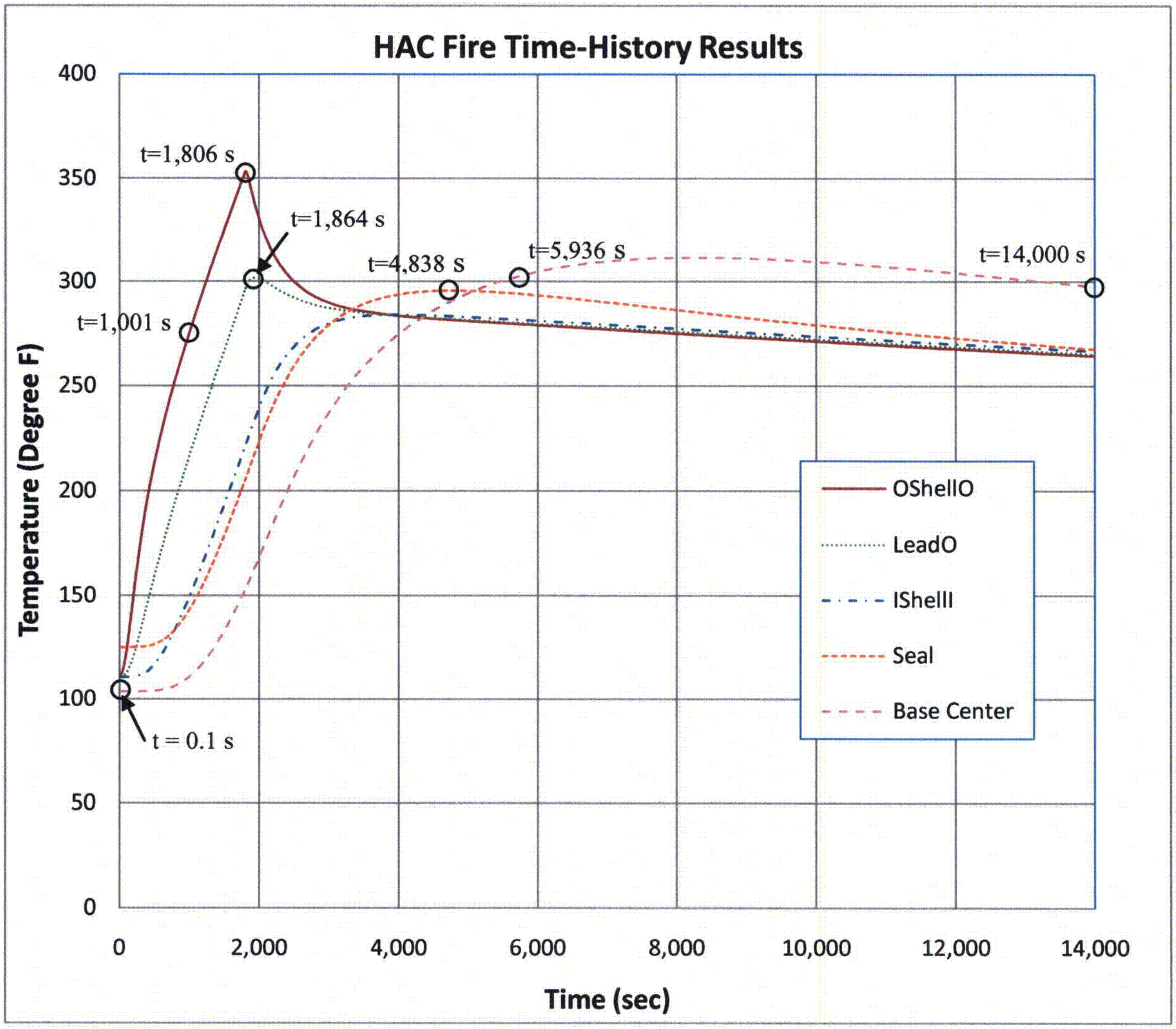


Figure 3-11 - Temperature Time-History Plot in Various Components of the Cask (Not Under Direct Contact with the Fire)

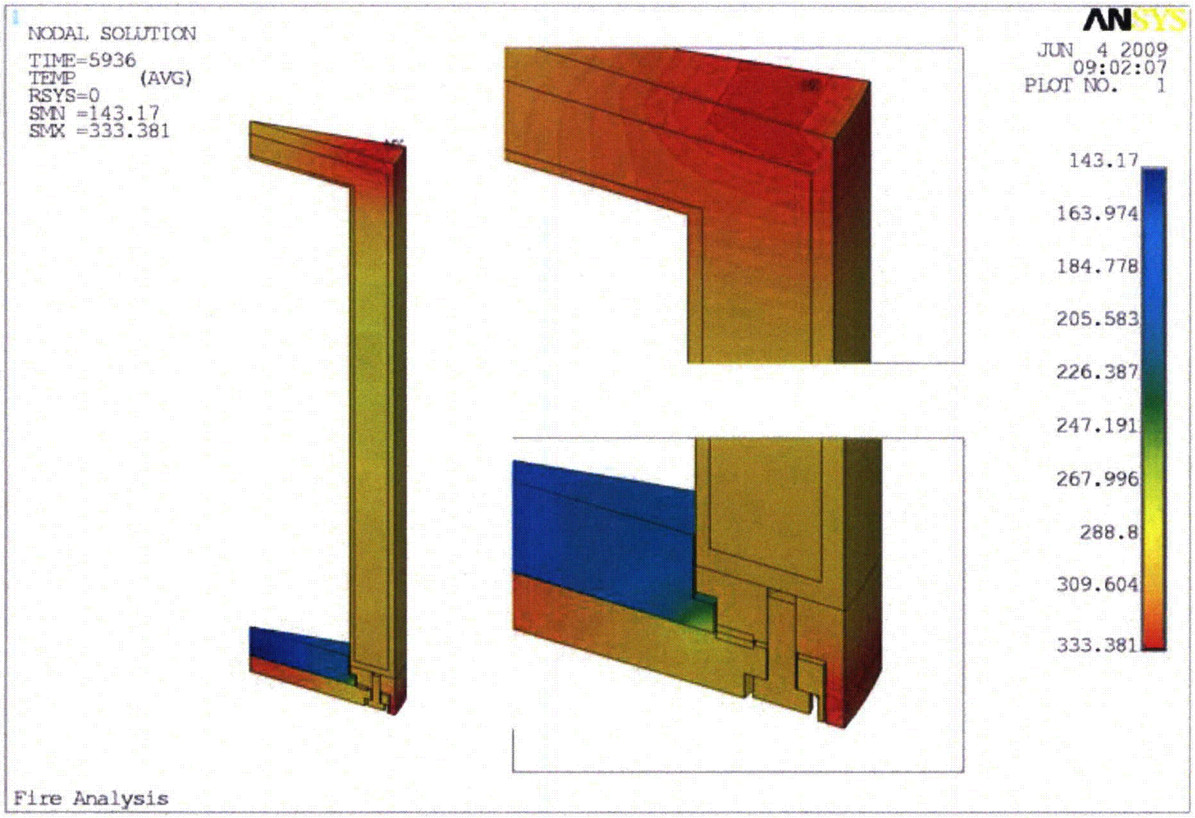


Figure 3-12 - Temperature Distribution – 5,936 Sec. After the Start of the Fire

(Please refer to [3-10] for temperature contour plots at various other times)

4.0 CONTAINMENT

The 3-60B package containment system is designed, constructed, operated, and maintained to assure no loss or dispersal of radioactive contents under the tests specified in 10 CFR 71, §71.71 and §71.73. This section identifies the 3-60B package containment system, describes how it complies with the containment requirements of 10 CFR Part 71, and defines the criteria for leak rate testing during package fabrication, use, maintenance, and repair.

4.1 DESCRIPTION OF CONTAINMENT SYSTEM

Containment Vessel

The containment systems for Configurations A and B of the 3-60B cask are shown in Figure 4-1 and Figure 4-2, respectively. The containment system is formed by the inner vessel of the cask body (i.e., bolt flange, inner shell, inner bottom plate, and drain port), lid, vent port plug, drain plug, and test port plugs (Configuration B only) along with associated O-rings, seals, welds, and fasteners. The closure lid, which is recessed within a protective skirt on the bolting ring, is secured to the cask body using sixteen (16) 1½-inch diameter high strength steel hex head bolts. The vent port plug assembly, which is recessed within a protective pocket in the lid outer plate, is secured to the lid outer plate using six (6) ½-inch diameter alloy steel socket head cap screws. The drain port plug, which is recessed within a pocket on the outside of the cask body, consists of a 1-inch diameter alloy steel socket head cap screw that threads into the drain port body. Finally, each test port (Configuration B only) is plugged by a single ½-inch diameter alloy steel socket head cap screw. Other than the closure lid, vent port, drain port, and test ports, there are no penetrations, valves, or pressure relief devices of any kind, in the 3-60B package containment system. The 3-60B package does not rely on any filter or mechanical cooling system to meet containment requirements.

The cask body bolt ring for both Configurations A and B incorporates a seal ring, as shown in Figure 4-1 and Figure 4-2, respectively. The seal ring is connected to the bolt ring by welds on both its inner and outer radii. The seal ring inner weld is relied upon to provide containment. However, the seal ring outer weld is not relied upon to provide containment. Its function is only to seal the space between the seal ring and bolt ring from pool water and prevent it from becoming contaminated. Alternatively, the bolt rings for both Configurations A and B may be fabricated with an integral seal ring that is machined into the forging.

The closure lid assembly and vent port plug assembly for Configuration A both incorporate welded seal rings in which O-ring grooves are machined. In all cases, the seal ring's inner welds provide containment, whereas the outer welds are seal welds that are not relied upon for containment. Welded seal rings are not used in the closure lid and vent port plug assembly of Configuration B. Instead, the seal rings in Configuration B are integral to the closure lid and vent port plug assembly, as shown in Figure 4-2.

With the exception of the bolts, plugs, and O-rings, all components on the containment system are constructed of stainless steel. As discussed in Section 2.2.2, the containment system

materials of construction are selected to avoid chemical, galvanic, or other reactions, and are compatible with each other and the chemical form of the payload.

Containment Penetrations

Containment vessel penetrations, also shown on Figure 4-1 and Figure 4-2, consist of the (1) closure lid, (2) vent port, (3) drain port, and (4) test ports (Configuration B only). The closure lid is constructed of multiple austenitic stainless steel plates with a total thickness of 10 ½ inches. The lid outer plate provides containment, whereas the lid inner plate(s) are provided for shielding and structural support. The lid outer plate fits inside an integral protective skirt on the bolting ring and has holes through which sixteen bolts are threaded into the bolting ring for attaching and sealing the lid to the cask body. For "Configuration A", the bottom surface of the lid outer plate incorporates a welded seal ring into which two O-ring grooves are machined. Two solid, elastomer O-rings are placed in the grooves, and when the lid is bolted shut these O-rings compress against a polished sealing surface on the cask bolting ring to form the containment seal. The inner of the two O-rings is the containment boundary seal. Two (2) diametrically opposed test port holes are provided through the seal ring plate between the O-rings that are used to perform the periodic and pre-shipment leak tests to verify proper seal closure. For "Configuration B", three (3) O-ring grooves are machined directly into the bottom surface of the lid outer plate, each housing a single solid elastomeric O-ring seal. For this configuration, the middle O-ring seal is for containment and the inner and outer O-rings are test seals. The "Configuration B" lid includes two (2) diametrically opposed test ports located between the inner test O-ring and the middle containment O-ring, and two (2) diametrically opposed test ports located between the middle containment O-ring and the outer test O-ring. These test ports are used to perform the periodic and pre-shipment leak tests to verify proper seal closure. However, the test ports located inboard of the containment O-ring include test port plugs and fastener seals that are included in the containment boundary, as shown in Figure 4-2.

The cask drain port located at the bottom (rear) end of the cask is used to drain water from the cask cavity. The drain port is formed by a steel drain port body that is attached to the cask cavity bottom plate by a full penetration weld. The drain port body is machined from a single piece of austenitic stainless steel. Optionally, the drain port body may be fabricated from two pieces connected by a full penetration weld. The outer end of the drain port body, which is recessed within the cask body, is connected to the cask outer shell by a steel coupling. The drain port body includes a 1-inch diameter hole from the inside (cavity), which turns 90° and exits at the outside of the drain port. The cask drain port is plugged and sealed with a drain port plug (i.e., socket head cap screw) that threads into the exterior opening of the drain port. The drain port plug is secured by applying a torque in accordance with the requirements of the drawing in Section 1.3. The elastomeric fastener seal (e.g., O-ring seal or Stat-O-Seal), located between the head of the drain port plug and the outer surface of the drain port body, seals the drain port and provides containment.

The cask vent port is located in the closure lid and used when draining the cask cavity of water. It consists of a stepped, cylindrical penetration through the lid that is plugged and sealed by the vent port plug assembly. The vent port plug assembly consists of a vent port plug cover plate and vent plug bar (i.e., solid steel rod). The inside surface of the vent port plug cover plate includes a seal ring with two (2) machined grooves to accommodate O-rings; an inner

containment O-ring and an outer test O-ring. The vent port plug seal plate may be fabricated as a separate piece (Configuration A) that is welded to the vent port plug cover plate on its inner and outer edges, or the seal ring may be integral to the vent port plug cover plate (Configuration B). For the separate seal ring used in Configuration A, the inner weld provides containment, but the outer weld is provided only to seal the space between the seal ring and cover plate for contamination control. As shown in Figure 4-1, the Configuration A vent port plug cover plate is penetrated by the vent plug bar (i.e., steel rod), and therefore the vent plug bar and its attachment welds are included in the Configuration A containment boundary. However, as shown in Figure 4-2, the Configuration B vent port plug cover plate is not penetrated by the vent plug bar, and therefore the vent plug bar and its attachment weld are not included in the Configuration B containment boundary. The vent port plug assembly is attached to the cask closure lid using six (6) ½-inch diameter hex head bolts, which are secured by applying a torque in accordance with the requirements of the drawing in Section 1.3. Two (2) test ports, diametrically opposed, are provided in the vent port plug assembly for leak testing the containment O-ring seal.

Welds

Containment boundary welds on the cask body inner vessel include the inner shell seam welds, inner shell-to-inner bottom plate weld, inner shell-to-bolt ring weld, drain port-to-inner bottom plate weld, and the seal ring's inner weld. In addition, the inner welds on the seal rings of the "Configuration A" lid and vent port plug assembly provide containment. The "Configuration A" vent port plug assembly containment boundary also includes the weld connecting the cylindrical plug to the cover plate. However, as shown in Figure 4-1, the "Configuration B" lid and vent port plug assembly do not include any welds in the containment boundary. All containment boundary welds are non-destructively examined using either radiographic or ultrasonic volumetric methods, as discussed in Section 8.1.2. In addition, all containment boundary welds are subjected to a pressure test and helium leak test during fabrication, as discussed in Sections 8.1.3 and 8.1.4, respectively.

O-rings

The lid O-ring seals, vent port plug O-ring seals, drain port plug fastener seal, and test port plug fastener seal are elastomeric seal having a durometer of 50 to 70, a normal service temperature range of -40°F to 250°F, which envelopes the temperature range for NCT, and a maximum short-term (1-hour) temperature limit that is ≥350°F, which envelopes the peak seal temperature for the HAC thermal test.

Closure

Secure closure of the containment boundary penetrations is assured by the threaded fasteners described under "Containment Penetrations" earlier in this section. These fasteners are torqued in accordance with the requirements of the drawing in Section 1.3. The containment penetrations will be covered by the impact limiters during transport, which will prevent inadvertent operation of the fasteners. The structural analysis in Section 2.0 shows that the threaded fasteners remain securely closed if subjected to pressure that could arise inside the package.

The 3-60B is not continuously vented.

4.2 CONTAINMENT UNDER NORMAL CONDITIONS OF TRANSPORT

The 3-60B package is designed, fabricated, and prepared for shipment so that, under the tests specified in 10 CFR 71.71, the package meets the containment requirements of 10 CFR 71.43(f) and 10 CFR 71.51(a)(1).

4.2.1 Pressurization of Containment Vessel

The Maximum Normal Operating Pressure (MNOP) of the 3-60B package is 35 psig, as shown in Section 3.3.2.

4.2.2 Containment Criteria

The 3-60B package is designed to a "leak-tight" containment criterion of 10^{-7} ref-cm^3/s per ANSI N14.5 [4-1].

4.2.3 Compliance with Containment Criteria

Compliance with the NCT containment criterion is demonstrated by analysis. The structural evaluation presented in Section 2.6 shows that there would be no loss or dispersal of radioactive contents, and that the containment boundary, seal region, and closure bolts do not undergo any inelastic deformation when subjected to the conditions of §71.71. The thermal evaluation presented in Section 3.3 shows that the seals, bolts, and containment system materials of construction do not exceed their temperature limits when subjected to the conditions of §71.71.

4.3 CONTAINMENT UNDER HYPOTHETICAL ACCIDENT CONDITIONS

The 3-60B package is designed, constructed, and prepared for shipment so that, under the tests specified in 10 CFR 71.73, the package meets the containment requirements of 10 CFR 71.51(a)(2).

4.3.1 Pressurization of Containment Vessel

The maximum internal pressure of the 3-60B package during the HAC fire is conservatively assumed to be 100 psig, as discussed in Section 3.4.3.

4.3.2 Containment Criteria

The 3-60B package is designed to a "leak-tight" containment criterion of 10^{-7} ref-cm^3/s per ANSI N14.5 [4-1].

4.3.3 Compliance with Containment Criteria

Compliance with the HAC containment criterion is demonstrated by analysis. The structural evaluation presented in Section 2.7 shows that there would be no loss or dispersal of radioactive contents, and that the containment boundary, seal region, and closure bolts do not undergo any inelastic deformation when subjected to the conditions of §71.73. The thermal evaluation

presented in Section 3.4 shows that the seals, bolts, and containment system materials of construction do not exceed their temperature limits when subjected to the conditions of §71.73.

4.4 **Leakage Rate Tests for Type B Packages**

Leak rate tests of the 3-60B package are required during fabrication, after maintenance activities or periodically, and prior to each shipment as described in the following sections and summarized in Table 4-1.

4.4.1 Fabrication Leak Rate Test

Each 3-60B package containment system is leak rate tested during fabrication to demonstrate that it satisfies the "leak-tight" containment criterion of 10^{-7} ref-cm^3/s. The Fabrication leakage tests are performed on the entire containment boundary including the closure lid, the vent and drain ports, the cask inner shell and base plate, and associated weldings using the "Gas Filled Envelope" method, similar to that described in Section A.5.3 of ANSI N14.5. The requirements for the fabrication leak rate test are described in Section 8.1.4.

4.4.2 Maintenance Leak Rate Test

Leak rate testing is performed on each 3-60B package after maintenance, repair, or replacement of components to confirm that the performance of the containment system has not been degraded. Maintenance leak rate tests are performed on the closure lid, plus the vent and drain ports using the "Gas Filled Envelope" method, similar to that described in Section A.5.3 of ANSI N14.5. Maintenance leak rate testing must demonstrate that the affected items, components, and assemblies satisfy the "leak-tight" containment criterion of 10^{-7} ref-cm^3/s. Requirements for maintenance leak rate testing are further described in Section 8.2.2.1.

4.4.3 Periodic Leak Rate Test

Each 3-60B package is leak rate tested annually to the "leak-tight" containment criterion of 10^{-7} ref-cm^3/s to demonstrate that the containment capabilities have not deteriorated over the previous year. Periodic leak rate tests are performed on the closure lid, plus the vent and drain ports using the "Gas Filled Envelope" method, similar to that described in Section A.5.3 of ANSI N14.5. Requirements for periodic leak rate testing are further described in Section 8.2.2.1.

4.4.4 Pre-shipment Leak Rate Test

Each 3-60B package is leak rate tested prior to shipment to 10^{-3} ref-cm^3/s to confirm that the containment system is properly assembled for shipment. The pre-shipment leak rate test is performed using the "Gas Pressure Drop" method in ANSI N14.5, Section A.5.1, as described further in Section 8.2.2.2.

Table 4-1 - Leakage Tests of the 3-60B Package

Test	Frequency	Test Gas	Acceptance Criteria
Maintenance	After maintenance, repair (such as weld repair), or replacement of components of the containment system.	helium	Test sensitivity $\geq 1x10^{-7}$ ref-cm^3/s (leaktight)
Fabrication	Prior to first use of each package.		
Periodic	Within 12 months prior to each shipment.		
Pre-Shipment	Before each shipment, after the contents are loaded and the package is closed.	dry air or nitrogen (optional)	Test sensitivity $\geq 1x10^{-3}$ ref-cm^3/s

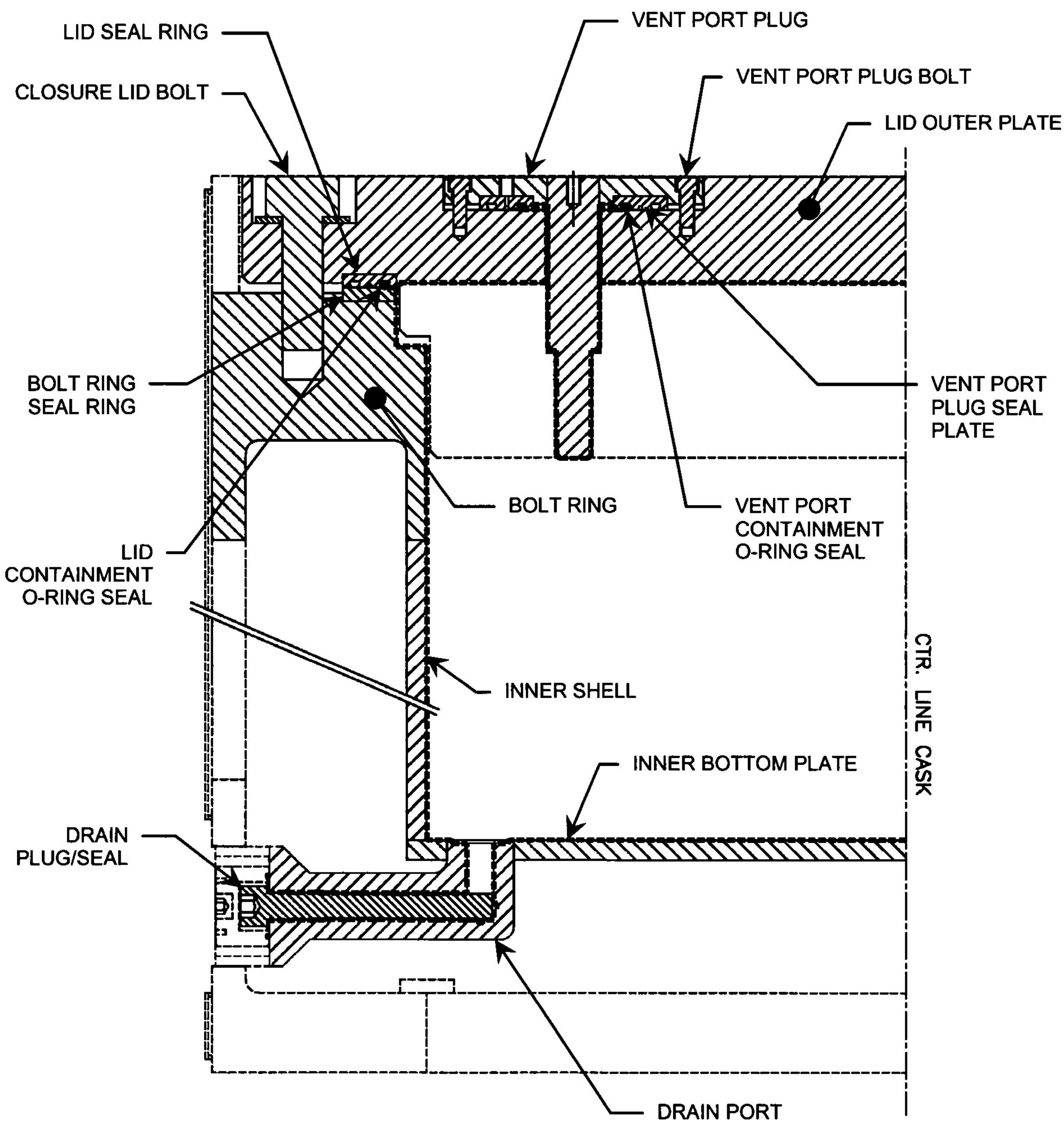


Figure 4-1 - Containment System Overview – Configuration A

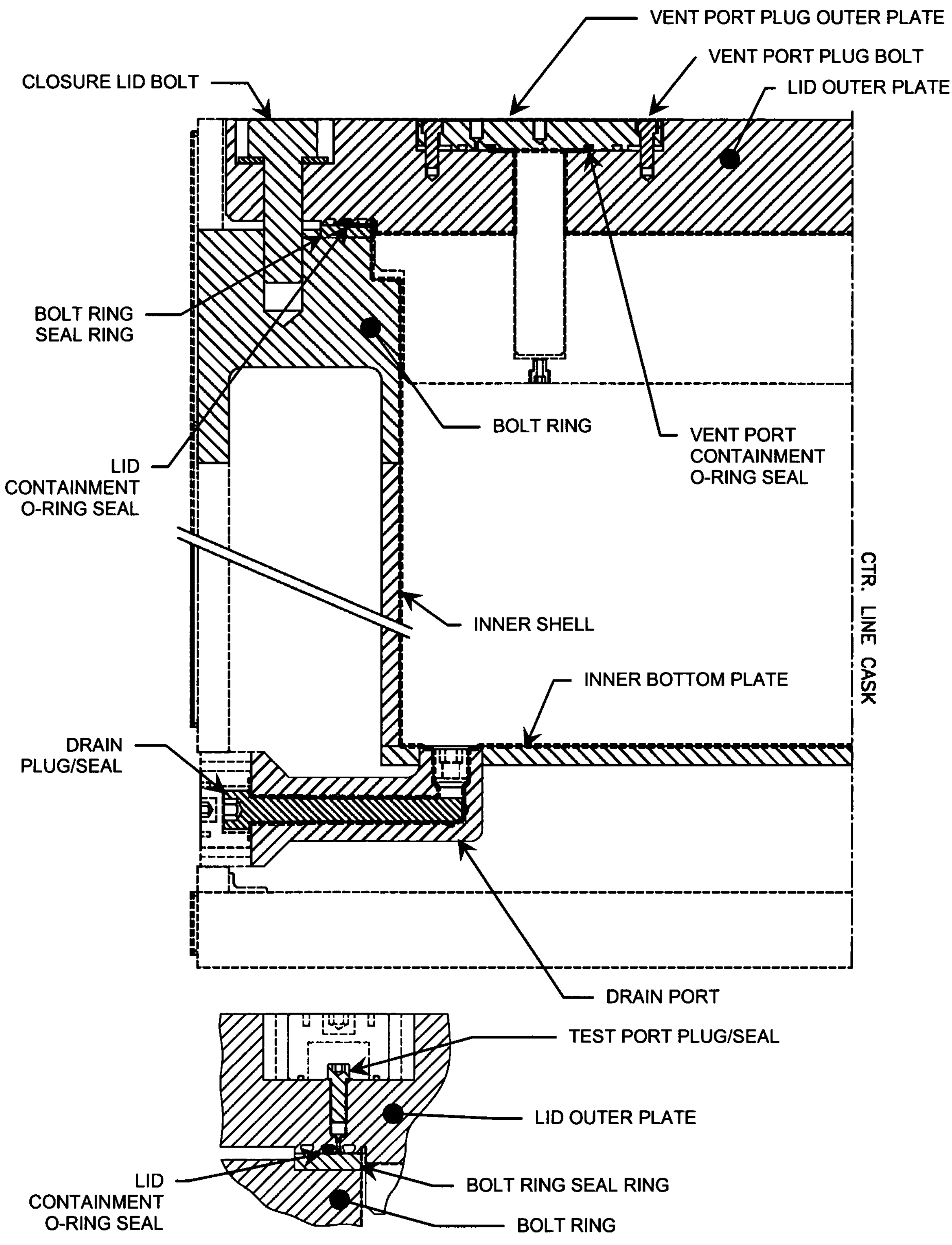


Figure 4-2 - Containment System Overview – Configuration B

4.5 **Appendix**

4.5.1 References

[4-1] ANSI N14.5, "American National Standard for Radioactive Materials – Leakage Tests on Packages for Shipment," 1997.

This page intentionally blank.

5.0 SHIELDING EVALUATION

5.1 DESCRIPTION OF DESIGN FEATURES

The 3-60B packaging consists of a lead and steel containment vessel that provides the necessary shielding for the various radioactive materials to be shipped within the package. (Refer to Section 1.2.3 for packaging contents.) Tests and analysis performed under chapters 2.0 and 3.0 have demonstrated the ability of the containment vessel to maintain its shielding integrity under NCT. Prior to each shipment, radiation readings will be taken based on individual loadings to assure compliance with 10CFR71.47.

The package shielding is sufficient to satisfy the dose rate limit of 10CFR71.51(a) (2) which states that any shielding loss resulting from the hypothetical accident will not increase the external dose rate to more than 1000 mrem/hr at one meter from the external surface of the cask.

5.1.1 Shielding Design Features

The cask sidewall consists of a ¾-inch thick stainless steel inner shell and a 1 ¼-inch thick stainless steel shell outer shell that encase a 6-inch thick (minimum) lead gamma shield. There is a stainless steel thermal shield around the cask body, which is ignored in the shielding evaluation.

The lid consists of several circular stainless steel plates, a total of 10.5 inches thick. The lid closure is made in a stepped configuration to eliminate radiation streaming at the lid/cask body interface.

The cask bottom has an outer 3-inch thick steel shell, a 5-inch lead shield layer, and a 3/4-inch inner containment layer.

Both ends of the cask are contained in polyurethane foam filled impact limiters. The impact limiters have a ½-inch steel base plate that is fixed to the cask ends.

Table 5-1 - Cask Components

Component	Material	Density (g/cc)	Dimensional Tolerance
Outer Shell	SS Type 304	7.94	Mill std
Shielding	Lead	11.34	Min. specified
Lid	SS Type 304	7.94	Mill std
Inner Shell	SS Type 304	7.94	Mill std
Liner	Carbon steel	7.82	Mill std
Liner	Polyethylene	0.941	nominal
Impact Limiter Foam	Polyurethane	0.40	nominal

5.1.2 Maximum Radiation Levels

Table 5-2 and Table 5-3 give NCT and HAC dose rates resulting from two content configurations, i.e., irradiated hardware in a steel liner and dewatered dispersible solid (e.g., swarf) in a high integrity container (HIC). The shielding evaluation is performed using the SAS4 module of the SCALE system [5-1]. The dose rates listed in Table 5-2 and Table 5-3 are the "total response" plus two times the "fractional standard deviation (fsd)" from the SCALE output [5-3]. As the contents are restricted to "fissile exempt" materials, the source activity does not include neutron emitters. Maximum allowable dose rates given in 10CFR71 are shown in the tables for comparison. The cask is always shipped "exclusive use". The cask is loaded vertically and transported horizontally. Top and bottom refer to the end surfaces of the cask and with top referring to the lid end.

Table 5-2 - Summary of Maximum Radiation Levels - Irradiated Hardware

Condition	Total Dose Rate (mrem/hr)						
	Package Surface		1 m from Surface		2 m from Vehicle*		Occupied Space (6 m from Top or Bottom
	Side	Top/ Bottom	Side	Top/ Bottom	Side	Top/ Bottom	
NCT							
Calculated	73.6	36.1/9.5	N.A.	N.A.	6.6	3.0/0.8	0.5
Allowable	200	200	N.A.	N.A.	10.0	10.0	2
HAC							
Calculated	N.A.	N.A.	61.5	43.9/10.1	N.A.	N.A.	NA
Allowable	N.A.	N.A.	1000.0	1000.0	N.A.	N.A.	NA

Table 5-3 - Summary of Maximum Radiation Levels - Swarf

Condition	Total Dose Rate (mrem/hr)						
	Package Surface		1 m from Surface		2 m from Vehicle*		Occupied Space (6m from Top or Bottom
	Side	Top/ Bottom	Side	Top/ Bottom	Side	Top/ Bottom	
NCT							
Calculated	67.6	46.5/13.0	N.A.	N.A.	7.7	3.8/1.0	0.8
Allowable	200	200	N.A.	N.A.	10.0	10.0	2
HAC							
Calculated	N.A.	N.A.	634	295/77.7	N.A.	N.A.	NA
Allowable	N.A.	N.A.	1000	1000	N.A.	N.A.	NA

* - The 2m dose rates for the top and bottom of the cask are at 2m from the surface not from the vehicle.

5.2 **Source Specification**

The 3-60B cask is designed for transport of Type B quantities of high gamma activity radioactive material typically consisting of irradiated metal components, dispersible solids typified by irradiated metal cutting debris (swarf), dewatered resins, solidified process wastes, and other similar items. Two bounding contents configurations were analyzed:

(1) A steel liner (34-inch outer diameter, 108-inch long) of irradiated stainless steel reactor control rod blades (irradiated hardware). A hardware liner normally has a thick wall (1-inch or greater) but for the purpose of the shielding calculation geometry, the wall is assumed to be ½-inch thick carbon steel. The amount of irradiated hardware is assumed to be the maximum contents or 9,500 pounds, minus the weight of the liner. The waste mass and activity are assumed to be uniformly distributed throughout the liner.

(2) A "high integrity container" (HIC) (34-inch outer diameter, 108-inch long) of a dewatered dispersible solid (irradiated stainless steel cutting debris or swarf). For the purpose of the shielding calculation geometry, the HIC wall is assumed to be ½-inch thick. The HIC material is polyethylene, thus providing minimal shielding. The amount of swarf is assumed to be the maximum contents or 9,500 pounds, minus the liner weight. The waste mass and activity are assumed to be uniformly distributed throughout the liner.

5.2.1 Gamma Source

The gamma source in each configuration is conservatively assumed to be ^{60}Co with an activity at the maximum for a Category II packaging, i.e., 30,000 Ci of ^{60}Co.

Photon Energy MeV	Intensity Photons/sec
0.6938	1.81e+011
1.1732	1.11e+015
1.3325	1.11e+015
Totals	**2.22e+15**

5.2.2 Neutron Sources

There are no sources of neutron radiation in the radioactive materials to be carried in the 3-60B cask.

5.3 **Model Specification**

5.3.1 Configuration of Source and Shielding

The source and liner configurations are given in Section 5.2. The dimensions of the cask axial and radial shielding elements are given in Table 5-4.

Table 5-4 - Model Shielding Elements

Component	Material	Outer Diameter (in)	Thickness (in)
Cavity	(void)	35	109.375 (length)
Inner Radial Shell	SS 304	36.5	0.75
Radial Shield	Lead	48.5	6
Outer Radial Shell	SS 304	51	1.25
Impact Limiter (axial)	Poly	82	18
Inner Axial Shell (lid)	SS 304	37	0.5
Axial Shield (lid)	SS 304	36	6
Outer Axial Shell (lid)	SS 304	48.75	4
Inner Axial Shell (bottom)	SS 304	36.5	0.75
Axial Shield (bottom)	Lead	48.5	5
Outer Axial Shell (bottom)	SS 304	51	3

The transport trailer is 8-feet wide and the cask will always be shipped "exclusive use". Thus, the dose point locations will include points 2m from the edge of the trailer.

Surface and point detectors in SAS4 are used to determine the doses from the cask. The SCALE program uses different algorithms to determine dose rates for surface detectors than for point detectors. Surface detectors are the recommended options to minimize computing time. A few point detectors are included in each model at the same distance from the cask as the surface detectors as a comparison to the surface detector results. Where both point and surface detector results were obtained from the same location, the larger result was used. Point detectors are used in the HAC model to detect streaming through the very small void created by the lead slump.

SCALE has four default locations for surface detectors. For the 3-60B, these are: for radial geometry, cask body surface (65 cm), 1m from the outer surface (165 cm), 2m from a highway trailer (322 cm), and 2m from a railcar (358 cm); for axial geometry, outer surface (top – 210 cm, bottom – 205 cm), 1, 2, and 3m from the outer surface. The default locations were used for the radial surface detectors for the models evaluating the NCT except that the second surface detector was set to the outer radial surface of the impact limiter (104.14 cm). The radial locations of interest are at the cask body surface, the impact limiter surface, and at 2m from the edge of the trailer, i.e. 322 cm. The default locations were used for the axial surface detectors for the models evaluating the NCT except that the last detector was set at 6m from the outer surface. The axial locations of interest are at the cask surface, at 2m from the cask surface, and at the expected occupied area of the tractor while in transit, i.e., 6m from the outer surface (top – 810 cm, bottom - 805 cm). When evaluating doses under HAC, surface detectors are placed at 1m from the cask surface (165 cm). Under HAC, the impact limiters are conservatively assumed to be absent. In all cases, the surface detectors are subdivided into small units so that maximums due to irregularities in the design can be detected.

Locations for most point detectors are shown in Figure 5-1 through Figure 5-4. For the NCT models, point detectors at the cask surface are shown, points 2m from the trailer edge or 6m from the axial cask surfaces are not shown due to the scale of the drawing. For the HAC models, all the point detectors are at 1m from the cask surface. Specific locations of the point detectors for each model are given in the input file (Attachment 5.3) on the line starting with "det" (in cm in x,y,z coordinates).

The NCT shielding models are shown in Figure 5-1 (top) and Figure 5-2 (bottom).

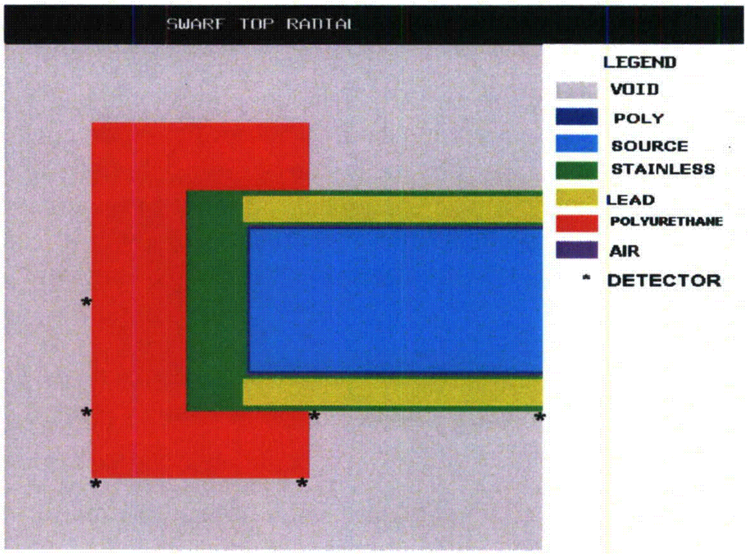


Figure 5-1 - 3-60 Cask Top

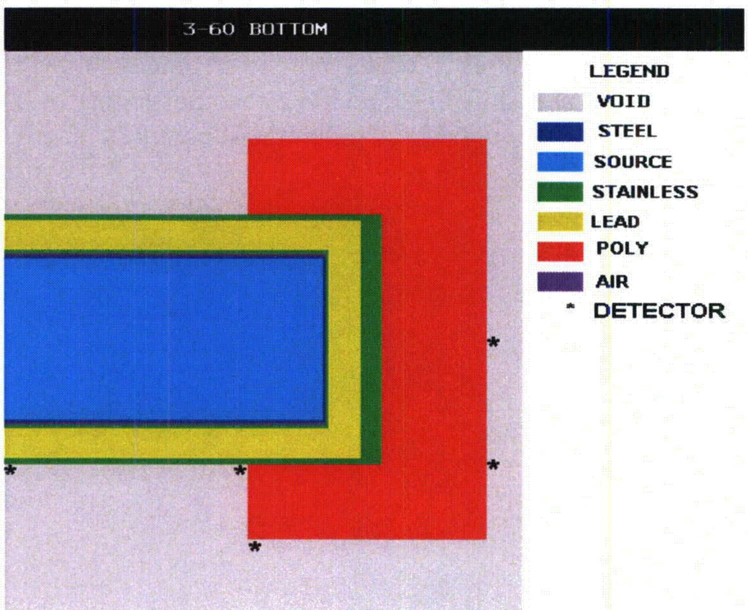


Figure 5-2 - 3-60 Cask Bottom

Under NCT, the material in the liner is assumed to be uniformly distributed over the liner interior cavity. For irradiated hardware, the calculated weight of the ½-inch thick liner is 1,858 pounds. With a payload maximum of 9,500 pounds, this gives a weight of hardware of 7,642 pounds for a mass density of 2.309 g/cc. For swarf, the calculated weight of the HIC is 222 lbs, giving a resulting mass density of 2.803 g/cc. The swarf is assumed to have a porosity of 50%, so the dewatered swarf will contain equal volumes of swarf and water. The shielding effect of the water is conservatively ignored.

Under HAC, there are some changes to the cask configuration that are incorporated into the models. The drop analysis shows the impact limiters will remain in place but there will be some deformation. To conservatively determine the 1m dose rate after the drop, the impact limiters are removed from the model, except for the ½-inch thick top plate, which remains in place, and the dose point is set at 1m from the cask outer shell. This configuration covers the result of the puncture test by assuming the hole caused by the puncture bar reaches all the way to the cask outer shell. As discussed in Chapter 2, the puncture test does not cause any loss of shielding or create a streaming path. Also as noted in Chapter 2, there is a slump in the lead side shield as a result of the 30-foot drop onto the bottom of the cask creating a 0.81 cm void at the top of the side shield.

The configuration of the irradiated hardware does not change, i.e., the shape and mass density stays the same. The forces on the contents, as determined in Chapter 2, are not large enough to deform the hardware.

For swarf, the material is assumed to compress as a result of the drop and form a disk at one end of the cask as shown in Figure 5-3 and Figure 5-4. Assuming a liner 90% full of dewatered swarf, if the swarf were to compress to the normal density of stainless steel, the compressed source height would be ~76 cm. To conservatively assess a concentrated source, the size of the compressed source is assumed to be a cylinder with the diameter of the liner and a height of 20 cm. However, this compressed source is conservatively assumed to have a density less than steel, i.e., 6 g/cc, which reduces self-shielding, and has a specific activity of 0.045 Ci/g. Dose rates are evaluated for this source positioned at the top or bottom of the liner.

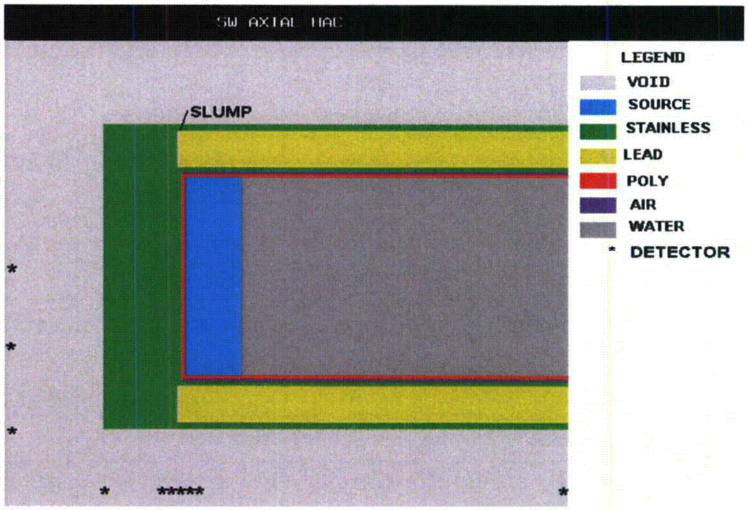


Figure 5-3 - 3-60 Cask Top (HAC)

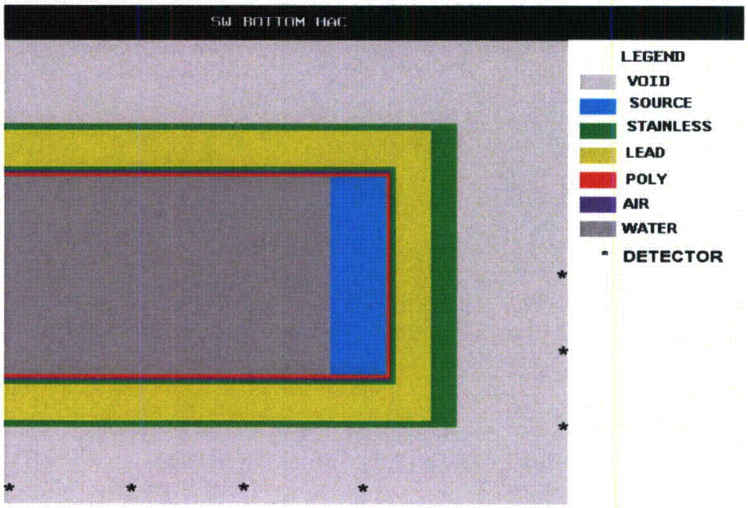


Figure 5-4 - 3-60 Cask Bottom (HAC)

The models developed to incorporate the conditions described above are listed in Table 5.4a , SCALE Models for NCT, and Table 5.4b, SCALE Models for HAC. The input files for these models are included in [5-3].

Table 5-4a - SCALE Models for NCT

Transport Direction	Cask Geometry	Waste Form	Secondary Container	Dose Locations	Filename
Radial	Cask Lid Half	Irradiated Hardware	Carbon Steel	Surface, 2m From Trailer	\HWtopRadialR2
Radial	Cask Bottom Half	Irradiated Hardware	Carbon Steel	Surface, 2m From Trailer	\HWbottomRadialR2
Axial	Cask Lid Half	Irradiated Hardware	Carbon Steel	Surface, 2m, 6m	\HWtopAxialR2
Axial	Cask Bottom Half	Irradiated Hardware	Carbon Steel	Surface, 2m, 6m	\HWbottomAxialR2
Radial	Cask Lid Half	Swarf	Polyethylene	Surface, 2m From Trailer	\SWtopRadialR2
Radial	Cask Bottom Half	Swarf	Polyethylene	Surface, 2m From Trailer	\SWbottomRadialR2
Axial	Cask Lid Half	Swarf	Polyethylene	Surface, 2m, 6m	\SWtopAxialR2
Axial	Cask Bottom Half	Swarf	Polyethylene	Surface, 2m, 6m	\SWbottomAxialR2

Table 5-4b - SCALE Models for HAC

Transport Direction	Cask Geometry	Waste Form	Secondary Container	Dose Locations	Filename
Radial	Cask Lid Half	Irradiated Hardware	Carbon Steel	1m From Cask Surface	\HWtopRadialHACR2
Radial	Cask Bottom Half	Irradiated Hardware	Carbon Steel	1m From Cask Surface	\HWbottomRadialHAC R2
Axial	Cask Lid Half	Irradiated Hardware	Carbon Steel	1m From Cask Surface	\HWtopAxialHACR2
Axial	Cask Bottom Half	Irradiated Hardware	Carbon Steel	1m From Cask Surface	\HWbottomAxialHAC R2
Radial	Cask Lid Half	Swarf Disc	Polyethylene	1m From Cask Surface	\SWtopRadialHACR2
Radial	Cask Bottom Half	Swarf Disc	Polyethylene	1m From Cask Surface	\SWbottomRadialHAC R2
Axial	Cask Lid Half	Swarf Disc	Polyethylene	1m From Cask Surface	\SWtopAxialHACR2
Axial	Cask Bottom Half	Swarf Disc	Polyethylene	1m From Cask Surface	\SWbottomAxialHACR 2

5.3.2 Material Properties

The properties of the shield materials are given in Table 5-1. The stainless steel of the contents is assumed to be Type 316 with densities for the various configurations as given in Section 5.3.1.

5.4 **Shielding Evaluation**

5.4.1 Methods

The shielding evaluation is performed using the SAS4 module of the SCALE system [5-1] The SAS4 control module performs a three-dimensional Monte Carlo shielding analysis of a radioactive material transport or storage container using an automated biasing procedure. Biasing parameters required by the Monte Carlo calculation are generated from results of a one-dimensional adjoint discrete-ordinates calculation. SAS4 performs resonance self-shielding treatment with either the BONAMI or NITAWL-II functional module and cell weighting with the XSDRNPM functional module; then it carries out adjoint discrete-ordinates and Monte Carlo calculations, respectively, with the XSDRNPM and MORSE-SGC functional modules. SCALE was developed to model spent fuel shipments. The radioactivity in the cask is assumed to be in the form of spent fuel rods, with an option to place radioactivity in the fuel hardware.

The NCT calculations were setup in SAS4 with the simplified geometry input option (IGO=0) using the ESPN (Easy Shielding Processor Input) graphical user interface. Since SAS4 models only half the cask at a time and in either the radial or axial direction, multiple models are required. Since the cask top and bottom have different configurations, radial and axial models for both the top and bottom cask halves are needed for each source configuration, resulting in eight models. The source configurations are: 1) irradiated hardware in a carbon steel liner, and 2) swarf in a polyethylene liner. For both configurations, the waste mass and activity are assumed to be uniformly distributed throughout the liner.

The HAC calculations were setup in SAS4 with the simplified geometry input option (IGO=0). As noted for the NCT models, eight models were evaluated for HAC. The SAS4 system requires that the source be axially symmetrical around the midpoint of the cask. Since SCALE requires the model be symmetric about the cask centerline, to properly represent the HAC swarf configuration of a concentrated source at one end of the cask, the activity is assigned to "fuel hardware", which, in the SAS4 model, is located at the ends of the liner. The activity specified in the model input is evenly divided between the hardware at each end of the liner. For the activity of the compressed source disc to equal the activity of the NCT swarf source, the model input activity must be doubled.

5.4.2 Input and Output Data

The key inputs to SCALE are the cask materials, the cask geometry, and the source. SAS4 geometry input is referenced to the cask mid-plane, i.e., the origin, 0,0,0 point, is set at the midpoint (axially and radially) of the cask.

The source term is defined by the SOE, source energy spectrum array, and the SFA, source normalization factor. The SOE is defined as the percent of total gamma intensity in each energy group with the groups specified by the selected cross section library (27n-18couple). The intensity of the gammas, at energy E, are normalized to the average energy (E_{ave}) of the energy group for the source being evaluated by direct multiplication by the factor E/E_{ave}. The modeled source is 30 kCi of Co-60 (see Section 5.2.1), which has three gammas. The highest energy gamma, E=1.332, is just on the boundary between energy groups 36 and 37. One-half the initial intensity is applied to each of these two groups and then normalized. The middle energy gamma, E=1.173, is entirely normalized in Group 37. This procedure maintains the conservation of energy rather than photon intensity, which gives a more correct computation of dose rates. The low energy gamma, E= 0.6938, is not included as it has no appreciable impact on the dose calculation due to its low energy and intensity compared to that of the other two gammas. The resulting SOE has a distribution of 22% in group 36 and 78% in group 37. The SFA equals the total intensity of 2.247E+15 photons per second, normalized as described above from a 30 kCi Co-60 source. For the swarf HAC cases, the SFA is doubled, as discussed above, to 4.494E+15 photons per second.

In SAS4, the gamma source is expected to be spent fuel with photons originating in the fuel or the hardware. For modeling the 3-60B, the photon location was set as the fuel for most cases. For the HAC swarf case, to model the compressed source at the ends of the cask cavity, the gamma source is placed in the hardware as a 20 cm thick disk, as discussed above, and the gamma intensity is doubled.

The number of source particles, nst, and number of batches, nit, is adjusted until the dose rate results have a small fractional standard deviation (fsd), typically less than 0.1. The dose rate reported is the "total response" plus two times the "fsd" from the SCALE output. If there are both point and surface detector results for the same location, the higher value is reported. Table 5-5 gives the primary geometry input parameters for the radial calculation for the top half of the cask containing swarf. The input files and output files are included as [5-3].

Table 5-5 - Geometry Parameters

Component	Material	Radius (cm)	Height (from midpoint) (cm)
Fuel	SS 316	41.91	135.88
Hardware	SS 316	41.91	135.89
Liner (insert)	Poly	43.18	137.15
Cavity	Air	44.45	137.16
Inner Shell	SS 304	46.36	138.11
Radial Shield	Lead	61.60	138.75
Axial Shield	SS 304	46.36	163.83
Outer Shell	SS 304	64.77	165.10*
Impact Limiter	Poly	104.14	107.95/209.55**

* includes ½-inch thick impact limiter attachment plate

** lower and upper limits of the impact limiter

5.4.3 Flux-to-Dose-Rate Conversion

Flux-to-dose-rate conversion factors on the SCALE cross-section libraries are applied in the ultimate calculation of the desired gamma and neutron dose rates predicted for the case. The conversion factors, specified by IRF=9504, are those derived (in multigroup format) from the American National Standard Institute Neutron and Gamma-Ray Flux-to-Dose-Rate Factors [5-2].

Table 5-6 - Gamma-Ray-Flux-To-Dose-Rate Conversion Factors

Photon Energy-E (MeV)	$DF_g(E)$ (Rem/hr)/(photons/cm^2-s)	Photon Energy-E (MeV)	$DF_g(E)$ (Rem/hr)/(photons/cm^2-s)
0.01	3.96-06	1.4	2.51-06
0.03	5.82-07	1.8	2.99-06
0.05	2.90-07	2.2	3.42-06
0.07	2.58-07	2.6	3.82-06
0.1	2.83-07	2.8	4.01-06
0.15	3.79-07	3.25	4.41-06
0.2	5.01-07	3.75	4.83-06
0.25	6.31-07	4.25	5.23-06
0.3	7.59-07	4.75	5.60-06
0.35	8.78-07	5.0	5.80-06
0.4	9.85-07	5.25	6.01-06
0.45	1.08-06	5.75	6.37-06
0.5	1.17-06	6.25	6.74-06
0.55	1.27-06	6.75	7.11-06
0.6	1.36-06	7.5	7.66-06
0.65	1.44-06	9.0	8.77-06
0.7	1.52-06	11.0	1.03-05
0.8	1.68-06	13.0	1.18-05
1.0	1.98-06	15.0	1.33-05

5.4.4 External Radiation Levels

The maximum dose rates under NCT for each of the source configurations, irradiated hardware and swarf, on the side, top, and bottom of the cask and the output files containing these results are shown in Table 5-7. The dose rate listed is the "total response" plus two times the "fsd" from the SCALE output. The surface dose rates on the top and bottom are on the outer flat surface of the impact limiter. The surface dose rates for the side is on the cylindrical cask surface which includes the impact limiter outer surface. The 2m locations on top and bottom are for a detector 2m outward from the impact limiter surface. The 2m side locations are 2m from the edge of the 8-foot wide trailer. The normally occupied space (driver location) is more than 6m from the end of the cask and is conservatively set at 6m.

Table 5-7 - NCT Maximum Dose Rates

	Surface	2m	6m	SAS4 file
Irradiated Hardware				
Top	36.1	3.0	0.5	HWtopAxialR2.out
Bottom	9.5	0.8	0.1	HWbottomAxialR2.out
Side	73.6	6.6*	NA	HWtopRadialR2.out *HWbottomRadialR2.out
Swarf				
Top	46.5	3.8	0.6	SWtopAxialR2.out
Bottom	13.0	1.0	0.8	SWbottomAxialR2.out
Side	67.6	7.7	NA	SWtopRadialR2.out

The maximum dose rates under HAC for each of the source configurations are shown in Table 5-8. For the hardware source, the change to the geometry from that of the NCT models is to include the lead slump in the side shield and to remove the impact limiters. The swarf source changes geometry under HAC so the dose rates reported for top, bottom, and side are from HAC models that include the compressed source and lead slump and have the impact limiters removed.

Table 5-8 - HAC Maximum Dose Rates at 1 meter from Package

Irradiated Hardware	Dose Rate (mrem/hr)	SAS4 file
Top	43.9	HWtopAxialHACR2.out
Bottom	10.1	HWbottomAxialR2HAC.out
Side	61.5	HWtopRadialHACR2.out
Swarf	Dose Rate (mrem/hr)	SAS4 file
Top	295	SWtopAxialHACR2.out
Bottom	77.7	SWbottomAxialHACR2.out
Side	634	SWTopRadialHACR2.out

As shown in Table 5-7 and Table 5-8, the external dose rates for the 3-60 cask comply with the limits specified in 10 CFR 71.47 and 71.51.

5.5 **Appendix**

5.5.1 References

[5-1] SCALE*: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluations,* NUREG/CR-0200, Rev.6 (ORNL/NUREG/CSD-2/R6), Vols. I, II, III, May 2000

[5-2] *American National Standard Neutron and Gamma-Ray Flux-to-Dose Rate Factors*, ANSI/ANS-6.1.1-1977, American Nuclear Society, LaGrange Park, Illinois, 1977.

[5-3] SCALE Input and Output Files for 3-60B, Energy*Solutions*, 2008.

6.0 CRITICALITY EVALUATION

Not applicable to the 3-60B package.

This page intentionally blank.

7.0 PACKAGE OPERATIONS

This Section describes the procedures to be used for loading and unloading the 3-60B cask. These procedures are intended to ensure the cask is prepared for transport and generally operated in a manner consistent with Sections 1.0 through 6.0, and that exposure to radiation by operating personnel is minimized. The operating procedures in this Section are presented sequentially in actual order of performance, unless otherwise indicated. Actual operations will be conducted using detailed procedures that are consistent with this Section.

7.1 Package Loading

Cask loading may be performed either in a pool ("wet") or in cask loading area ("dry"). Cask unloading is normally performed "dry" – typically at a licensed burial facility. The sequence of the procedural steps described below may be modified, if necessary, provided that the change does not impact other steps.

7.1.1 Preparation for Loading

7.1.1.1 Visually inspect the exterior of the package to ensure there is no damage that will impair its ability to function as intended.

7.1.1.2 Loosen and remove the fasteners that secure each impact limiter to the cask body. Attach rigging to the impact limiters and remove each impact limiter from the cask body.

7.1.1.3 Disconnect the front and rear trunnion tie down equipment.

7.1.1.4 Using a lifting yoke, upend the cask by lifting from the lifting trunnions with a lifting yoke and then lift it vertically to remove it from the shipping cradle. Place the cask in the loading area (dry loading) or preparation area (wet loading). If necessary, clean the exterior surfaces.

7.1.1.5 Detach and remove the vent port plug assembly, if required. Visually inspect each vent port plug assembly bolt for excessive wear and/or damage in accordance with the applicable requirements of Section 8.2.3.3. Visually inspect the vent port plug assembly O-rings and sealing surfaces in accordance with the applicable requirements of Sections 8.2.3.1 and 8.2.3.2. Apply a thin coating of vacuum grease to the exposed surfaces of the vent port plug assembly O-rings, as necessary to lubricate the elastomer surface.

Note: If the vent port plug assembly containment O-ring (i.e., the inner O-ring) requires replacement, then the maintenance leak rate test of the vent port plug assembly containment O-ring seal shall be performed in accordance with Section 8.2.2.1 prior to shipment.

7.1.1.6 Remove the socket set screws from the test ports of the vent port plug assembly. Visually inspect each socket set screw for excessive wear and/or damage in accordance with the applicable requirements of Section 8.2.3.3.

7.1.1.7 Loosen and remove the lid bolts. Visually inspect each lid bolt for excessive wear and/or damage in accordance with the applicable requirements of Section 8.2.3.3.

7.1.1.8 Attach the rigging to the lid.

7.1.1.9 Remove the lid from the cask. Visually inspect the lid O-rings and sealing surfaces in accordance with the applicable requirements of Sections 8.2.3.1 and 8.2.3.2. Apply a thin coating of vacuum grease to the exposed surfaces of the lid O-rings, as necessary to lubricate the elastomer surface.

Note: If the lid containment O-ring (i.e., the inner O-ring on the "Configuration A" lid or the middle O-ring on the "Configuration B" lid) is replaced, then the maintenance leak test of the lid containment O-ring shall be performed in accordance with Section 8.2.2.1 prior to shipment.

7.1.1.10 Remove the test/drain port cap assemblies from the lid test ports. Visually inspect each test/drain port cap assembly bolt for excessive wear and/or damage in accordance with the applicable requirements of Section 8.2.3.3.

7.1.1.11 If using cask Configuration B, remove the test port plug (screw) from the inner test ports. Visually inspect each test port plug for excessive wear and/or damage in accordance with the applicable requirements of Section 8.2.3.3. Visually inspect the test port plug fastener seal and sealing surfaces in accordance with the applicable requirements of Sections 8.2.3.1 and 8.2.3.2. Apply a thin coating of vacuum grease to the exposed surfaces of the test port plug fastener seal, as necessary to lubricate the elastomer surface.

Note: If the test port plug fastener seal requires replacement, then the maintenance leak rate test of the test port plug fastener seal shall be performed in accordance with the requirements of Section 8.2.2.1 prior to shipment.

7.1.1.12 Install lid alignment pins in the cask bolt ring.

7.1.1.13 Inspect accessible areas of the cavity for damage, loose materials, and liquids or moisture.

Note: Material removed from the cask cavity may be radioactively contaminated and shall be performed in accordance with the applicable precautions and safeguards.

7.1.1.14 For wet loading and optionally for dry loading, remove the drain port plug and visually inspect the drain port plug, fastener seal, and sealing surfaces in accordance with the applicable requirements of Sections 8.2.3.1 through 8.2.3.3. Apply a thin coating of vacuum grease to the exposed surfaces of the drain port plug seal, as necessary to lubricate the elastomer surface.

Note: If the drain port plug seal is replaced, then the maintenance leak test of the drain port plug seal shall be performed in accordance with Section 8.2.2.1 prior to shipment.

7.1.1.15 Engage the cask lifting (upper) trunnions with the lifting yoke and lift the cask.

7.1.1.16 If dry loading, move the cask and position it in the dry loading area. If wet loading, lower the cask into pool.

Note: Precautions should be taken to minimize possible spread of contamination, such as first filling the cavity with clean water or rinsing the sides of the cask with clean water as it is lowered into the pool.

7.1.1.17 Disengage and the lifting yoke from the cask lifting trunnions and remove the lifting yoke.

7.1.2 Loading of Contents

7.1.2.1 Confirm that the intended contents meet the requirements of the Certificate of Compliance for the 3-60B package and perform the following steps:

a. For contents loaded wet or which contain water, determine the maximum decay heat to limit hydrogen generation per Attachment 7.1, and verify the contents do not exceed this decay heat.

b. Ensure the contents, secondary container, and packaging are chemically compatible, i.e., will not react to produce flammable gases. The EPA's Chemical Compatibility Chart, Attachment 7.2, should be used to guide the evaluation of chemical compatibility.

Note: Payload qualification activities may be performed any time prior to initiating loading operations, but must be completed prior to shipment.

7.1.2.2 If dry loading, perform the following steps. If wet loading, proceed to Step 7.1.2.3

a. Load the contents into the cask cavity.

Note. Shoring may be used as necessary to minimize movement of contents during transport.

b. Attach rigging to the closure lid.

c. Lift the closure lid, align the closure lid to the cask body, and carefully lower the closure lid onto the cask.

d. Survey the cask for safe radiation levels and visually inspect the lid for proper seating.

e. Install two or more lid bolts hand tight.

f. Detach and remove the closure lid rigging.

g. Go to Step 7.1.2.4.

7.1.2.3 If wet loading, perform the following steps.

a. Load the contents into the cask cavity.

b. Attach rigging the closure lid.

c. Lift the closure lid, slowly lower the closure lid into the pool, align the closure lid to the cask body, carefully lower closure lid onto the cask and visually verify proper lid installation.

d. Disengage the crane hook from the lid rigging.

e. Engage the cask lifting trunnions with the lifting yoke.

f. Carefully lift the cask until the bottom end of the cask clears the surface of the pool and allow the water to drain from the cask cavity into the pool.

Note: The cask exterior may be rinsed with demineralized water while it is lifted out of the pool or suspended over the pool.

g. When water has stopped draining from the cask cavity, survey the cask for safe radiation levels and inspect the lid for proper seating.

Note: If the lid is not properly seated, it may either be returned to the pool for re-seating or moved to the preparation area for re-seating.

h. Move the cask to the preparation area.

i. Survey the cask for safe radiation levels.

j. Install two or more lid bolts hand tight.

k. Disengage the lifting yoke from the cask lifting trunnions and remove the lifting yoke.

l. Remove the rigging from the lid.

m. Using a vacuum or other suitable means to remove water from the holes for the lid bolts and vent port plug assembly bolts, and from the annular spaces between the lid O-rings.

7.1.2.4 Re-install the vent port plug assembly and drain port plug with their O-rings and fastener seal. Torque the drain port plug and vent port plug assembly bolts to 20 ± 2 ft-lbs.

7.1.2.5 Remove the alignment pins from the lid bolt holes.

7.1.2.6 Install the remaining lid bolts. Torque all lid bolts to 300 ± 30 ft-lbs.

7.1.2.7 Decontaminate the exterior surfaces of the cask as necessary.

7.1.3 Preparation for Transport

7.1.3.1 Perform pre-shipment leak tests of the cask lid, vent port plug, and drain port plug in accordance with the Section 8.2.2.2.

7.1.3.2 Install a test/drain port cap assembly in the drain port.

7.1.3.3 Install socket set screws in the vent port plug assembly test ports.

7.1.3.4 If using cask Configuration A, go to Step 7.1.3.7.

7.1.3.5 If using cask Configuration B, install the test port plug screws in the two inner test ports of the lid. Torque the test port plug screws to 20 ± 2 ft-lbs.

7.1.3.6 If using cask Configuration B, perform the pre-shipment leak tests of the two (2) inner test port plugs in accordance with the Section 8.2.2.2.

7.1.3.7 Install test/drain port cap assemblies in the lid test ports.

7.1.3.8 Engage the cask lifting trunnions with the lifting yoke, lift the cask, move it to the conveyance loading area, down end the cask onto the shipping cradle on the transport trailer, and attach the front and rear trunnion tie down equipment.

7.1.3.9 Lift the impact limiters, place them on the respective ends of the cask, and install the impact limiter fasteners. Torque the impact limiter fasteners to 75 ± 7 ft-lbs.

7.1.3.10 Attach the tamper-indicating seals to the cask as required.

7.1.3.11 Verify that external radiation and contamination levels do not exceed the limits of 49 CFR 173.441 or 49 CFR 173.443.

7.1.3.12 Verify that the exterior surface of the package does not exceed the temperature limits specified in 49 CFR 173.442.

7.2 Package unloading

Packages containing radioactive material in excess of Type A quantities shall be received, monitored, and handled by the licensee receiving the package in accordance with requirements in 10CFR20.1906 as applicable.

7.2.1 Receipt of Package from Carrier

7.2.1.1 Inspect the package to ensure there is no damage to the exterior that will impair its ability to function as intended. Perform a radiation and contamination survey of the exterior. Verify that the tamper-indicating seals are still attached.

7.2.1.2 Loosen and remove the fasteners the secure each impact limiter to the cask body. Attach rigging to the impact limiters and remove each impact limiter from the cask body.

7.2.1.3 Disconnect the front and rear trunnion tie down equipment.

7.2.1.4 The cask can be removed from the shipping cradle in either the vertical or horizontal orientation. If removed in the vertical orientation, upend the cask by lifting it from lifting trunnions using a lifting yoke, and then lift it vertically to remove it from the shipping craddle. If it is removed in the horizontal orientation, attach the lifting equipment to all four trunnions and lift the cask from the shipping cradle.

7.2.1.5 Place the cask in the work area in either the vertical or horizontal orientation.

7.2.2 Removal of Contents

7.2.2.1 (Optional Step). Open the vent port in the cask lid. Precautions must be taken to protect personnel opening the port from gases escaping while it is being opened.

7.2.2.2 Loosen the lid bolts and remove the lid.

7.2.2.3 Remove the contents from the cavity.

7.2.2.4 The cask may be removed from service for maintenance or other purposes, or it may reassembled per steps 7.1 or 7.3.

7.3 PREPARATION OF AN EMPTY PACKAGE FOR TRANSPORT

7.3.1 Preparation

7.3.1.1 Confirm the cavity is empty of contents are far as practicable

7.3.1.2 Survey the interior; decontaminate the interior if the limits of 10 CFR 428(e) are exceeded

7.3.1.3 Install the lid.

7.3.1.4 Install the lid closure bolts. Torque all bolt to 300±30 ft-lbs.

7.3.1.5 Re-install the vent and drain port plugs with their O-rings and seals. Torque the drain and vent port bolts to 20±2 ft-lbs.

7.3.1.6 Decontaminate the exterior surfaces of the cask as necessary.

7.3.1.7 Inspect the exterior and confirm it is unimpaired.

7.3.1.8 Attach lifting and handling equipment to the cask lifting trunnions, move the cask to the conveyance loading area, and mount the cask in its shipping cradle on the transport trailer.

7.3.1.9 Install the impact limiters.

7.3.1.10 Attach the tamper-indicating seals.

7.3.1.11 Confirm the requirements of 49 CFR 173.428 are met.

7.3.2 Special Preparations

No special preparations or procedures are required for transporting the 3-60B empty.

ATTACHMENT 7.1

DECAY HEAT LIMIT

The maximum allowable decay heat, W, that will result in a 5% hydrogen concentration at the end of the shipping period, T (conservatively set at 60 days), can be determined from the weight fraction of water in the contents and the void fraction, which is the smallest void volume in which hydrogen could collect divided by the cask cavity volume, V_{CC}, (105231 in^3 or 1,724,000 cm^3). With the shipment decay heat limited to W, the flammable gas (hydrogen) concentration is limited to less than 5% and the cask limit is not exceeded. W is determined as follows:

$$W = 4.46\text{watt} \times F_V \times F_{H2O}^{-1} \text{ or 500 watt, whichever is less}$$

where,

W = the maximum allowable decay heat in watts

F_V = void fraction

F_{H2O} = weight fraction of water in the contents

Decay Heat Limit Calculation Process (performed by the shipper's engineering staff or approved consultants)

1. Water Weight Fraction Determination

   1.1. Determine the mass of the secondary container (liner), M_L.

   1.2. Determine the mass of contents, M_C.

   1.3. Determine the mass of water in the cask, M_W, after de-watering, if applicable, and draining the cavity, if applicable.

   1.4. Calculate the water weight fraction, F_{H2O}
   $$F_{H2O} = M_W / (M_L+M_C+M_W)$$

2. Void Fraction Determination

   2.1. Determine the volume of contents, V_C

   2.2. Determine the interior volume (cavity) of the secondary container (liner), V_{IL}.

   2.3. Determine the exterior volume of the liner, V_{EL}.

   2.4. Calculate the void, V
   for a sealed liner,
   $$V = V_{IL} - V_C$$
   for an open or screened liner,
   $$V = V_{CC} - V_C - (V_{EL} - V_{IL})$$

2.5. Calculate the void fraction, F_V

$$F_V = V / V_{CC}$$

3. Decay Heat Limit Determination

3.1. Calculate the decay heat limit, W, in watts

$$W = 4.46 \times F_V \times F_{H2O}^{-1} \text{ or } 500 \text{ (the cask heat limit), whichever is less}$$

3.2. Ensure the radionuclide decay heat of the shipment contents does not exceed W.

Several examples of the calculation of the maximum decay heat for various contents and configurations follow.

EXAMPLE 1 - IRRADIATED HARDWARE

The hydrogen generation calculation for typical irradiated hardware waste forms loaded underwater depends on the amount of water in the cask cavity after the cask is drained. Acceptance testing of the cask after fabrication has demonstrated that no more than 2 gallons of water is retained in the cavity after draining. The liner is a screened steel canister 34-inch outer diameter by 108-inch long with ½-inch thick walls, base, and lid. The measured mass of the liner, M_L, is 1858 lbs. An engineering assessment of the irradiated hardware loaded into the liner by plant engineering staff has determined that no more than 2 gallons of water will be retained in the liner after draining. Thus, the total amount of water retained in the cask is 4 gallons, weighing 33 lbs (M_w). The cask contents are limited to 9500 lbs. To ensure compliance, the solid contents are limited by the user to 9400 lbs.

The mass of irradiated hardware, M_H, is 9400-1858 = 7542 lbs.

The water weight fraction, F_w, is:

$$F_w = M_w / (M_L + M_H + M_w)$$

$$F_w = 0.0035$$

The density of the irradiated hardware and the liner, ρ, is 8 g/cc or 0.289 lb/in^3

The volume of the cask cavity, V_{CC}, is 105231 in^3.

The volume of the contents, V_H, is:

$$V_H = M_H / \rho$$

The interior volume of the liner, V_{IL}, is

$$V_{IL} = \pi r^2 H = \pi \times (33/2)^2 \times (108\text{-}1)$$

The exterior volume of the liner, V_{EL}, is:

$$V_{EL} = \pi\, r^2\, H = \pi \times (34/2)^2 \times (108)$$

Since the liner has open screens at the bottom, the void, V, is

$$V = V_{CC} - V_H - (V_{EL} - V_{IL}) = 72573 \text{ in}^3$$

The void fraction, F_V, is:

$$F_V = VOID_H / V_{cavity}$$

$$F_V = 0.69$$

Thus, the decay heat limit, W, is:

$$W = 4.46 \text{ watts} \times F_V / F_w \text{ or } 500 \text{ watts, whichever is less}$$

$$W = 879 \text{ watts or } 500 \text{ watts, whichever is less}$$

$$W = 500 \text{ watts}$$

EXAMPLE 2 - DEWATERED SWARF

Swarf is contained in a sealed steel liner, 34-inch outer diameter by 108 inches long, dewatered to 1% of the waste volume. The mass of swarf is limited so the cask contents limit is not exceeded. The cask contents are limited to 9500 pounds. To ensure compliance, the solid contents are limited by the user to 9400 pounds.

The liner is a sealed steel canister with ½-inch thick walls, base, and lid. The mass of the liner, M_L, is 1858 pounds.

The liner has an internal volume of 1500 L.

The mass of swarf, M_{sw}, is:

$$M_{sw} = 9400\text{-}1858 = 7542 \text{ lbs}$$

Swarf has a measured density of 4.0 g/cc. Therefore, the volume of the swarf, V_{sw} is:

$$V_{sw} = 7542 \text{ lbs} \times 454 \text{ g/lb} \div 4.0 \text{ g/cc} = 856{,}000 \text{ cc}$$

The volume of water, V_w, after dewatering, is 1% of the swarf volume or:

$$V_w = 1\% \times V_{sw} = 8{,}560 \text{ cc}$$

With a density of 1 g/cc, the mass of water, M_w, is:

$$M_w = V_w \times 1 \text{ g/cc} = 8{,}560 \text{ g} = 18.9 \text{ lbs}$$

The water weight fraction, F_w, is:

$F_w = M_w / (M_L + M_{sw} + M_w) = 0.002$

The calculated volume of the cask cavity, V_{cavity}, is 105231 in^3 or 1,724,000 cc

The void in the liner is:

VOID = $V_L - V_{sw}$ = 1,500,000 – 856,000 = 644,000 cc

The void fraction, F_V, is:

$$F_V = VOID / V_{cavity}$$

$$F_V = 0.37$$

Thus, the decay heat limit, W, is:

W = 4.46 watts x F_V / F_w or 500 watts, whichever is less

W = 825 watts or 500 watts, whichever is less

W = 500 watts

EXAMPLE 3 – DE-WATERED INORGANIC RESIN

The resin is contained in a sealed metal liner, 34-inch outer diameter by 108 inches long, dewatered to 1% of the waste volume. The filling/dewatering process results in the liner being 85% full. The de-watered resin has a measured density of 0.65 g/cc. The liner is a sealed metal canister with ½-inch thick walls, base, and lid having a calculated internal volume of 1500 L (V_{IL}). The measured weight of the liner, M_L, is 1950 pounds.

The volume of the resin, V_R is:

V_R = 1500 L x 85% = 1,275,000 cc

The mass of resin, M_R, is:

M_R = 1,275,000 x 0.65 = 828750 g = 1825 lbs

The volume of water, V_w, after dewatering, is 1% of the resin volume or:

V_w = 1% x V_R = 12,750 cc

With a density of 1 g/cc, the mass of water, M_w, is:

$M_w = V_w$ x 1 g/cc = 12,750 g = 28.1 lbs

The water weight fraction, F_{H2O}, is:

$F_{H2O} = M_w / M_L + M_{sw} + M_w = 0.007$

The calculated volume of the cask cavity, V_{CC}, is 105231 in^3 or 1,724,000 cc

The void in the liner is:

$VOID = V_{IL} - V_R = 1{,}500{,}000 - 1{,}275{,}000 = 225{,}000$ cc

The void fraction, F_V, is:

$$F_V = VOID / V_{CC}$$

$$F_V = 0.13$$

Thus, the decay heat limit, W, is:

$$W = 4.46 \text{ watts} \times F_V \times F_{H2O}^{-1} \text{ or } 500 \text{ watts, whichever is less}$$

$$W = 83 \text{ watts or } 500 \text{ watts, whichever is less}$$

$$W = 83 \text{ watts}$$

EXAMPLE 4 – SOLIDIFIED LIQUID

An aqueous radioactive liquid is solidified with cement. Surrogate testing has established that a 60/40 cement to liquid ratio produces an acceptable solid product and a drying test shows that 50% of the water is unbound after curing. Only unbound water is subject to radiolysis. The solidified waste is contained in a sealed metal liner, 34-inch outer diameter by 108 inches long. The filling process results in the liner being 85% full. The surrogate waste has a measured density of 2 g/cc. The liner is a sealed metal canister with ½-inch thick walls, base, and lid having a calculated internal volume of 1500 L(V_{IL}). The measured weight of the liner, M_L, is 1950 pounds.

The volume of the solidified waste, V_{sw} is:

$V_{sw} = 1500 \text{ L} \times 85\% = 1{,}275{,}000$ cc

The mass of solidified waste, M_{sw}, is:

$M_{sw} = 1{,}275{,}000 \times 2 = 2{,}550{,}000 \text{ g} = 5617$ lbs

The mass of unbound water, M_{uw}, is:

$M_{uw} = M_{sw} \times 0.4 \times 0.5 = 1124$ lbs

The mass of bound water, M_{bw}, is:

$M_{bw} = M_{sw} \times 0.4 \times 0.5 = 1124$ lbs

The mass of cement, M_c, is:

$M_c = M_{sw}$ x 0.6 = 3370 lbs

The water weight fraction, F_{H2O}, is:

$F_{H2O} = M_{uw} / M_L + M_c + M_{uw} + M_{bw} = 0.15$

The calculated volume of the cask cavity, V_{CC}, is 105231 in^3 or 1,724,000 cc

The void in the liner is:

VOID = $V_{IL} - V_{sw}$ = 1,500,000 – 1,275,000 = 225,000 cc

The void fraction, F_V, is:

$$F_V = VOID / V_{CC}$$

$$F_V = 0.13$$

Thus, the decay heat limit, W, is:

W = 4.46 watts x F_V x F_{H2O}^{-1} or 500 watts, whichever is less

W = 3.9 watts or 500 watts, whichever is less

W = 3.9 watts

EPA's Chemical Compatibility Chart

EPA-600/2-80-076 April 1980
A METHOD FOR DETERMINING THE COMPATIBILITY OF CHEMICAL MIXTURES

Please Note: [illegible]

CODE	CONSEQUENCE
H	Heat Generation
F	Fire
G	Innocuous and non-flammable gas generation
GT	Toxic Gas formation
GF	Flammable Gas formation
E	Explosion
P	Violent Polymerization
S	Solubilization of toxic substance
U	May be hazardous, but Unknown

#	REACTIVITY GROUP NAME	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	101	102	103	104	105	106	107
1	Acids, Mineral, Non-oxidizing																																									
2	Acids, Mineral, Oxidizing																																									
3	Acids, Organic		G H																																							
4	Alcohols and Glycols	H	H F	H P																																						
5	Aldehydes	H P	H F	H P																																						
6	Amides	H	H GT																																							
7	Amines, Aliphatic and Aromatic	H	H GT	H		H																																				
8	Azo Compounds, Diazo Compounds and Hydrazines	H G	H GT	H G	H G	H																																				
9	Carbamates	H G	H GT						G H																																	
10	Caustics	H	H	H		H				H G																																
11	Cyanides	GT GF	GT GF	GT GF					G																																	
12	Dithiocarbamates	H,F GF	H,F GF	H,GT GF		GF GT		U	H G																																	
13	Esters	H	H F						H G		H																															
14	Ethers	H	H F																																							
15	Fluorides, Inorganic	GT	GT	GT																																						
16	Hydrocarbons, Aromatic		H F																																							
17	Halogenated Organics	H GT	H,F GT					H GT	H G		H GF	H																														
18	Isocyanates	H G	H,F GT	H G	H P			H P	H G		H,P G	H G	U																													
19	Ketones	H	H F						H G		H	H																														
20	Mercaptans and Other Organic Sulfides	GT GF	H,F GT						H G									H	H	H																						
21	Metals, Alkali and Alkaline Earth, Elemental	H,F GF	H,F GF	H,F GF	H,F GF	H,F GF	GF H	GF H	GF H	GF H	GF H	GF H	GF,H GT	GF H				H E	GF H	GF H	GF H																					
22	Metals, Other Elemental & Alloys as Powders, Vapors, or Sponges	H,F GF	H,F GF	G F					H,F GT	U	GF H							H E	GF H		H,F GF																					
23	Metals, Other Elemental & Alloys as Sheets, Rods, Drops, etc.	H,F GF	H,F GF						H,F G									H F																								
24	Metals and Metal Compounds, Toxic	S	S	S			S	S			S																															
25	Nitrides	GF HF	H,F E	H GF	H,E GF	GF H			U	H G	U	GF H	GF H	GF H				GF H	U	GF H	GF H	E																				
26	Nitriles	H,GT GF	H,F GT	H							U											H P			S	GF H																
27	Nitro Compounds, Organic		H,F GT			H					H E											H,E GF				H,E GF																
28	Hydrocarbons, Aliphatic, Unsaturated	H	H F			H																	H E																			
29	Hydrocarbons, Aliphatic, Saturated		H F																																							
30	Peroxides and Hydroperoxides, Organic	H G	H E		H F	H G		H GT	H,F E	H,F GT		H,E GT	H,F GT					H E	H	E	H,F GT	H E	H G		H G	H,E GF	H,P GT		H P													
31	Phenols and Cresols	H	H F						H G										H P			GF H				GF H					H											
32	Organophosphates, Phosphothioates, Phosphodithioates	H GT	H GT						U		H E											H									U											
33	Sulfides, Inorganic	GT GF	HF GF	GT		H			E										H												H GT											
34	Epoxides	H P	H P	H P	H P	U		H P	H P		H P	H P	U								H P	H P	H P		H P	H P					H P	H P	U	H P								
101	Combustible and Flammable Materials, Miscellaneous	H G	H,F GT																			H,F G				H,F GF					H,F GT											
102	Explosives	H E	H E	H E					H E		H E			H E								H E	H E	H E	E	E					H E	H E		H E	H E	H E						
103	Polymerizable Compounds	P H	P H	P H					P H		P H	P H	U									P H	P H	P H	P H	P H					P H	P H		P H			H E					
104	Oxidizing Agents, Strong	H GT		H GT	H F	H F	H,F GT	H,F GT	H E	H,F GT		H,E GT	H,F GT	H F	H F		H F	H GT	H,F GT	H F	H,F GT	H,F E	H,F E	H F		H,F E	H,F GT	H E	H F	H F	H G	H F	H,F GT	H,F GT	H,F G	H,F G	H E	H,F GT				
105	Reducing Agents, Strong	H GF	H,F GT	H GF	H,F GF	H,F GF	H GF	H G				H GT	H F				H,F E	H E	H GF	H GF	H GF						H GF	H E			H E	H GF	H,GT GF		H	H GF	H E	H,P GF	H,F E			
106	Water and Mixtures Containing Water	H	H						G										H G			H GF	H GF		S	H GF								GT GF						GF GT		
107	Water Reactive Substances	<—EXTREMELY REACTIVE! DO NOT MIX WITH ANY CHEMICAL OR WASTE MATERIAL! EXTREMELY REACTIVE!—>																																								

8.0 ACCEPTANCE TESTS AND MAINTENANCE PROGRAM

8.1 **Acceptance Tests**

Prior to the first use of the 3-60B package, the following tests and evaluations will be performed:

8.1.1 Visual Inspections and Measurements

Throughout the fabrication process, confirmation by visual examination and measurement are required to be performed to verify that the 3-60B packaging dimensionally conforms to the general arrangement drawing in Section 1.3.

The packaging is also required to be visually examined for any adverse conditions in materials or fabrication that would not allow the packaging to be assembled and operated per Section 7.0 or tested in accordance with the requirements of Section 8.0.

Throughout the fabrication process, the fabricator shall request approval from Energy*Solutions* prior to implementation of any options allowed in the drawing.

8.1.2 Weld Examinations

All package welds shall be examined to the requirements of general arrangement drawing in Section 1.3. Nonconforming welds shall be reworked or rejected.

8.1.3 Structural and Pressure Tests

8.1.3.1 Hydrostatic Pressure Test

Before the first use of the package and prior to the lead pour, the containment system will be subjected to a hydrostatic pressure test and inspected in accordance with the requirements of ASME Code, Section III, Division 1, Subsection ND, Article ND-6220 to verify the capability of the containment system to maintain its structural integrity at the test pressure. The hydrostatic test may be performed using temporary seals, which will later be replaced. Separate hydrostatic tests may be performed for the cask body containment system and the cask lid, provided that the testing conditions adequately simulate the cask body-to-lid interface. The hydrostatic pressure test will be performed using a test pressure not less than 52.5 psig (150% of the package MNOP), as required by 10CFR71.85(b). The acceptance criterion for the hydrostatic pressure test is no unacceptable leakage, in accordance with Article ND-6224. Nonconforming packages shall be reworked or rejected.

8.1.3.2 Lifting Trunnion Load Test

Before the first use of the package, the lifting trunnions shall be load tested in accordance with the requirements of ANSI N14.6 [8-4], Article 6.2.1 to verify the capability of the lifting trunnions and their connections to the cask outer shell to maintain structural integrity at the test load. The load test shall be performed on the finished Cask Body Assembly (Items A3 or A4). Alternatively, the load test may be performed prior after the Trunnions and Trunnion Back-Up Plates (Items 18 and 19) are welded to the Outer Cask Shell (Item 7), but prior to attaching the

Outer Cask Shell (Item 7) to the Bolt Ring (Item 6) to allow access to both sides of the Trunnion Back-Up Plate-to-Outer Cask Shell weld following the load test. A test load not less than 120,000 pounds (150% of the package gross weight) shall be applied to the lifting (upper) trunnions for a period of not less than 10 minutes. The critical areas of the lifting trunnions, including the welds between the Trunnion (Item 18) and Trunnion Back-Up Plate (Item 10) and between the Trunnion Back-Up Plate (Item 10) and the Outer Cask Shell (Item 7) shall be inspected by liquid penetrant (PT) examination in accordance with the requirements of ASME Code, Section III, Division 1, Subsection NF, Article NF-5350 before and after the test.

8.1.4 Leakage Tests

Prior to initial use, the package containment boundary of each newly fabricated package shall be leak rate tested in accordance with Section 8 of ANSI N14.5 [8-2] to verify that all containment boundary component base materials and containment welds satisfy the ANSI N14.5 leaktight acceptance criterion of 1×10^{-7} ref-cm^3/s. The acceptance leak rate test shall be performed using a written procedure based on the *Helium Mass Spectrometer Hood Testing* technique in accordance with Article 10, Mandatory Appendix IX of the ASME Code, Section V [8-5], which is the *Gas Filled Envelope* method described in Sections A.5.3 of ANSI N14.5 [8-2]. The procedure shall be approved by personnel that are certified in leak testing by a nationally recognized society (e.g., ASNT NDT Level III) and qualified in the specific methods used in the leak test procedure. Helium shall be used as the tracer gas for the acceptance leak rate test. A suitable helium leak detector with a minimum sensitivity of 5×10^{-8} ref-cm^3/s shall be used for the test. Calibration of the leak detector shall be performed using a leak rate standard traceable to NIST.

Acceptance leak testing of the cask body containment system, as described in Section 4.1, shall be performed prior to the lead pour to allow access to the outer surfaces of the inner vessel. For the package seal rings, leak testing of the base metal and the containment (inner) weld shall be performed prior to completing the outer seal weld to allow potential leaks in these containment components to be detected. Separate acceptance leak tests may be performed for the cask body assembly, cask lid assembly, and/or vent port plug assembly containment boundaries using test heads or manifolds, as appropriate. Furthermore, the acceptance leak test of the package containment system may be performed using temporary seals, which must be replaced prior to final acceptance. All containment system O-rings and seals that are not used for the acceptance leak test shall be subjected to the periodic/maintenance leak test described in Section 8.2.2.1 prior to initial use.

8.1.5 Component and Material Tests

Energy*Solutions* will apply its USNRC approved 10CFR71 Appendix B Quality Assurance Program, which implements a graded approach to quality based on a component's or material's importance to safety consistent with the guidance provided in NUREG/CR-6407 [8-3] to assure all materials used to fabricate and maintain the 3-60B package are procured with appropriate documentation which meet the appropriate tests and acceptance criteria for packaging materials.

8.1.5.1 Steel Materials

ASTM steel material used for shells, lids, bolts, etc. will comply with and meet ASTM manufacturing requirements.

8.1.5.2 Elastomeric O-rings and Seals

Containment O-rings will be made from elastomeric compounds (e.g., silicone rubber) that have been qualified based on hardness, low temperature compatibility, permeability, and temperature-pressure testing. Fabricated O-rings are acceptable for use provided that they are traceable to a batch of material manufactured under the same process and having the same chemical composition as a qualified elastomeric compound. Each batch of elastomeric material will be subjected to hardness and low temperature compatibility acceptance testing. In addition, each O-ring will be subjected to dimensional acceptance testing.

8.1.5.3 Impact Limiter Foam

The impact limiter foam will meet the requirements of ES-M-172 [8-1]. Each batch of foam shall be tested for material density, static crush strength, and flame retardancy. Foam not meeting the acceptance criteria shall be rejected.

8.1.6 Shielding Tests

Shielding integrity of the packaging will be verified by gamma scan or gamma probe methods to assure the packaging is free of significant voids in the poured shield annulus. All gamma scanning will be performed on a 4-inch square or less grid system. The acceptance criteria will be that voids resulting in shield loss in excess of 10% of the normal lead thickness in the direction measured shall not be acceptable. Any results not meeting this requirement will be remedied and the test and inspection will be repeated.

8.1.7 Thermal Tests

No thermal acceptance testing will be performed on the 3-60B packaging. Refer to the Thermal Evaluation, Section 3.0 of this report.

8.1.8 Miscellaneous Tests

The 3-60B will be tested to demonstrate the cavity will adequately drain in a vertical orientation. The acceptance criterion is: No more than 2 gallons of water may be retained in the cask cavity and drain port when the cask sits vertically on an essentially flat surface.

8.2 Maintenance Program

The 3-60B package will be subjected to a maintenance program that includes routine and periodic inspection, tests, and maintenance activities that are designed to ensure continued performance of the packaging. This section describes the periodic inspection, tests, and maintenance activities that are required, as well as the criteria for replacement and repair of components and subsystems on an as-needed basis. Table 8-1 provides a summary of the maintenance program requirements.

8.2.1 Structural and Pressure Tests

No routine or periodic structural or pressure testing will be performed on the 3-60B packaging.

8.2.2 Leakage Tests

8.2.2.1 Maintenance Leak Rate Test

Maintenance leak rate testing of all 3-60B package containment seals is required to be performed prior to returning the package to service following maintenance, repair, or replacement of any components of the containment system, in accordance with Section 7.4 of ANSI N14.5 [8-2]. As discussed in Section 8.2.3.1, maintenance leak rate testing is required annually, or within the 12-month period prior to any shipment, after the required replacement of all package O-ring and fastener seals. In addition, maintenance leak rate testing is required after replacement of any containment O-ring or fastener seal or after repair or replacement of and any containment sealing surface during for each use, as discussed in Section 8.2.3.1.

Maintenance leak rate testing of the 3-60B package is performed to the leaktight acceptance criteria of 1×10^{-7} ref-cm^3/s. The maintenance leak rate test shall be performed using a written procedure based on the *Helium Mass Spectrometer Hood Testing* technique in accordance with Article 10, Mandatory Appendix IX of the ASME Code, Section V, Subsection A [8-5], with the exception that the mass spectrometer instrument sensitivity need be no better than 1/10th of the acceptance criteria. The *Helium Mass Spectrometer Hood Testing* technique is the *Gas Filled Envelope* method described in Sections A.5.3 of ANSI N14.5 [8-2]. The procedure shall be approved by personnel that are certified in leak testing by a nationally recognized society (e.g., ASNT NDT Level III) and qualified in the specific methods used in the leak test procedure. Helium shall be used as the tracer gas for the maintenance leak rate test. A suitable helium leak detector with a minimum sensitivity of 5×10^{-8} ref-cm^3/s shall be used for the test. Calibration of the leak detector shall be performed using a leak rate standard traceable to NIST.

Any containment seal that does not satisfy the maintenance leak rate test acceptance criteria shall be reworked, replaced, or repaired, as required, and retested prior to returning the package to service The maintenance leak rate test results and any associated rework, replacement, or repairs shall be documented in a package maintenance log.

8.2.2.2 Pre-Shipment Leak Test

Pre-shipment leak testing of the loaded package is required before each shipment to verify that the containment system has been properly assembled for shipment. Pre-shipment leak tests of the cask lid O-rings and test port plug seals (Configuration B only), vent port plug O-rings, and drain port plug seal are required for all shipments, even if the port plugs have not been opened during loading operations. The only exception to this requirement is for the Configuration B cask lid O-ring seal, when the containment O-ring is replaced during loading operations. Under this scenario, the periodic/maintenance leak test described in Section 8.2.2.1 must be performed prior to shipment, and may be performed at the loading site. Since the periodic/maintenance leak test acceptance criterion is orders of magnitude more sensitive than that of the pre-shipment leak test (i.e., 1×10^{-3} ref-cm^7/s versus 1×10^{-3} ref-cm^3/s), there is no need to perform the pre-shipment leak test if the periodic/maintenance leak test is performed at the loading site and the cask lid bolts are not loosened prior to making the shipment.

Pre-shipment leak tests shall be performed using written procedures that follow the guidelines provided in Section 7.6 of ANSI N14.5 [8-2]. The pre-shipment leak test procedure shall be

based on the *Gas Pressure Drop* or *Gas Pressure Rise* methods, similar to those described in Sections A.5.1 and A.5.2 of ANSI N14.5. These tests are performed by either pressurizing test volume with dry air or nitrogen to a specified test pressure or pulling a vacuum on the test volume, and measuring the pressure drop or pressure rise within the test volume for a given period of time. The acceptance criterion for the pre-shipment leak test is no detectable leakage when tested to a sensitivity of 1×10^{-3} ref-cm^3/s. The pressure gauge used to perform the pre-shipment leak test shall have a range between 1.5 and 4 times the specified test pressure and be accurate to within 1%, or less, of its full scale.

The procedure for the pre-shipment leak test shall be approved by personnel that are certified by a nationally recognized society (e.g., ASNT NDT Level III) and qualified in the specific methods used in the leak test procedure. Furthermore, the procedure qualification is required to demonstrate that it will reliably produce a test sensitivity of 1×10^{-3} ref-cm^3/s or better. Procedure qualification shall be based on the guidance provided in Article 1, T-150(d) of the ASME Code, Section V, Subsection A [8-5] using a calibrated leak standard for the T-150(d)(2) test specimen. Any change in the essential variables identified in Mandatory Appendix VI, Table VI-1021 of the ASME Code, Section V, Subsection A [8-5] shall require requalification of the written procedure, in accordance with the requirements of Article 10, T-1021.3 of the ASME Code, Section V, Subsection A [8-5]. Alternatively, leak test procedures that rely upon detection of a system calibrated leak standard in each performance of the test do not require separate procedure qualification, as these procedures are inherently qualified each time they are performed.

Any containment seal that does not satisfy the pre-shipment leak test acceptance criteria shall be inspected, cleaned (if needed), reassembled, and retested prior to shipment. Any containment seal that does not satisfy the pre-shipment leak test acceptance criteria after repeated attempts, may require replacement of the O-ring seal or fastener seal or repair of the sealing surface. As discussed in Sections 8.2.3.1 and 8.2.3.2, a maintenance leak rate test is required for all new/replaced containment O-ring and fastener seals and any repaired sealing surfaces for containment O-rings and fastener seals. Replacement of non-containment O-rings (i.e., test O-rings and the vent/drain port cap O-rings) and repair of sealing surfaces for non-containment O-rings does not require a maintenance leak rate test.

A typical pre-shipment leak test procedure based on the *Gas Pressure Drop* method, which incorporates a system calibrated leak standard, is provided for references below. The following procedure it typical of the procedure that could be used for the pre-shipment leak test of the lid O-ring seals (for both Configuration A and Configuration B) and the vent port plug O-ring seals. As shown in the drawing in Section 1.3, two (2) test ports, located 180° apart, provide access to the interspace volumes between O-rings for the purpose of leak testing. The Configuration B lid, which includes three O-rings, can be leak tested using either the inner or outer interspace volumes and corresponding test ports. The procedure for performing the pre-shipment leak test of the lid and vent port plug O-ring seals is as follows:

1. Connect the pre-shipment leak test manifold and gas supply to test port #1 of the test object and connect a calibrated leak (1×10^{-3} ref-cm^3/s) to test port #2 of the test object, as shown in Figure 8-1.

2. Close vent valve, V_{atm}, open valves to the test gas supply, V_{gas}, and calibrated leak, V_{leak}, and pressurize the test volume to an initial pressure range of 16 to 21 psig.

3. Close the test gas supply valve, V_{gas}, and wait for at least two (2) minutes for thermal stabilization, adding test gas as needed to maintain the test pressure within the acceptable range during the thermal stabilization period, then turn on the vacuum pump to evacuate the air from the test volume.

4. After the end of the thermal stabilization period, record the pressure reading, P_1, and monitor elapsed time until the pressure reading has decreased by at least 10 divisions on the pressure gauge (i.e., a division being the smallest increment or resolution of the pressure gauge). After the pressure has dropped by at least 10 divisions on the pressure gauge, record the pressure reading, P_2, and the elapsed time, Δt_1.

5. Close the calibrated leak valve, V_{leak}, wait at least three (3) seconds, record the pressure reading, P_3, wait for a time of at least Δt_1 (from step 4), and then record the pressure reading, P_4, and the elapsed time, Δt_2.

6. If there has been no detectable change in the test pressure (i.e., if $P_3 - P_4$ is less than 1 division on the pressure gauge), then promptly open the calibrated leak valve, V_{leak}, wait at least three (3) seconds, record the pressure reading, P_5, wait for a time of at least Δt_1 (from step 4), and then record the pressure reading, P_6, and the elapsed time, Δt_3.

7. Calculate the following values based on the test records:

   $P_{DR1} = (P_1\text{-}P_2)/\Delta t_1$, Pressure decay rate of the pre-measurement calibration

   $P_{DR2} = (P_5\text{-}P_6)/\Delta t_3$, Pressure decay rate of the post-measurement calibration

8. The pre-shipment leak test results are acceptable and valid if the following conditions are met:

   a. The pressure drop during the pre-measurement calibration is greater than 10 division on pressure gauge (i.e., $(P_1\text{-}P_2) \geq 0.1$ psi for division of 0.01 psi)

   b. The elapsed time for the pre-measurement pressure decay, Δt_1, is less than 5 minutes (300 seconds).

   c. The pressure drop during the post-measurement calibration is greater than 8 divisions on pressure gauge (i.e., $(P_5\text{-}P_6) \geq 0.08$ psi for division of 0.01 psi)

   d. The pre-measurement and post-measurement leak rates are within ±30% of each other (i.e., $0.77 \leq P_{DR1}/P_{DR2} \leq 1.42$).

   e. No detectable change in the test pressure occurs during the test (i.e., $P_3 - P_4$ is less than 1 division on the pressure gauge.)

8.2.3 Component and Material Tests

The following sections describe the inspection, test, and maintenance activities required for the various packaging components. A summary of the maintenance program requirements is provided in Table 8-1.

8.2.3.1 O-rings and Seals

Prior to each shipment, all accessible package O-ring seals and fastener seals are visually inspected for any damage or defects (e.g., cracks, tears, cuts, or discontinuities) that may prevent them from sealing properly when the package is assembled. If the vent port plug and/or drain port plug are not removed during the loading operations, the associated O-ring and fastener seals are not subjected to visual inspection. However, a pre-shipment leak test is required for all containment O-ring and fastener seals to verify that the package is properly assembled for shipment, as discussed in Section 8.2.2.2. Damaged or defective O-ring and fastener seals shall be replaced with new seals that meet the requirements on the drawing in Section 1.3 and the requirements of Section 8.1.5.2, as applicable. A maintenance leak rate test is required for all new containment O-ring and fastener seals, per Section 8.2.2.1. The lid and vent port plug test O-rings and the vent/drain port cap assembly O-ring, which do not provide containment, do not require a pre-shipment leak test or periodic/maintenance leak test when replaced. The inspection results and any necessary O-ring or fastener seal replacements and required leak tests shall be documented in a package maintenance log.

All package O-ring and fastener seals shall be replaced annually, or within the 12-month period prior to any shipment, with new seals that meet the requirements on the drawing in Section 1.3 and the requirements of Section 8.1.5.2, as applicable. A maintenance leak rate test is required for all containment O-ring and fastener seals that are replaced annually, per Section 8.2.2.1. Test O-rings that are replaced annually do not require a maintenance leak rate test, however, they are used to perform the maintenance leak rate test of the associated containment O-ring. The vent/drain port cap assembly O-ring, which only serves as a dust/weather seal, does not require any leak testing when replaced. The annual replacement of O-ring or fastener seal and the required leak tests shall be documented in a package maintenance log.

New O-ring and fastener seals shall be lightly coated with a lightweight lubricant, such as Parker Super O-Lube or equivalent, prior to installation to minimize deterioration or cracking of the elastomer during usage and the potential for tearing if removal from the dovetail groove is necessary for inspection. The exposed surfaces of installed O-ring and fastener seals that do not require replacement shall also be coated with the lightweight lubricant prior to assembling the package to minimize deterioration or cracking of the seal during use. Remove excess lubricant from the O-ring and fastener seals prior to assembling the package.

8.2.3.2 Sealing Surfaces

Prior to each shipment and annually, or within the 12-month period prior to any shipment, the sealing surfaces for all O-rings and fastener seals shall be cleaned and inspected for wear and/or damage (e.g., scratches, gouges, nicks, cracks, etc.) that may prevent the containment O-rings and fastener seals from sealing properly. Worn or damaged sealing surfaces may be repaired using emery cloth or other suitable polishing agent to restore the surface finish as required for proper sealing. A maintenance leak rate test is required for all repaired sealing surfaces for

containment O-rings and fastener seals, per Section 8.2.2.1. Repaired sealing surfaces for non-containment O-rings (i.e., test O-rings and the vent/drain port cap O-rings) do not require a maintenance leak rate test. The inspection results and any necessary sealing surface repairs and leak tests shall be documented in a package maintenance log.

8.2.3.3 Fasteners

Prior to each shipment, all package threaded fasteners (e.g., impact limiter attachments, lid bolts, vent port plug assembly bolts, test and drain port plugs, vent/drain port cap assembly, including associated washers) that are removed during package loading operations shall be visually inspected for excessive wear and/or damage. However, if the vent port plug and/or drain port plug are not removed during the loading operations, the associated fasteners do not require visual inspection. In addition, all package threaded fasteners shall be visually inspected for excessive wear and/or damage annually, or within the 12-month period prior to any shipment.

Fasteners that have minor damage or wear may be refurbished by chasing the threads. Barbs may also be removed, taking care not to cause further thread damage. Minor surface corrosion on fasteners may be removed by polishing with and emery cloth or other fine abrasives. Fasteners that show visible signs of excessive wear or significant corrosion or damage shall be replaced with new fasteners that meet the requirements on the drawing in Section 1.3. The inspection results and any necessary fastener repairs and replacements shall be documented in a package maintenance log.

Tapped holes for threaded fasteners do not require visual inspection. Tapped holes may be refurbished by chasing the threads or repaired as necessary using threaded insert per the drawing in Section 1.3. Annually, or within the 12-month period prior to any shipment, all fastener holes with threaded inserts shall be visually inspected to verify that the threaded inserts are not displaced or damaged.

Displaced threaded inserts shall be re-positioned and secured in the hole or replaced with a new threaded insert, as necessary. Damaged threaded inserts shall be replaced with new threaded inserts that meet the applicable requirements on the drawing in Section 1.3. The associated assemblies shall be functionally tested to confirm proper fit and function of the threaded connections. The inspection results and any necessary thread insert repairs and replacements shall be documented in a package maintenance log.

8.2.3.4 Exposed Package Surfaces

Prior to each shipment, the exterior of the package, including the impact limiters and cask assembly, is visually inspected to verify that its physical condition is unimpaired. Superficial defects on the exterior of the package, such as marks, scratches, or dents, do not require repair. However, any significant damage the package exterior, such as holes in the steel skins on the impact limiters or cask thermal shield, shall be repaired prior to shipment. The inspection results and any necessary repairs to the exterior of the cask shall be documented in a package maintenance log.

Annually, or within the 12-month period prior to any shipment, all exposed interior and exterior surfaces of the cask body assembly, cask lid assembly, vent port plug assembly, and impact limiter assemblies, shall be visually inspected for damage or degradation that could impair the

physical condition of the package. Superficial defects, such as minor surface corrosion, scratches, blemishes, and adhered material/particles, may be removed by polishing the package surfaces with emery cloth or other fine abrasives. Significant damage of the package exterior shall be repaired to restore the packaging to the applicable requirements on the drawing in Section 1.3 or the damaged components may be replaced. Replacement components shall satisfy the applicable requirements on the drawing in Section 1.3 and the applicable acceptance tests described in Section 8.1. The inspection results and any necessary repairs to the package surfaces or replacement of packaging components shall be documented in a package maintenance log.

Painted surfaces, identification markings, and match marks used for closure orientation shall be visually inspected annually, or within the 12-month period prior to any shipment, to ensure that painted surfaces are in good condition, identification markings are legible, and that match marks used for closure orientation remain legible and are easy to identify.

Lifting attachments (e.g., lift lugs and trunnions) and their welded attachments to the package shall be inspected annually, or within the 12-month period prior to any shipment, to verify that there is no evident permanent deformation and no obvious damage or defects. Damaged or defective lifting attachments shall be repaired or replaced in accordance with the applicable requirements on the drawing in Section 1.3 and the applicable acceptance tests described in Section 8.1.

8.2.4 Thermal Tests

No periodic or routine thermal testing will be performed on the 3-60B packaging.

8.2.5 Miscellaneous Tests

No other miscellaneous testing is required on the 3-60B packaging.

8.3 **Appendices**

8.3.1 References

[8-1] Polyurethane Foam Specification ES-M-172.

[8-2] ANSI N14.5, "American National Standard for Radioactive Materials – Leakage Tests on Packages for Shipment," 1997.

[8-3] NUREG/CR-6407, Classification of Transportation Packaging and Dry Spent Fuel Storage System Components Accordance to Importance to Safety, February 1996.

[8-4] ANSI N14.6, "American National Standard for Radioactive Materials – Special Lifting Devices for Shipping Containers Weighing 10000 Pounds (4500 kg) or More," 1993.

[8-5] ASME Boiler and Pressure Vessel Code, Section V, *Nondestructive Examination*, Subsection A, *Nondestructive Methods of Examination*, 2013 Edition, July 1, 2013.

Table 8-1 - Package Maintenance Program Summary

Item/Component	Reference SAR Section	Inspection/Test/Maintenance[(1)]		
		Each Use	Replace / Repair[(2)]	Annual
Lid Containment O-ring	8.2.3.1	V, T1	T2	R, T2
Lid Test O-ring(s)	8.2.3.1	V		R
Lid Test Port Plug Seal	8.2.3.1	V, T1	T2	R, T2
Vent Port Plug Containment O-ring	8.2.3.1	V, T1	T2	R, T2
Vent Port Plug Test O-ring	8.2.3.1	V		R
Drain Port Plug Seal	8.2.3.1	V, T1	T2	R, T2
Sealing Surfaces	8.2.3.2	V	T2	V
Lid Closure Bolts	8.2.3.3	V		V
Lid Test Port Plugs	8.2.3.3	V		V
Vent Port Plug Closure Bolts	8.2.3.3	V		V
Drain Port Plug	8.2.3.3	V		V
Vent Port Plug Test Port Plugs	8.2.3.3	V		V
Vent Drain Port Cap Assembly	8.2.3.3	V		V
Vent/Drain Port Cap Assembly O-ring	8.2.3.1	V		R
Lid Lift Hole Set Screws	8.2.3.3			V
Impact Limiter Attachments	8.2.3.3	V		V
Tapped holes[(3)]	8.2.3.3			
Threaded Inserts	8.2.3.3			V
Exposed Package Exterior Surfaces	8.2.3.4	V		V
Exposed Package Interior Surfaces	8.2.3.4			V
Nameplate/package markings	8.2.3.4			V
Lifting Attachments	8.2.3.4			V, T3

Notes:

(1) R = Replace; V = Visual inspection; T1 = Pre-shipment leak test; T2 = Maintenance leak rate test; T3 = Load test.

(2) Tests or inspections necessary when item is repaired or replaced.

(3) Tapped bolt holes without threaded inserts.

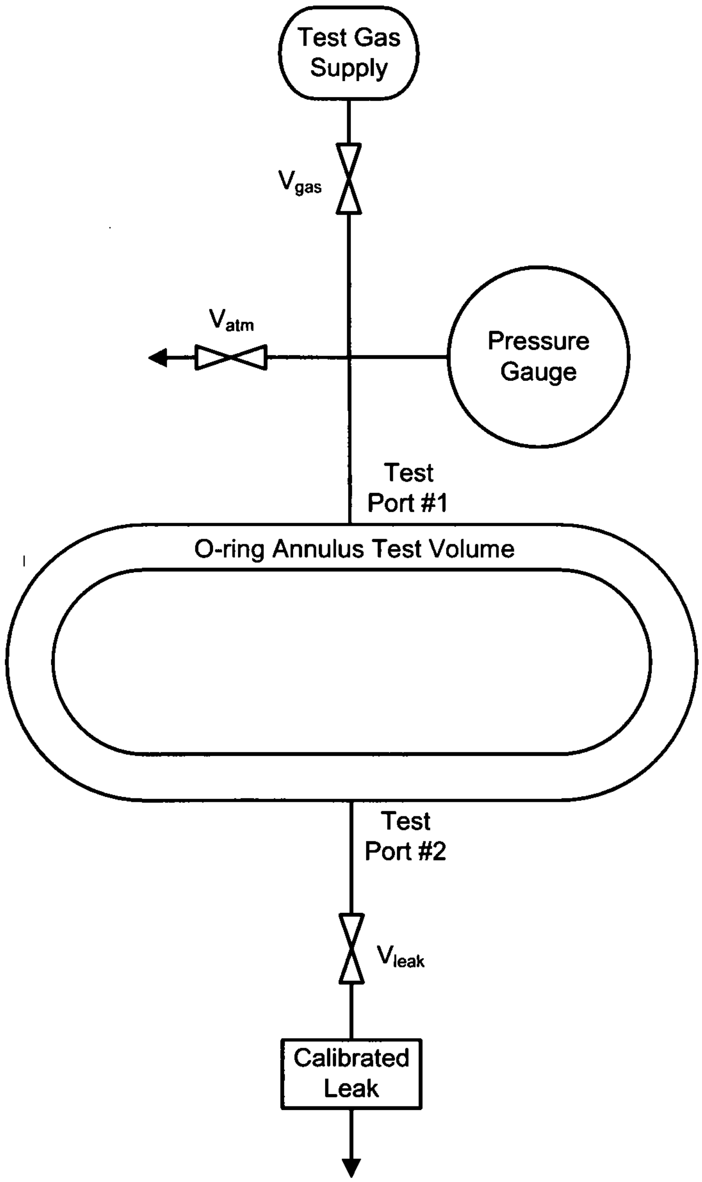


Figure 8-1 - Pre-Shipment Leak Test Configuration for O-Ring Annulus (Typical)