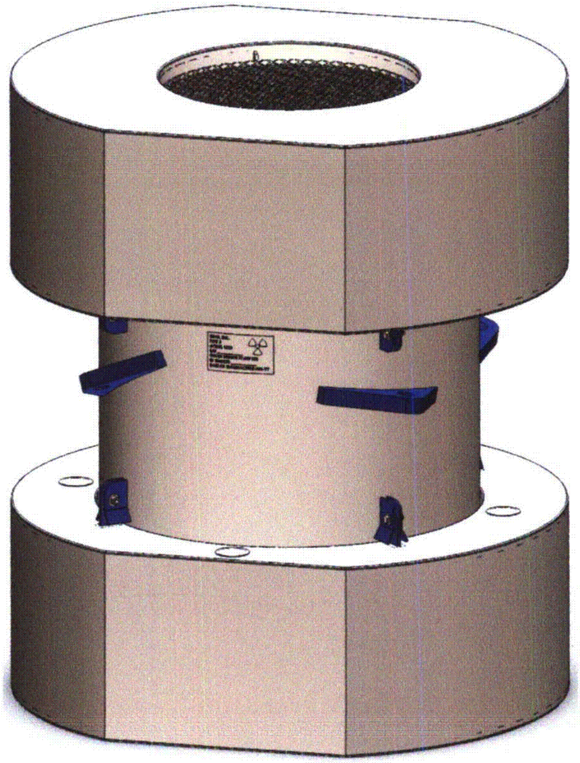
WMG-150B TYPE B CASK



SAFETY ANALYSIS REPORT

DOCKET NUMBER 71-9366

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1.0 GENERAL INFORMATION

1.1 Introduction

This document presents the drawings, specifications, analyses and documentation to demonstrate that the radioactive materials package, designated WMG 150B, complies with requirements of 10CFR Part 71 for transport of Type B quantities of radioactive material. The package is designed to transport Type B quantities of solid radioactive materials in the form of dewatered or solidified resins and sludges, solidified or dewatered filter assemblies, or activated metals components placed in disposable metal or polyethylene containers that, in the absence of shoring, essentially fill the package cavity. The design features of this package are similar to those that have historically been used to transport similar quantities and kinds of Type B quantities of radioactive materials such packages designated 10-142B, 8-120B and 10-160B. The design features of the WMG 150B package improve on earlier designs, particularly with regard to use of high strength steel for structural members and the design of the closure seal. The WMG 150B package also employs toroidal impact limiters consisting of canned rigid fire retardant polyurethane. The impact limiters have been truncated in the transverse direction to minimize truck width.

The form and content of this document complies with Regulatory Guide 7.9 and the drawings enclosed conform to NUREG/CR-5502. Other relevant USNRC Guides, NUREGs and Bulletins as well as relevant ANSI and ASME standards are cited throughout the document. This application was prepared under WMG's 10 CFR Part 71 Quality Assurance Program Description and the package will be manufactured under WMG's 10 CFR Part 71 Quality Assurance Program.

The WMG 150B is not intended for the packaging and transport of fissile material in quantities in excess of those exempted from consideration in accordance with 10 CFR 71.15. A Criticality Safety Index is not applicable.

1.2 Package Description

This section summarizes design aspects of the WMG 150B, its contents, and its modes of operation.

1.2.1 General Packaging Description

The WMG 150B shipping cask is a lead shielded cask for transport of solid radioactive material. The package configuration is shown in Figures 1-1 and 1-2. The overall dimensions of the cask with impact limiters are 129 inches high by 106 ½ inches in diameter in the fore and aft direction. In the transverse direction the impact limiters are 101 ½ inches from flat to flat.

The cask consists of two concentric carbon steel shells surrounding a 3-3/8 inch lead shield. The 3/4 inch thick inner shell has a 66 inch inner diameter and the outer shell has a 77 ½ inch outer diameter. A step welded primary lid is attached to the upper flange of the cylindrical shells by 24, 1-1/2 inch - 6 UNC x 4 inch long cap screws and washers. The primary lid is comprised of a 6 inch thick weldment of three carbon steel plates. The base consists of a 3-1/4 inch thick outer carbon steel plate and a ¾ inch thick inner carbon steel plate with 1-1/2 inches of lead between them. The center 38 inch diameter of the outer base plate will be milled if an optional ¼" thick insulation disk is used. The base carbon steel plates are welded to the cylindrical shells. The primary lid to upper flange joint is sealed with two 3/8 inch diameter fluroelastomer gaskets with a test port between them. Centered within the primary lid is a 41-3/4 inch diameter secondary lid comprised of a 3 inch thick carbon steel outer plate, 1 ½ inches of lead shield and a ¾ inch carbon steel inner plate. The secondary lid is also sealed with two 3/8 inch diameter fluroelastomer gaskets with a test port between them and closed with 15, 1-1/2 inch diameter equally spaced cap screws.

The containment cavity has a 66 inch inner diameter (less liner) and is 76 inches high (less liner). The primary lid is provided with plugged pressurization and test ports and the secondary lid has a plugged test port. A cross section of the cask is shown in Figure 1-1. The cavity surfaces are covered with a 12 gauge stainless steel liner to facilitate decontamination.

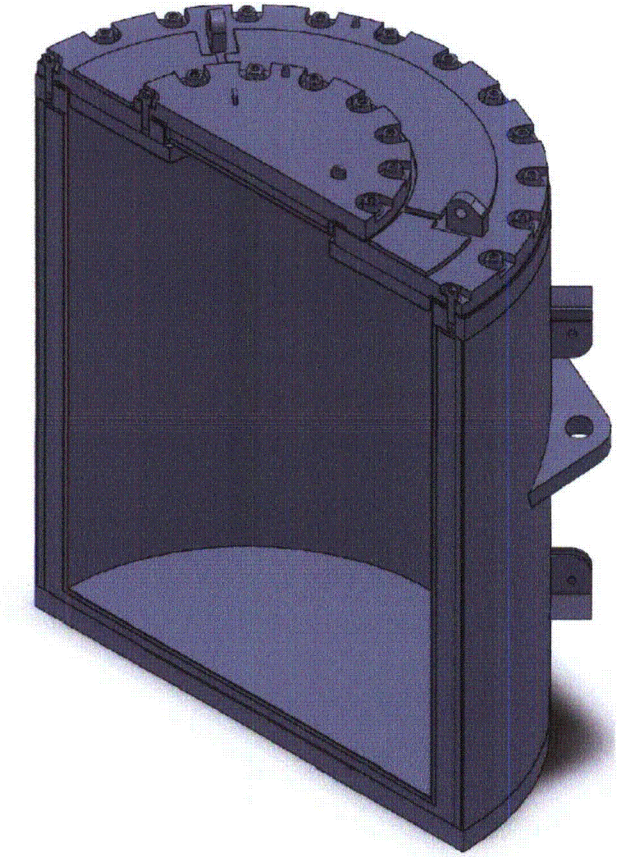

FIGURE 1-1 – WMG 150B Cask Body & Lid Cutaway

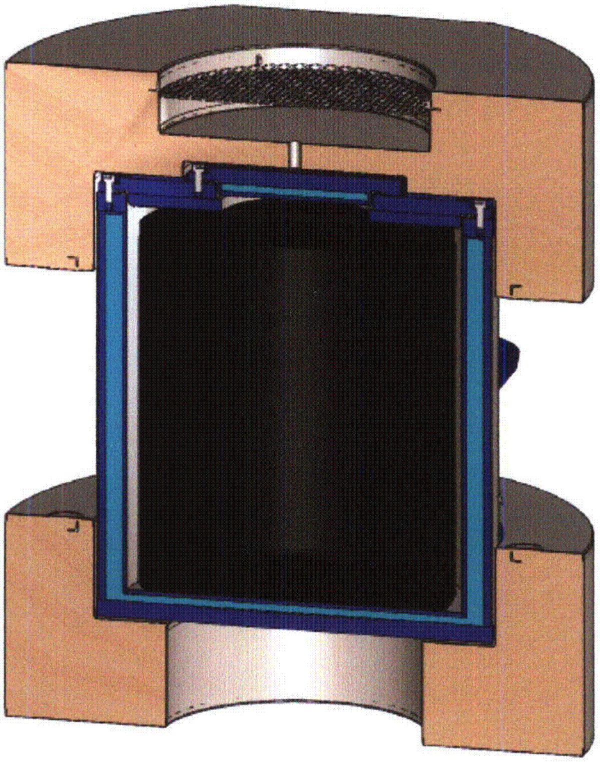

FIGURE 1-2 – WMG 150B Cask Package Cutaway

The top and bottom impact limiters are toroidal in shape and are comprised of 11 gauge stainless steel cans filled with fire retardant crushable polyurethane. The rigid foam is sprayed into the cans and allowed to expand until all voids are filled. Note that the upper impact limiter covers the secondary lid acting as a thermal shield for the secondary lid closure seal. The foam bonds to the shell, thus providing for unitized construction of the limiters. Rolled angle iron rings are used for enhanced lifting of the impact limiter assembly. The upper and lower impact limiters are secured to the cask body with a series of twelve bolted fastener assemblies (six top and six bottom) equally spaced around the periphery of the cask body.

The cask outer side walls are covered with 7 gauge stainless steel sheet functioning as a thermal barrier by providing an air barrier between the wall of the outer carbon steel cylinder and the stainless steel sheeting. There are twelve pair of clevis tie down attachments welded to the outer carbon steel cylinder for impact limiter attachment.

Appendix 1.3 contains general arrangement drawings for the package and includes dimensions and materials specifications.

1.2.1.1 Overall Dimensions

	With Impact Limiters	Without Impact Limiters	Cavity
Height	129 in	91-3/4 in	76 in
Maximum Diameter	106 ½ in	77-1/2 in	66 in
Across Limiter Flats	101-1/2	N/A	N/A

1.2.1.2 Package Weight

The empty WMG 150B cask weighs 52,000 lbs. without impact limiters and is designed for a gross weight of 77,500 lbs. including a 15,500 lb. payload.

1.2.1.3 Containment Features

The WMG 150B containment boundary consists of the inner steel shell of the cask body together with closure features comprised of the primary and secondary bearing and seal rings, inner O-rings, pressurization port, cask lids and cap screws.

1.2.1.4 Test and Pressure Ports

The primary lid contains pressurization and test ports while the secondary lid contains a test port. Each port is plugged and sealed with a silicone gasket.

1.2.1.5 Neutron Shielding

The WMG 150B was not designed to provide effective neutron shielding. There are no materials specifically designated as neutron absorbers or moderators in the package.

1.2.1.6 Gamma Shielding

The cask walls provide a shield thickness of 3-3/8 inch of lead plus 2 inches of steel for a 5-3/8 inch wall thickness (neglecting stainless steel inner liner and outer thermal-shield). The primary lid provides 6 inches of steel shielding. The secondary lid provides 1-1/2 inch of lead plus 3-3/4 inches of steel shielding (neglecting stainless steel inner liner). The cask bottom contains 4 inches of steel plus 1 ½ inches of lead (neglecting stainless steel inner liner). The contents of the package will be limited to assure that radiation levels at the cask exterior comply with DOT and IAEA regulatory requirements.

The WMG 150B does not require the use of personnel barriers to meet DOT and IAEA dose rate regulatory requirements.

1.2.1.7 Criticality Control Features

The WMG 150B is not intended for the packaging and transport of fissile material in quantities in excess of those exempted from consideration in accordance with 10 CFR 71.15. Design features of the WMG 150B were not specifically intended for as criticality control features.

1.2.1.8 Structural Features – Lifting Devices

Lifting and tie-down devices are a structural part of the package. Three equally spaced lifting lugs are attached to the primary cask lid for both cask and primary lid handling. A second set of smaller lifting lugs are attached to the secondary lid for its handling. The General Arrangement drawings in Appendix 1.3 show these lifting lugs and their attachment to the primary and secondary lids. During transport, these lifting lugs are under the upper impact limiter. Thus, cask lifting requires removal of the upper impact limiter. Section 2.5 presents a detailed analysis of these lifting lugs.

1.2.1.9 Structural Features – Tie-Down Devices

Tie-down devices are also structural part of the package. The General Arrangement drawing in Appendix 1.3 show four tie-down devices for attachment of the cask body to the trailer bed. Section 2.5 presents a detailed analysis of the cask tie-down devices.

1.2.1.10 Structural Features – Impact Limiters

The WMG 150B is afforded shock and thermal protection by torodial upper and lower impact limiters. The external shell of each impact limiter is made from 11 gauge stainless steel and is filled with fire retardant crushable polyurethane foam. The upper impact limiter covers the secondary lid and acts as a thermal shield for the secondary lid closure seal. Rolled angle iron rings are used for enhanced lifting of the impact limiter assemblies. The General Arrangement drawing in Appendix 1.3 show the upper and lower impact limiters are secured to the cask body with a series of twelve 1 inch bolted clevis attachment assemblies (six top and six bottom) equally spaced around the periphery of the cask body. Section 2.7 presents a detailed analysis of the impact limiter attachment devices.

1.2.1.11 Structural Features – Internal Positioning Devices

WMG 150B cavity contents, placed in disposable metal or polyurethane secondary containers that essentially fill the cavity in the radial and axial directions do not require any internal positioning device. Secondary containers substantially smaller than the cavity will be shored in the radial or axial directions as needed by the user to essentially fill the cavity and avoid excess movement of the cavity contents.

1.2.1.12 Structural Features – Outer Shell

The WMG 150B uses a 1-1/4 inch thick cylindrical outer carbon steel shell to provide shock and shielding protection. Tie-down loads are also transmitted via the outer shell.

1.2.1.13 Structural Features – Closure Devices

Access to the WMG 150B cavity for contents is accomplished by primary and secondary lids. Both the primary and secondary lids are precisely located in only one azimuthal orientation by the use of two 3/4 inch diameter tapered locating pins on the Primary lid and one pin on the Secondary lid. A step welded primary lid is attached to the upper flange of the cylindrical shells by 24, 1-1/2 inch - 6 UNC x 4 inch long cap screws and washers. The primary lid is comprised of a 6 inch thick weldment of three carbon steel plates. Centered within the primary lid and closed with 15, 1-1/2 inch diameter equally spaced cap screws, is a 41-3/4 inch diameter secondary lid comprised of a 3 inch thick carbon steel outer plate, 1 ½ inches of lead shield and a ¾ inch carbon steel inner plate.

Both lid joints are sealed by two 3/8 inch diameter fluroelastomer gaskets with a test port between them. The gaskets are retained by milled grooves in stainless steel seal plates that butt-up against stainless steel bearing plates. The surface of the bearing plate is polished to help ensure a good seal with the fluroelastomer gasket.

1.2.1.14 Heat Transfer Features

There are no special provisions for dissipation of heat from the WMG 150B cask cavity outwards. However, the impact limiters and outer stainless steel sheet are designed to insulate the WMG 150B cask during Hypothetical Accident Conditions. The insulation provided by the upper impact limiter helps protect the lid seals. The air gap between the outer carbon steel cylindrical wall and the outer stainless steel sheet helps protect the cylindrical lead shield. As discussed in Section 1.2.1, a 38 inch diameter ¼ inch thick alumina insulating disk may be used as an option to protect the lead in the cask base, if required.

1.2.1.15 Packaging Markings

A name plate will be affixed to the outer stainless steel sheet that identifies the package as WMG 150B, 71-9366, Type B(U)-96, 77,500 lbs Gross Weight, and the nuclear trefoil.

1.2.1.16 Additional Information

There are no receptacles on the WMG 150B cask.

The WMG 150 B cask does not use any coolants.

There are no WMG 150B cask protrusions other than the lifting and tie-down lugs.

1.2.2 Contents

The authorized contents of the WMG 150B cask are generally described in the following sections and more fully described in Chapter 5.

1.2.2.1 Identification and Maximum Quantity

The WMG 150B cask contents shall consist of:

1) Radioactive material in secondary containers.
2) Radioactive material that does not contain more than 200 thermal watts of radioactive decay heat.
3) The weight of the cask cavity contents will be limited to 15,500 lbs
4) The activity of all radionuclides shall not exceed 3,000 A2 and shall be less than 100 curies of Co-60 or equivalent, subject to the shielding limitations (Chapter 5) determined in accordance with Attachment 7-1 in Chapter 7.

1.2.2.2 Identification and Maximum Quantity of Fissile Material

WMG 150B cask contents shall satisfy the requirements for exemption from classification as fissile material of 10 CFR 71.15, hence fissile material shall not be transported in the WMG 150B.

1.2.2.3 Contents Chemical and Physical Forms

The types and forms of radioactive material contents shall include:

1) By product source or special nuclear material consisting of process solids in the form of dewatered or solidified resins and sludges, dewatered, solid or solidified filter assemblies, and dewatered, solid or solidified filter media, all in secondary containers.
2) Neutron activated metals or metal oxides in solid form in secondary containers.
3) Miscellaneous radioactive solid waste materials including special form materials in secondary containers.

The density of the contents will vary substantially depending on the actual material. Generally, density of the contents can range from 0.5 g/cc for some metal oxides to as much as 12 g/cc for some neutron activated metals.

1.2.2.4 Location and Configuration

WMG 150B contents are packaged in metal or polyurethane secondary containers that essentially fill the cavity in the radial and axial directions. Secondary containers substantially smaller than the cavity will be shored in the radial or axial directions as needed by the user to essentially fill the cavity and avoid excess movement of the cavity contents.

1.2.2.5 NonFissile Material Absorbers or Moderators

Because the WMG 150B cask is not used to transport materials classified as fissile, there are no nonfissile material contents intended for use as neutron moderating or absorbing purposes.

1.2.2.6 Chemical, Galvanic, and Gas Generating Reactions

The interior containment surfaces of the WMG 150B are lined with stainless steel sheets for ease of decontamination and to mitigate against the potential for significant chemical, galvanic and other detrimental reactions between the contents and/or secondary containers and the liner. WMG 150B cask exterior surfaces that are not stainless steel are painted to mitigate against adverse conditions from corrosion or from minor leakage/spillage of contents from secondary containers.

Radiolytic or organic decomposition of water or organic substances may generate gases.

The WMG 150B cask user will ensure that the total amount of hydrogen gas in the secondary container generated during previous storage and during twice the expected shipping time will be limited to a molar quantity less than 5% of the volume of the cask cavity at STP conditions.

Determination of hydrogen generation should be made using the methods in NUREG/CR-6673, Hydrogen Generation in TRU Waste Transportation Packages. NUREG/CR-6673 provides equations that allow prediction of the hydrogen concentration as a function of time for simple nested enclosures and for packages containing multiple contents packaged within multiple nested confinement layers. The inputs to these equations include the bounding effective G(H2)-value for the contents, the G(H2)-values for the packaging material(s), the void volume in the containment vessel and in the confinement layers (when applicable), the temperature when the package was sealed, the temperature of the package during transport, and the contents decay heat.

Immediately prior to use for transport, the WMG 150B cask user shall prepare the secondary container in the same manner in which the determination for gas generation is made. The shipment period begins when the WMG 150B cask is sealed and is considered complete at the conclusion of twice the expected shipping time.

Neither a hydrogen gas generation determination nor restriction of shipping time is required for any secondary package containing materials with radioactive concentrations less than LSA and shipped within 10 days of preparation (or within 10 days of venting the secondary container).

1.2.2.7 Maximum Weight

The weight of the cask cavity contents including secondary containers and shoring will be limited to 15,500 lbs.

1.2.2.8 Maximum Decay Heat

Radioactive material that does not contain more than 200 thermal watts of radioactive decay heat.

1.2.2.9 Loading Restrictions

1) Explosive, corrosive, and non-radioactive pyrophoric contents are prohibited.

2) Pyrophoric radionuclides may be present only in residual amounts below 1 w/o.

3) Materials that may auto-ignite or change phase at temperatures below 350°F, excluding water shall not be included in the contents.

4) Contents shall not include any materials that may cause significant chemical, galvanic or other reactions.

1.2.3 Special Requirements for Plutonium

The WMG 150B package is not designed to contain quantities of solid form Plutonium in excess of 20 Curies.

1.2.4 Operational Features

There are no unique or complex operating procedures associated with use of this package. The openings, seals, and containment boundaries can be reviewed in Appendix 1.3.

1.3 Appendix

1.3.1 Drawings

- WMG-150B-DW-004-P71, General Arrangement & Details

(Withheld from public disclosure as security-related sensitive information.)

1.3.2 References

1-1 Regulatory Guide 7.9, Standard Format and Content of Part 71 Applications for Approval of Packages for Radioactive Material
1-2 10CFR Part 71, Packaging and Transportation of Radioactive Material
1-3 NUREG/CR-5502, Engineering Drawings for 10 CFR Part 71 Package Approvals
1-4 WMG 10 CFR Part 71 Quality Assurance Program

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2.0 STRUCTURAL EVALUATION

This chapter identifies, describes and analyzes the structural design of the WMG 150B Cask and the safety systems that demonstrate compliance with the performance requirements of 10 CFR 71 (Reference 2-1).

2.1 Description of Structural Design

The WMG 150B Cask is designed to provide a shielded containment vessel that can withstand the loading due the Normal Condition of Transport (NCT), as well as those associated with the Hypothetical Accident Conditions (HAC). The package is designed to protect the payload from the following conditions:

- Transport environment;
- 30-foot (9m) drop test;
- 40-inch (1m) puncture test;
- 1475°F (800°C) thermal exposure and transfer or dissipation of any generated heat of 200W.

The package satisfies these requirements, having the following principal safety system elements:

- . Containment Boundary;
- Lead Shielding;
- Impact Limiters

These components are identified in the WMG 150B General Arrangement and Details Drawing of Appendix 1.3. The design and function of these components in meeting of 10 CFR 71 is discussed in this SAR.

Figure 2-1 shows the nomenclature of the components of the cask used throughout this SAR.

2.1.1 Discussion

2.1.1.1 Containment Boundary

The containment boundary of the package is made up of the cask body, the primary lid and the secondary lid. 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 consists of two baseplates. The two baseplates sandwich lead-shielding between them. A removable primary lid is attached to the cask body with 24 equally spaced 1½"-6UNC bolts. A secondary lid is centered and attached to the primary lid with 15 equally spaced 1½"-6UNC bolts. The lid-to-cask and lid-to-lid surfaces are each sealed by pairs of solid elastomer O-rings. The cask containment boundary consists of the inner shell, the inner baseplate, the bolting ring, the seal plates, the inner O-rings, and the top plates of the primary and secondary lids. The boundary is penetrated by the pressurization port. Thus parts of this port up to the stat-o-seal are also considered to be on the containment boundary.

Figure 2-2 shows the containment boundary of the WMG 150B cask package.

For contamination protection the cask interior is lined with thin metal sheets, referred to in this SAR as "the liner". These sheets are welded to the cask interior with minimal amount of welds to keep them in place. No structural credit is taken for either these liners or the welds in the structural evaluation of the package.

2.1.1.2 Shielding

The lead shield is located between two cylindrical steel shells at its periphery and two circular steel plates at the bottom. The secondary lid of the cask also includes lead shielding. The lead shielding is subjected to a gamma scan inspection during fabrication to assure lead integrity. The design thickness assures that no biological hazard is presented by the package and all dose rate requirements of 10 CFR 71 [Ref. 2-1] are met with the cask's anticipated radioactive waste loadings.

2.1.1.3 Impact Limiters

The impact limiters protect the package from damage during the HAC drop test and provide thermal protection during the hypothetical fire accident condition. They are constructed of fully welded shells filled with foam-in-place closed-cell rigid-polyurethane foam. The foam deforms and provides energy absorption during impact. Each impact limiter is connected to the cask body at 6 circumferential locations.

Detailed discussions of all components and materials utilized in the WMG 150B 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 the normal conditions of transport (NCT) and hypothetical accident conditions (HAC). 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 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 WMG 150B package. Table 2-1 has been developed from the recommendations of Regulatory Guide 7.8 (Reference 2-2).

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

The allowable stresses under normal conditions (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 (Reference 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 hypothetical accident conditions (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. 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 150B Cask analyses documented in this SAR.

The acceptance criterion for prevention of buckling is based on the criteria detailed in Section 2.7.1.7. Factors of safety of 2.0 for the normal conditions of transport and 1.34 for hypothetical accident conditions have been used in the buckling evaluation of the cask.

The primary structural components of the package are fabricated with ASTM A543, Type B, Class 1 high strength steel with supplemental nil ductility temperature (NDT) requirements. Fracture toughness requirements specified in Regulatory Guide 7.11 (Reference 2-5), "Fracture Toughness Criteria for Ferritic Steel Shipping Casks Containment Vessels with a Maximum Wall Thickness of Four Inches", (June 1991) and NUREG/CR-1815, "Recommendations for Protecting Against Failure by Brittle Fracture in Ferritic Steel Shipping Containers up to Four Inches Thick" (August 1981) (Reference 2-6) are both complied with. Section 2.6.2 evaluates the critical components of the cask.

The design criteria, used for the evaluation of the impact limiters, is based on a proprietary methodology developed by WMG and is fully documented in WMG proprietary document AR-111 (Reference 2-7).

2.1.3 Weight and Center of Gravity

The following is a conservative estimate of the weight of various components of the WMG 150B package:

Cask Body	44,600 lb
Lid	7,340 lb
Payload (max.)	15,500 lb
Impact Limiter Upper	4,870 lb
Impact Limiter Bottom	4,540 lb
Misc.	650 lb
Package	77,500 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 WMG 150B package is designed as a Type-B, Category II package per U.S. NRC Regulatory Guide 7.11 (Reference 2-5). Based on the recommendations of NUREG/CR-3854 (Reference 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. However, since the material of construction of the major components of the cask (A-543, Type B, Class 1) is included in approved list of materials for ASME B&PV Code Section III, Class 1 components only, for which the applicable Subsection is NB, the WMG 150B cask containment components are fabricated, examined, and inspected per ASME B&PV Code Section III, Subsection NB. The non-containment components of the package are fabricated, examined, and inspected per ASME B&PV Code Section III, Subsection NF.

2.2 Materials

The mechanical properties of the materials used in the analysis of the package are provided in Table 2-4. This table presents the following temperature dependent mechanical characteristics of the materials: Yield Stress (S_y), Ultimate Stress (S_u), Membrane Allowable Stress (S_m), Young's Modulus (E), Coefficient of Thermal Expansion (α), Poisson's Ratio (ν), Elongation (δ). The thermal properties of these materials that were used in the evaluation of the temperature distribution in the package are provided in Section 3.2.1.

2.2.1 Material Properties and Specifications

All the components of the cask body are specified to be ASTM A543, Type B, Class 1 or 2 high strength steel, except for the seal rings that are specified to be ASTM A-240, Type 316 stainless steel. These materials are approved for the construction of the ASME Section III, Subsection NB vessels. The material properties for these materials have been obtained from the ASME Code Section II.

The bolting used for connecting the primary lid to the cask body, the secondary lid to the primary lid, and the impact limiter to the cask body, has been specified to be ASTM A-540, Gr. B24, Class

1 material. This material is approved for use in the ASME Section III, Subsection NB vessels. The material properties for this material have been obtained from the ASME Code Section II.

The poured-in-place lead shielding is specified to be ASTM B29, Chemical Grade lead. This material has been used in numerous shipping casks over the last 40 years. The material properties for lead are obtained from NUREG/CR-0481 (Reference 2-9).

Various seals, used in the cask for maintaining the internal pressure during NCT and HAC events, are specified to be elastomeric O-rings. The lid and pressurization port seals are flouro-elastomer (Viton), have a hardness of 70-80 durometer and have a usable temperature range that meets or exceeds the temperature range required to meet the normal condition of transport (elastomer long range temperature criteria, minimum = -40°F, maximum = 150.9°F, see Table 3-1) and meets or exceeds the temperature required to meet the hypothetical accident conditions (elastomer temperature criteria of 380°F for 10 hours, see Table 3-2). Elastomers that have been successfully used in similar packages over the last 40 years.

The impact limiters use closed-cell rigid polyurethane foam, incased in stainless steel sheet metal. The foam is procured based on the WMG specification WMG-150B-ES-002-P71 (See Appendix 1, Section 8 of this SAR), which specifies, among other things, the mechanical properties, flame retardant characteristics, and the test requirement for the foam material. The type of foam specified is General Plastic Manufacturing Company's Type FR-3700. The General Plastic's Technical Manual (Reference 2-10) provides the stress-strain properties of various density foams. The WMG specification uses the 23 lb/ft^3 nominal density foam's stress-strain properties parallel-to-rise direction as the required property. However, in the analyses both parallel-to-rise and perpendicular-to-rise direction properties have been used, as appropriate. The stress-strain properties of the foam, in various directions, and at various temperatures, are documented in AR-105 (Reference 2-11). The plots of these properties with the tolerance band of ±10% is shown in Figures 2-3 and 2-4.

2.2.2 Chemical, Galvanic and Other Reactions

The 150B cask is fabricated from carbon steel, stainless steel and lead and has impact limiters containing polyurethane foam. These materials will not cause chemical, galvanic, or other reactions in air or water environments. 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. Evaluation of the cask components that come in contact with the molten lead during the cask fabrication for liquid metal embrittlement has been evaluated in Reference 2-40.

2.2.2.1 Materials of Construction

The WMG 150B package is primarily constructed of ASTM A543, Type B, Class 1 steel with the tie-down arms and lifting ears made from ASTM A543, Type B, Class 2 steel. These materials are painted and are 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. 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 solid elastomeric O-ring seals contain no corrosive material that would adversely affect the packaging.

2.2.2.2 Materials of Construction and Payload Compatibility

The typical contents of the WMG 150B cask will be similar to the primary materials of construction, i.e., carbon 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. Water will not react with the painted steel cask body.

2.2.3 Effects of Radiation on Materials

The material from which the package is fabricated (carbon steel, stainless steel, lead, solid elastomeric 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. Polyurethane can absorb more than 10^8 rad without any degradation in mechanical properties (Reference 2-10). The maximum dose to the WMG 150B impact limiters is less than 3×10^3 rad/yr. For the service life of the package (approximately 50 years), radiation will not have any effect on the impact limiter properties.

The flouro-silicone seals do not exhibit degradation in properties up to 10^6 rad (Reference 2-28). The expected dose rate on the seals is less than 4×10^5 rad/year. Therefore, the seals will not be affected due to radiation for 2½ years. They will be replaced at least every 2 years.

2.3 Fabrication and Examination

As discussed in Section 2.1.4, the WMG 150B 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, WMG 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 (Reference 2-12), NUREG/CR-3854 (Reference 2-8), NUREG/CR-3019 (Reference 2-13) and industry practice.

2.3.1 Fabrication

As specified in the above referenced documents, fabrication of the WMG 150B containment components will be based on ASME B&PV Code, Section III, Subsection NB 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 WMG 150B containment components will be based on ASME B&PV Code, Section III, Subsection NB-5000 and that of the non-containment components will be based on ASME B&PV Code, Section III, Subsection 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 (77.5″), 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 WMG 150B package incorporates tamper resistant seals that are installed between one of the primary and secondary lid bolt-heads, and the corresponding lid, 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 WMG 150B package uses 24 bolts that fasten the primary lid to the cask body and 15 bolts to attach the secondary lid to the primary lid. Additionally, the pressurization port is closed with the help of threaded attachment. 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

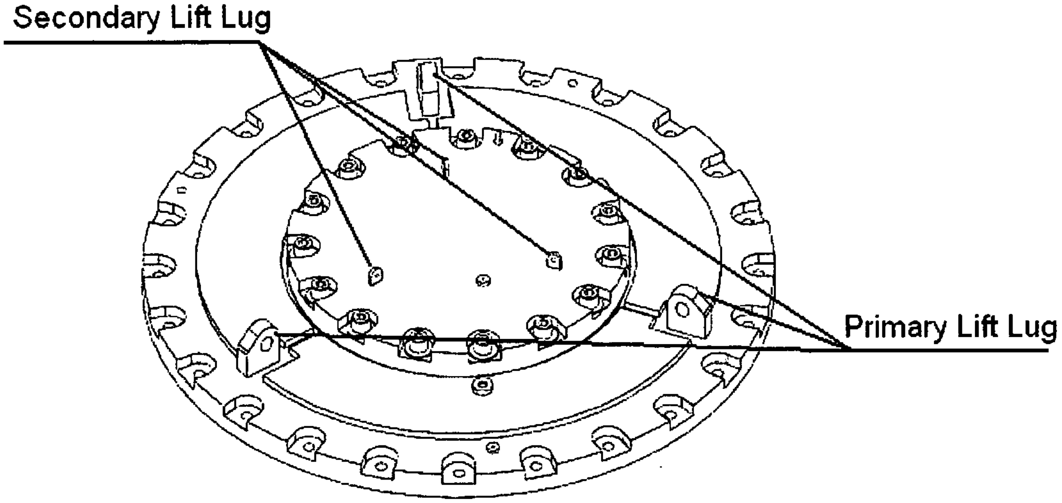
10 CFR 71.45 (Reference 2-1) specifies the requirements for the lifting and tie-down devices that are a "structural part of the package". The WMG 150B cask is designed to be lifted with three lift lugs that are attached to the primary lid plate. The same lift lugs are used to remove the primary lid from the cask. The secondary lid is also equipped with three lift lugs by which the secondary lid may be removed from the cask. The upper impact limiter is designed to be lifted with three lift lugs that are attached to the impact limiter casing. The cask is also furnished with four tie-down lugs that are used for the tie-down of the WMG 150B cask during transportation.

2.5.1 Lifting Devices

According to 10 CFR 71.45(a) (Reference 2-1), "*Any lifting devices, 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 analyses presented in this section demonstrate the compliance with the regulatory requirements. The details of the analyses are documented in WMG document AR-112 (Reference 2-14).

The primary and secondary lift lugs are illustrated in the following sketch. These lugs are made of ASTM A543 Type B Class 1 material.



2.5.1.1 Primary Lifting Lug

2.5.1.1.1 Weight Analysis

In general, the cask lifting lugs should be used with both impact limiters removed. Nevertheless, it can be assumed that the cask and the lower impact limiter will be lifted together as a unit. Therefore, the total lifted weight is:

$$W=77{,}500-5{,}000=72{,}500 \text{ lbs}$$

According to the requirements of 10 CFR71 the lifting system should provide a safety factor of 3 on the yield stress of the material. For three times of the cask weight, the effective weight to be lifted by each lug, Pv, can be determined as:

$$P_v=\frac{3\times f_D\times W}{3lugs}=\frac{3\times 1.1\times 72{,}500}{3lugs}=79{,}750 \text{ lbs}$$

Where $f_D = 1.1$ – an additional 10% dynamic load factor according to ASME NQA-1 Subpart 2.15 paragraph 403.1(a) (5) (Reference 2-15).

Considering the position at 60° lift angle, the total load per lug (see the accompanying sketch) is determined as:

$$P = \frac{P_V}{\sin(60^\circ)} = \frac{79{,}750}{0.866} = 92{,}090 \text{ lbs.}$$

This results in a shear force of:

$$P_H = P\cos(60^\circ) = 92{,}090 \times (0.5) = 46{,}045 \text{ lbs.}$$

2.5.1.1.2 Primary Lifting Lug Tear-out Stress Analysis

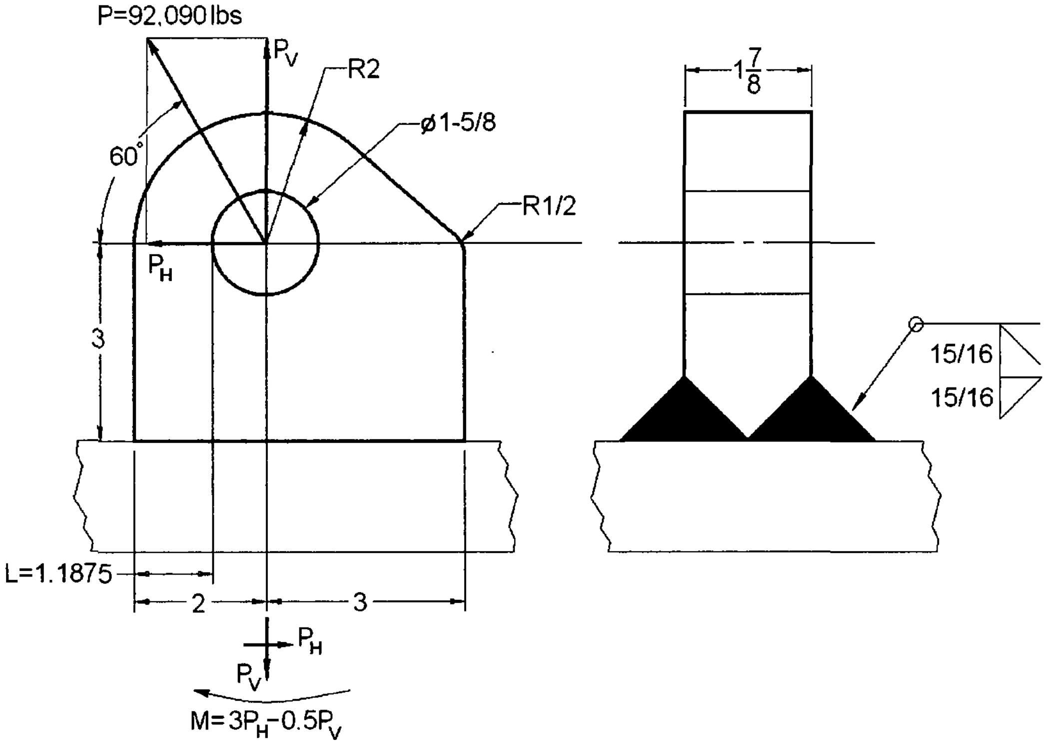
The critical section for the primary lifting lug tear-out was determined to be as shown in the following sketch. Numerically, the area of tear-out cross section is:

$$A_{tear-out} = 2 \times L \times t = 2 \times 1.1875 \times 1.875 = 4.453 \text{in}^2,$$

where:

L =1.1875 in - length of tear-out section,

t = 1.875 in - section thickness.



The total cable force is P = 92,090 lbs. This results in a shear stress due to tear-out of:

$$\tau = \frac{P}{A_{tear-out}} = \frac{92{,}090}{4.453} = 20{,}680 \text{ psi}$$

The primary lift lugs are fabricated from ASTM A543 Type B Class 1 material with minimum yield stress of $S_y = 85{,}000$ psi. Therefore, the allowable shear stress is:

$$\tau_{allowable} = 0.6 \times S_y = 0.6 \times 85{,}000 = 51{,}000 \text{ psi}$$

This results into a safety factor of:

$$F.S. = \frac{\tau_{allowable}}{\tau} = \frac{51{,}000}{20{,}680} = 2.46$$

2.5.1.1.3 Base Stresses

The tensile stress in the welds at the bottom of the primary lifting lug is:

$$\sigma_{tensile} = \frac{P_V}{A_b} = \frac{79{,}750}{25.781} = 3{,}093 \text{ psi}$$

$$A_b = (w + 2 \cdot t_W) \times (b + 2 \cdot t_W) = (5 + 2 \cdot 0.9375) \times (1.875 + 2 \cdot 0.9375) = 25.781 \text{in}^2,$$

where:

A_b= 25.781 in^2 -base area,

w =5 in - lug width,

b = 1.875 in - lug thickness,

t_W =15/16 in =0.9375 in - weld thickness,

P_V=79,750 lbs – vertical force.

The bending stress, maximum at the bottom outer edge of each of the lug, is:

$$\sigma_{bending} = \frac{M \times c}{I} = \frac{98{,}260 \times 2.5}{101.55} = 2{,}419 \text{psi}$$

$$M = 3 \times P_H - 0.5 \times P_V = 3 \times 46{,}045 - 0.5 \times 79{,}750 = 138{,}135 - 39{,}875 = 98{,}260 \text{in} \cdot \text{lbs}$$

$$I = \frac{(b + 2 \times t_W) \times (h + 2 \times t_W)^3}{12} = \frac{3.75 \times 6.875^3}{12} = 101.55 \text{ in}^4,$$

where:

M = 98,260 in-lbs- bending moment,

c =2.5 in - distance to neutral axis,

I = 101.55 in^4 - moment of inertia,

b= 1.875 in- lug thickness,

h= 5 in - lug height,

t_w= 15/16 in =0.9375 in - weld thickness.

At the outer edge of the primary lift lug, the bending stress will add to the tensile stress to produce a total tensile stress of:

$$\sigma_{total} = \sigma_{bending} + \sigma_{tensile} = 2{,}419 + 3{,}093 = 5{,}512 \text{ psi}$$

The shear stress at the bottom of the lift ear is:

$$\tau = \frac{P_H}{A_b} = \frac{46{,}045}{25.781} = 1{,}786 \text{psi},$$

where:

P_H= 46,045 lbs - shear force,

A_b=25.781 in^2 - base area.

The effect of the shear and total tensile stresses are combined to form the principal stress for the lifting lugs as follows (Reference 2-16):

$$\sigma_{p1,p2} = \frac{\sigma_{total}}{2} \pm \left[\left(\frac{\sigma_{total}}{2} \right)^2 + (\tau)^2 \right]^{\frac{1}{2}}$$

Thus,

$$\sigma_{p1} = \frac{5{,}512}{2} + \left[\left(\frac{5{,}512}{2} \right)^2 + (1{,}786)^2 \right]^{\frac{1}{2}} = 6{,}040 \text{psi}$$

$$\sigma_{p2} = \frac{5{,}512}{2} - \left[\left(\frac{5{,}512}{2} \right)^2 + (1{,}786)^2 \right]^{\frac{1}{2}} = -528 \text{psi}$$

The maximum shear stress will be:

$$\tau_{maximum} = \frac{\sigma_{p1} - \sigma_{p2}}{2} = 3{,}284 \text{psi}$$

The primary lift lugs are fabricated from ASTM A543 Type B Class 1 material with minimum yield stress of S_y = 85,000 psi. Therefore, the allowable shear stress is:

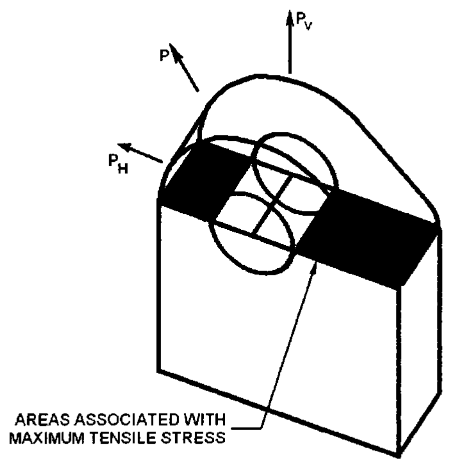
$$\tau_{allowable} = 0.6 \times S_y = 0.6 \times 85{,}000 = 51{,}000 \text{ psi}$$

The factor of safety will be:

$$F.S. = \frac{\tau_{allowable}}{\tau_{maximum}} = \frac{51{,}000}{3{,}284} = 15.5$$

2.5.1.1.4 Primary Lifting Lug Stress Analysis at Pin Hole

The maximum tensile stress in the primary lifting lug occurs in the section of the least cross-section area, as show in the following sketch.



Numerically, this area is found to be:

$$A = (w - D) \times t = (5 - 1.625) \times 1.875 = 6.33\,\text{in}^2$$

Where:

$w = 5$ in - width of lifting lug at the hole centerline,

$D = 1.625$ in - diameter of hole,

$t = 1.875$ in - plate thickness.

From Section 2.5.1.1.1, the shear and tensile forces were determined as:

P_V=79,750 lbs,

P_H=46,045 lbs.

This translates into a nominal shear and tensile stress of:

$$\tau = \frac{P_H}{A} = \frac{46{,}045}{6.33} = 7{,}274\,\text{psi},$$

$$\sigma_t = \frac{P_V}{A} = \frac{79{,}750}{6.33} = 12{,}598\,\text{psi}.$$

Combining the effects of the shear and tensile stresses to form the principal stresses yields (Reference 2-16):

$$\sigma_{p1,p2} = \frac{\sigma_t}{2} \pm \left[\left(\frac{\sigma_t}{2}\right)^2 + (\tau)^2\right]^{\frac{1}{2}}$$

$$\sigma_{p1} = \frac{12{,}598}{2} + \left[\left(\frac{12{,}598}{2}\right)^2 + (7{,}274)^2\right]^{\frac{1}{2}} = 15{,}921\,\text{psi}$$

$$\sigma_{p2} = \frac{12{,}598}{2} - \left[\left(\frac{12{,}598}{2}\right)^2 + (7{,}274)^2\right]^{\frac{1}{2}} = -3{,}323\,\text{psi}.$$

The maximum shear stress is found to be:

$$\tau_{maximum} = \frac{\sigma_{p1} - \sigma_{p2}}{2} = 9{,}622\,\text{psi}$$

Using an allowable shear =0.6×S_y and a yield stress of S_y=85,000 psi, the allowable shear stress is:

$$\tau_{allowable} = 0.6 \times S_y = 0.6 \times 85{,}000 = 51{,}000\,\text{psi}$$

This translates into a factor of safety of:

$$F.S. = \frac{\tau_{allowable}}{\tau_{maximum}} = \frac{51{,}000}{9{,}622} = 5.3$$

2.5.1.1.5 Primary Lifting Lug Bearing Stress Analysis

The critical section for the primary lifting lug bearing was determined to be as

$$A_{bearing} = d \times t = 1.625 \times 1.875 = 3.047\,\text{in}^2$$

Where:

d = 1.625 in - shackle pin diameter,

t = 1.875 in - section thickness.

As determined above in Section 2.2.1, the total cable force is 92,090 lbs. This results in a shear stress due to tear-out of:

$$\sigma = \frac{P}{A_{bearing}} = \frac{92{,}090}{3.047} = 30{,}223\,\text{psi}$$

The primary lift lugs are fabricated from ASTM A543 Type B Class 1 material with minimum yield stress of S_y=85,000 psi. Therefore, the allowable bearing stress is:

$$\sigma_{allowable} = k \times \sigma_y = 1.15 \times 85{,}000 = 97{,}750\ \text{psi}$$

Where k=1.15 is an empirical coefficient of a compression stress (Reference 2-17, Page 976).

This translates into a factor of safety of:

$$F.S. = \frac{\sigma_{allowable}}{\sigma} = \frac{97{,}750}{30{,}223} = 3.23.$$

2.5.1.6 Primary Lifting Lug Stress Summary

The results of the primary lifting lug stress analysis are summarized as follows:

Case	Max. Shear Stress Membr. + Bending (psi)	Factor of Safety
Lug Tear-out	20,680	2.46
Base Weld	3,284	15.5
Pin Hole	9,622	5.3
Bearing	30,223	3.23

2.5.1.1.7 Failure of the Cask Primary Lifting Lugs under Excessive Loads

From the stress summary presented above it is observed that the primary lifting lug design has the minimum margin of safety against the tear-out. Therefore, under excessive loading the failure of the lifting lug will occur by tear-out at the hole. This will not impair the ability of the package to meet other regulatory requirements.

2.5.1.2 Secondary Lift Lug

2.5.1.2.1 Weight Analysis

The Secondary Lid is lifted using three Secondary Lift Lugs. We conservatively use the lifted weight of 2,000 lbs. The effective weight to be lifted by each lug, Pv, is determined as:

$$P_v = \frac{3 \times f_D \times W}{3 lugs} = \frac{3 \times 1.1 \times 2{,}000}{3 lugs} = 2{,}200 \text{ lbs}$$

Where $f_D = 1.1$ - additional 10% dynamic load factor.

Considering a 60° lift angle, the total load per lug (see the accompanying sketch) is determined as:

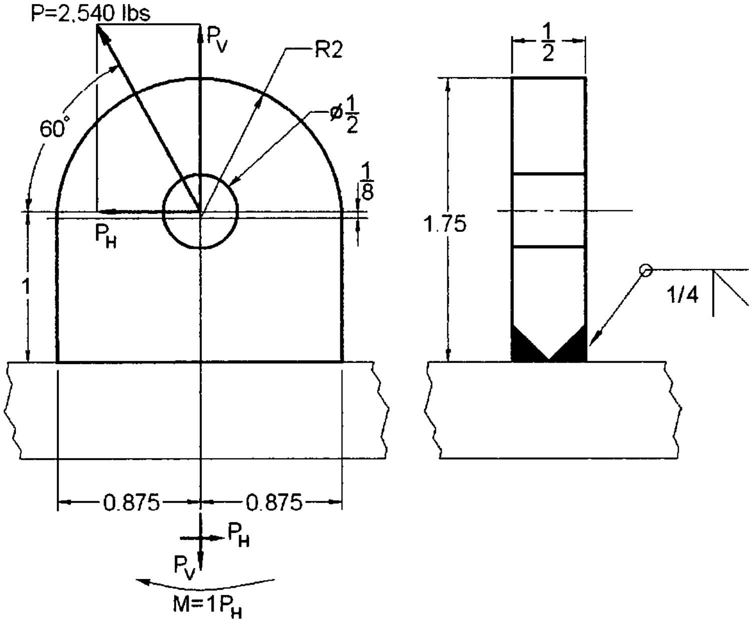
$$P = \frac{P_V}{\sin(60^\circ)} = \frac{2{,}200}{0.866} = 2{,}540 \text{ lbs}$$

This results in a shear force of:

$$P_H = P\cos(60^\circ) = 2{,}540 \times 0.5 = 1{,}270 \text{ lbs}$$

2.5.1.2.2 Secondary Lifting Lug Tear-out Stress Analysis

The critical section for lifting lug tear-out was determined to be as shown in the following sketch.



Numerically, this area is:

$$A_{tear-out} = 2 \times L \times t = 2 \times 0.5 \times 0.5 = 0.5\,\text{in}^2,$$

where:

L =0.5 in -length of tear-out section,

t = 0.5 in - section thickness.

As previously determined in Section 2.5.1.2.1, the total cable force is 2,540 lbs. This results in a shear stress due to tear-out of:

$$\tau = \frac{P}{A_{tear-out}} = \frac{2{,}540}{0.5} = 5{,}080\,\text{psi}$$

The secondary lugs are fabricated from ASTM A543 Type B Class 1 material with minimum yield stress of S_y=85,000 psi. Therefore allowable shear stress is:

$$\tau_{allowable} = 0.6 \times 85{,}000 = 51{,}000 \ \text{psi}$$

This translates into a factor of safety of:

$$F.S. = \frac{\tau_{allowable}}{\tau} = \frac{51{,}000}{5{,}080} = 10.$$

2.5.1.2.3 Base Stresses

The tensile stress at the bottom of the lifting lug as shown in the accompanying sketch is:

$$\sigma_{tensile} = \frac{P_V}{A_b} = \frac{2{,}200}{0.875} = 2{,}514\,\text{psi}$$

$$A_b = W \times b = 1.75 \times 0.5 = 0.875\text{in}^2.$$

Where:

A_b = 0.875 in^2 - base area,

W =1.75 in - lug width,

b = 0.5 in - lug thickness.

P_V=2,200 lbs - tensile load.

The bending stress, maximum at the bottom outer edge of each of lug, is:

$$\sigma_{bending} = \frac{M \times c}{I} = \frac{1{,}270 \times 0.875}{0.2233} = 4{,}976\,\text{psi}$$

$$M = P_H \times 1 = 1{,}270\,\text{in}\cdot\text{lbs},$$

$$I = \frac{b \times h^3}{12} = \frac{0.5 \times 1.75^3}{12} = 0.2233\,\text{in}^4.$$

Where:

$M = 1{,}270$ in-lbs - bending moment,

$c = 0.875$ in - distance to neutral axis,

$I = 0.2233$ in ^{4} - moment of inertia,

$b = 0.5$ in - lug thickness,

$h = 1.75$ in - lug height.

At the outer edge of the lift lug, the bending stress will add to the tensile stress to produce a total tensile stress of:

$$\sigma_{total} = \sigma_{bending} + \sigma_{tensile} = 4{,}976 + 2{,}514 = 7{,}490 \text{ psi}$$

The shear stress at the bottom of the lift ear is:

$$\tau = \frac{P_H}{A_b} = \frac{1{,}270}{0.875} = 1{,}451 \text{psi}$$

Where:

$P_H = 1{,}270$ lbs - shear force,

$A_b = 0.875$ in^{2} - base area.

The effect of the shear and total tensile stresses are combined to form the principal stress for the lifting lugs as follows (Reference 2-16):

$$\sigma_{p1,p2} = \frac{\sigma_{total}}{2} \pm \left[\left(\frac{\sigma_{total}}{2}\right)^2 + (\tau)^2\right]^{\frac{1}{2}}$$

Thus,

$$\sigma_{p1} = \frac{7{,}490}{2} + \left[\left(\frac{7{,}490}{2}\right)^2 + (1{,}451)^2\right]^{\frac{1}{2}} = 7{,}761 \text{psi}$$

$$\sigma_{p2} = \frac{7{,}490}{2} - \left[\left(\frac{7{,}490}{2}\right)^2 + (1{,}451)^2\right]^{\frac{1}{2}} = -271 \text{psi}$$

The maximum shear stress will be:

$$\tau_{maximum} = \frac{\sigma_{p1} - \sigma_{p2}}{2} = \frac{7{,}761 - (-271)}{2} = 4{,}016 \text{psi}$$

Using an allowable shear =0.6×S$_y$ and a yield stress of S$_y$=85,000 psi, the allowable shear stress is:

$$\tau_{allowable} = 0.6 \times S_y = 0.6 \times 85{,}000 = 51{,}000 \text{psi}$$

The factor of safety will be:

$$F.S. = \frac{\tau_{allowable}}{\tau_{maximum}} = \frac{51{,}000}{4{,}016} = 12$$

2.5.1.2.4 Secondary Lifting Lug Bearing Stress Analysis

The critical section for the primary lifting lug bearing was determined to be as

$$A_{bearing} = d \times t = 0.5 \times 0.5 = 0.25 \text{ in}^2$$

Where:

d = 0.5 in - shackle pin diameter.

t = 0.5 in - section thickness.

As determined above in Section 2.5.1.2.1, the total cable force is 2,540 lbs. This results in a shear stress due to tear-out of:

$$\sigma = \frac{P}{A_{bearing}} = \frac{2{,}540}{0.25} = 10{,}160 \text{psi}$$

The secondary lift lugs are fabricated from ASTM A543 Type B Class 1 material with minimum yield stress of Sy= 85,000 psi. Therefore, the allowable bearing stress is:

$$\sigma_{allowable} = 1.15 \times S_y = 1.15 \times 85{,}000 = 97{,}750 \text{psi}$$

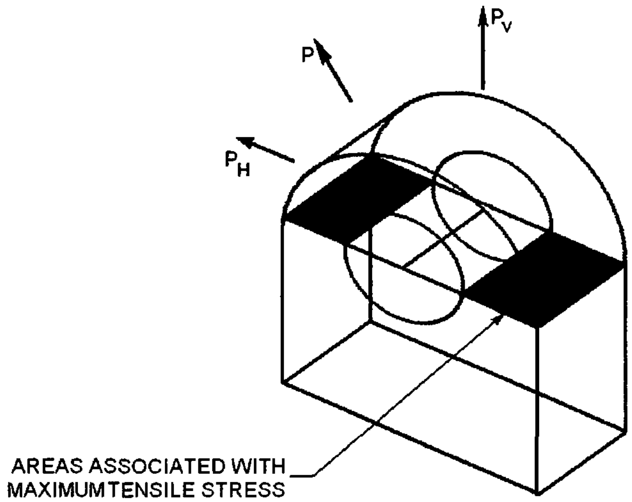
Where k=1.15 is an empirical coefficient of a compression stress (Reference 2-17).

This translates into a factor of safety of:

$$F.S. = \frac{\sigma_{allowable}}{\sigma} = \frac{97{,}750}{10{,}160} = 9.6.$$

2.5.1.2.5 Secondary Lifting Lug Stress Analysis at Pin Hole

The maximum tensile stress in the secondary lifting lug occurs in the section of the least cross-section area, as show in following sketch.



Numerically, this area is conservatively found to be:

$$A = 2\times(W/2 - r - q)\times t = 2\times(0.875 - 0.25 - 0.125)\times 0.5 = 0.5\,\text{in}^2$$

Where:

W =1.75 in - lug width,

r =1/4 in - radius of hole,

q =1/8 in - distance between center of circles,

t = 1/2 in plate thickness,

From Section 2.5.1.2.1, the shear and tensile forces were determined as:

P_V=2,200 lbs,

P_H=1,270 lbs.

This translates into a nominal shear and tensile stress of:

$$\tau = \frac{P_H}{A} = \frac{1{,}270}{0.5} = 2{,}540\,\text{psi},$$

$$\sigma_t = \frac{P_V}{A} = \frac{2{,}200}{0.5} = 4{,}400\,\text{psi},$$

Combining the effects of the shear and tensile stresses to form the principal stresses yields (Reference 2-16):

$$\sigma_{p1,p2} = \frac{\sigma_t}{2} \pm \left[\left(\frac{\sigma_t}{2}\right)^2 + (\tau)^2\right]^{\frac{1}{2}}$$

$$\sigma_{p1} = \frac{4{,}400}{2} + \left[\left(\frac{4{,}400}{2}\right)^2 + (2{,}540)^2\right]^{\frac{1}{2}} = 5{,}561\,\mathrm{psi}$$

$$\sigma_{p2} = \frac{4{,}400}{2} - \left[\left(\frac{4{,}400}{2}\right)^2 + (4{,}540)^2\right]^{\frac{1}{2}} = -1{,}161\,\mathrm{psi}$$

The maximum shear stress is found to be:

$$\tau_{maximum} = \frac{\sigma_{p1} - \sigma_{p2}}{2} = 3{,}361\,\mathrm{psi}$$

Using an allowable shear =0.6×S_y and a yield stress of 85,000 psi, therefore the allowable shear stress is:

$$\tau_{allowable} = 0.6 \times 85{,}000 = 51{,}000\,\mathrm{psi}$$

This translates into a factor of safety of:

$$F.S. = \frac{\tau_{allowable}}{\tau_{maximum}} = \frac{51{,}000}{3{,}361} = 15$$

2.5.1.2.6 Secondary Lifting Lug Stress Summary

The results of the secondary lifting lug stress analysis are summarized as follows:

Case	Max. Shear Stress Membr. + Bending (psi)	Factor of Safety
Lug Tear-out	5,080	10
Base Weld	4,016	12
Bearing	10,160	9.6
Pin Hole	3,361	15

2.5.1.3 Socket Head Cap Screws

2.5.1.3.1 Socket Head Cap Screws Preloading Stresses

The primary lid plate is attached to the cask using twenty four 1-1/2" -6 UNC-2A, 4 inch long ASTM A540 socket head cap screws. The lid bolts are tightened to a torque of 500±50 ft-lb. The upper end torque value is:

$$Q = 550\,ft \cdot lbs.$$

According to NUREG 6007, Table 4.1 (Reference 2-18) the torque and non-prying tensile bolt force are connected by the following equation:

$$F_a = \frac{Q}{K \cdot D_b} = \frac{6{,}600}{0.0851 \times 1.5} = 51{,}703\,\text{lbs},$$

where:

Q=550 ft · lbs=6,600 in-lb - the applied torque for the preload,

K= 0.0851 - nut factor for empirical relation between the applied torque and the achieved preload,

D_b =1.5 in - nominal diameter of the closure bolt.

According to equation 8-14 Mark's Standard Handbook (Reference 2-19) nut factor are defined

$$K = \left(\frac{d_m}{2d}\right)\left(\frac{\tan(\lambda) + \mu \cdot \sec(\alpha)}{1 - \mu \cdot \tan(\lambda) \cdot \sec(\alpha)}\right) + 0.625\mu_c = 0.0851,$$

Where:

$$\tan\lambda = \frac{l}{\pi \cdot d_m};$$

$d_m = 1.3917\,\text{in}$ - 'basic pitch' diameter,

$l = \frac{1}{6}$ in - step of thread,

$\alpha = 30°$ - angle,

$\mu = \mu_C = 0.058$ - coefficient of friction of 0.058 for graphite lubricated hard steel on hard steel from Mark's Standard Handbook (Reference 2-19) Table 3.2.1.

The stress area for the screw is A_s = 1.405 in^2, consistent with Reference 2-19 Table 8.2.2. The resulting tensile stress will be:

$$\sigma_{tigh} = \frac{F_a}{A_S} = \frac{51703}{1.405} = 36{,}799\,\text{psi}$$

According to Reference 2-18, Table 6.1, using an allowable tensile stress of (2/3)×S_y and a yield stress S_y =150,000 psi, therefore the allowable tensile stress is:

$$\sigma_{allowable} = \frac{2 \times 150{,}000}{3} = 100{,}000\,\text{psi}$$

This translates into a factor of safety of:

$$F.S. = \frac{\sigma_{allowable}}{\sigma_{tigh}} = \frac{100{,}000}{36{,}799} = 2.7$$

According to Reference 2-18, Table 4.1, torsional bolt moment is

$$Mt = 0.5 \cdot Q = 0.5 \cdot 6600 = 3300 \ \text{ft} \cdot \text{in}$$

According to the Reference 2-18, Table 5.1, maximum shear stress caused by tensional bolt moment is:

$$\tau_{bt} = 5.093 \cdot Mt / D^3 = 5.093 \cdot 3300 / 1.5^3 = 4{,}979 \ \text{psi}$$

According to Reference 2-18, Table 6.1, using an allowable tensile stress of 0.6× (2/3)×S_y and a yield stress S_y = 150,000 psi, therefore the allowable tensile stress is:

$$\tau_{allowable} = \frac{0.6 \times 2 \times 150{,}000}{3} = 60{,}000 \text{psi}$$

This translates into a factor of safety of:

$$F.S. = \frac{\tau_{allowable}}{t_{bt}} = \frac{60{,}000}{4{,}979} = 12$$

According to Reference 2-18, Table 6.1, using conditions for estimated factor of safety:

$$R_t^2 + R_s^2 < 1$$

Where:

$$R_t = \frac{\sigma_{tigt}}{\sigma_{allowable}} = \frac{36{,}799}{100{,}000} = 0.37 \text{ - stress ratio for average tensile stress}$$

$$R_s = \frac{\tau_{bt}}{\tau_{allowable}} = \frac{4{,}979}{60{,}000} = 0.08 \text{ - stress ratio for average shear stress}$$

$$R_t^2 + R_s^2 = 0.143 < 1$$

Thus, the tension and shear conditions are satisfied.

In order to maintain the seal during the lifting operation, the WMG-150B package primary lid bolts are tightened to a torque value of 500 ± 50 ft-lbs (lubricated). Under the lift loading, the total lifted weight on the 24 bolts is:

$$W = 77{,}500 - 5{,}000 = 72{,}500 \text{ lbs}$$

For three times the weight of the cask, the effective weight to be lifted by each bolt, F_{lift}, is therefore determined as:

$$F_{lift} = \frac{3 \times f_D \times W}{24 bolts} = \frac{3 \times 1.1 \times 72{,}500}{24 bolts} = 9{,}968 \ \text{lbs}$$

Where f_D = 1.1 – an additional 10% dynamic load factor per ASME NQA-1 Subpart 2.15 paragraph 403.1(a) (5) (Reference 2-15).

The required preload is:

$$F_{lift} = 9{,}968 \text{ lbs}$$

Using the customary torque equation:

$$Q = K \cdot D_b \cdot F_{lift} = 0.0851 \cdot 1.5 \cdot 9{,}968 = 1272 \text{in-lb} = 106 \text{ ft-lb},$$

where:

K= 0.0851 - nut factor for empirical relation between the applied torque and the achieved preload,

D_b =1.5 in - nominal diameter of the closure bolt.

Therefore, the specified torque of 500 ± 50 ft-lb (lubricated) is sufficient to maintain the needed bolt preload for the lifting loading. The 1.5"-6UNC, Gr. B24 Class 1 Screw may be installed though 2.5" long Heli-Coil Inserts which develop strengths equal or greater than that of the bolt.

2.5.1.3.2 Socket Head Cap Screws Stress Summary

The results of the Socket Head Cap Screws stress analyses are summarized as follows:

Case	Stress (psi)	Factor of Safety
Max. Preloading Stress	36,799	2.7
Max. Shear Stress	4,979	12

2.5.1.4 Lifting Lugs of Top Impact Limiter

2.5.1.4.1 Weight Analysis

The top impact limiter is lifted using three lifting lugs (Item 323), (see the following sketch). The weight of the top impact limiter is W = 4,870 lbs. (Reference 2-20). Conservatively using weight of 5,100 lb:

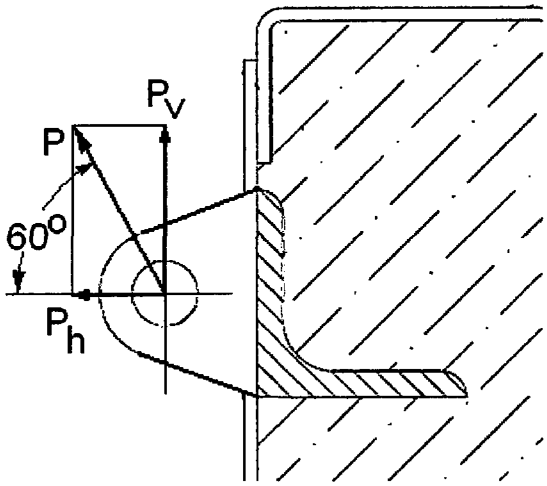
$$W=5{,}100 \text{ lbs}$$

According to 10 CFR 71.45(a)] a design factor of 3 in reference to Yield must be used for analyzing Lifting Lugs of Top Impact Limiter. The effective weight to be lifted by each lug, P_V, is therefore determined as:

$$P_V = \frac{3 \times f_D \times W}{3 lugs} = \frac{3 \times 1.1 \times 5{,}100}{3 lugs} = 5{,}610 \text{ lbs},$$

Where f_D = 1.1 - additional 10% dynamic load factor. Considering a 60° lift angle, the total load per lug (see the following sketch) is determined as:

$$P = \frac{P_V}{\sin 60} = \frac{5{,}610}{0.866} = 6{,}478 \text{ lbs}$$



2.5.1.4.2 Top Impact Limiter Lifting Lug Tear-out Stress Analysis

Considering α =60° lift angle, the tear-out and shear force per lug (Please see the accompanying sketch) is determined as:

$$P_V = 5{,}610 \text{ lbs}$$

$$P_H = P \cdot \cos(60^\circ) = 6{,}478 \times 0.5 = 3{,}239 \text{ lbs}$$

Numerically, the critical section area is conservatively found to be:

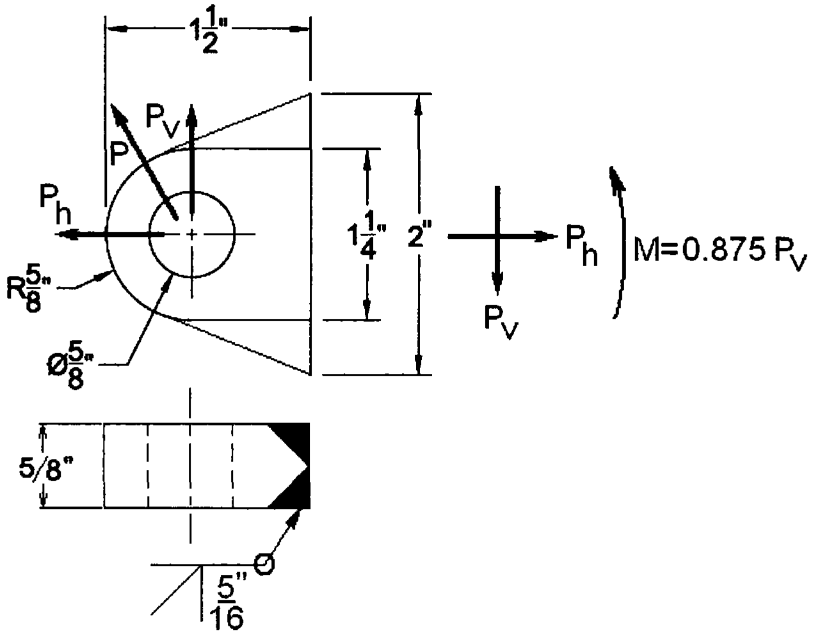
$$A = 2\times(R-r)\times t = 2\times(0.625-0.3125)\times 0.625 = 0.390625 \text{ in}^2.$$

Where:

R =5/8 in - radius of lift lug,

r = 5/16 in - radius of hole,

t= 5/8 in - plate thickness.



As determined above the total cable force is P=6,478 lbs. This results in a shear stress due to tear-out of:

$$\tau = \frac{P}{A_{shear}} = \frac{6{,}478}{0.390625} = 16{,}584 \text{ psi}$$

The top impact limiter lift lugs are fabricated from ASTM A240 316 SS material with minimum yield stress of 30,000 psi. The allowable shear stress is:

$$\tau_{allowable} = 0.6 \times 30{,}000 = 18{,}000 \text{ psi}$$

This translates into a factor of safety of:

$$F.S. = \frac{\tau_{allowable}}{\tau} = \frac{18{,}000}{16{,}584} = 1.1.$$

2.5.1.4.3 Base Stresses

The tensile stress at the bottom of the lifting lug as shown in the sketch is:

$$\sigma_{tensile} = \frac{P_H}{A_b} = \frac{3{,}239}{1.25} = 2{,}591 \text{ psi}$$

Where:

$A_b = w \times b = 2 \times 0.625 = 1.25 \text{ in}^2$ - base area,

$w = 2$ in - lug width,

b= 0.625 in - lug thickness,

P_H=3,239 lbs.

The bending stress maximum at the bottom outer edge of each of lugs is:

$$\sigma_{bending} = \frac{M \times c}{I} = \frac{4{,}908 \times 1}{0.4167} = 11{,}780\,\text{psi}$$

M=0.875×P_V=0.875×5,610 = 4,908 in-lbs -bending moment.

$$I = \frac{b \times h^3}{12} = \frac{0.625 \times 2^3}{12} = 0.4167 \ \text{in}^4 \text{ - moment of inertia.}$$

Where:

c = 1 in - distance to neutral axis,

b = 0.625 in - lug thickness,

h = 2 in - lug height.

At the outer edge of the lift lug, the bending stress will add to the tensile stress to produce a total tensile stress of:

$$\sigma_{total} = \sigma_{bending} + \sigma_{tensile} = 11{,}780 + 2{,}591 = 14{,}371 \text{ psi}$$

The shear stress at the bottom of the lift lug is:

$$\tau = \frac{P_V}{A_b} = \frac{5{,}610}{1.25} = 4{,}488\,.$$

Where:

P_V= 5,610 lbs - shear force,

A_b = 1.25in^2 - base area.

The effect of the shear and total tensile stresses are combined to form the principal stress for the lifting lugs as follows (Reference 2-16):

$$\sigma_{p1,p2} = \frac{\sigma_{total}}{2} \pm \left[\left(\frac{\sigma_{total}}{2} \right)^2 + (\tau)^2 \right]^{\frac{1}{2}}$$

Thus,

$$\sigma_{p1} = \frac{14{,}371}{2} + \left[\left(\frac{14{,}371}{2} \right)^2 + (4{,}488)^2 \right]^{\frac{1}{2}} = 15{,}657\,\text{psi}$$

$$\sigma_{p2} = \frac{14{,}371}{2} - \left[\left(\frac{14{,}371}{2} \right)^2 + (4{,}488)^2 \right]^{\frac{1}{2}} = -1{,}286\,\text{psi}$$

The maximum shear stress will be:

$$\tau_{maximum} = \frac{\sigma_{p1} - \sigma_{p2}}{2} = 8{,}471\,\text{psi}$$

The top impact limiter lift lugs are fabricated from ASTM A240 316 SS material with minimum yield stress of 30,000 psi. The lift lugs are welded to the 2x2x1/4 Angle (Item 322) from A36 with minimum yield stress of 36,000 psi. The allowable shear stress is:

$$\tau_{allowable} = 0.6 \times 30{,}000 = 18{,}000 \ \text{psi}$$

The factor of safety will be:

$$F.S. = \frac{\tau_{allowable}}{\tau_{maximum}} = \frac{18{,}000}{8{,}471} = 2.1$$

2.5.1.4.4 Top Impact Limiter Lifting Lug Bearing Stress Analysis

The critical section for the primary lifting lug bearing was determined to be as

$$A_{bearing} = d \times t = 0.625 \times 0.625 = 0.3906\,\text{in}^2$$

Where:

d= 0.625 in - shackle pin diameter,

t= 0.625 in - section thickness.

As determined above, the total cable force is 6,478 lbs. This results in a shear stress due to tear-out of:

$$\sigma = \frac{P}{A_{bearing}} = \frac{6{,}478}{0.3906} = 16{,}585\,\text{psi}$$

The limiter lift lugs are fabricated from ASTM A240 316 SS material with minimum yield stress of 30,000 psi.

Therefore, the allowable bearing stress is:

$$\sigma_{allowable} = k \times S_y = 1.15 \times 30{,}000 = 34{,}500 \ \text{psi.}$$

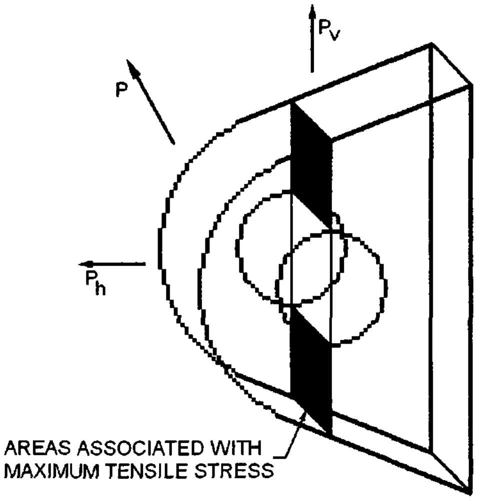
Where k=1.15 is an empirical coefficient of a compression stress (Reference 2-17, Page. 976).

This translates into a factor of safety of:

$$F.S. = \frac{\sigma_{allowable}}{\sigma} = \frac{34{,}500}{16{,}585} = 2.08.$$

2.5.1.4.5 Top Impact Limiter Lifting Lug Stress Analysis at Pin Hole

The maximum tensile stress in the lifting lug occurs in the section of least cross-section area, as shown in the sketch.



Numerically, this area is conservatively found to be:

$$A = 2\times (R-r) \times t = 2\times(0.625-0.3125)\times0.625 = 0.390625 \text{ in}^2.$$

Where:

$R = 5/8$ in - radius of lift lug,

$r = 5/16$ in - radius of hole,

$t = 5/8$ in - plate thickness.

Above, the shear and tensile forces were determined as:

$$P_V = 5{,}610 \text{ lbs}$$

$$P_h = 3{,}239 \text{ lbs}$$

This translates into a nominal shear and tensile stress of:

$$\tau = \frac{P_V}{A} = \frac{5{,}610}{0.390625} = 14{,}362 \text{ psi},$$

$$\sigma_t = \frac{P_h}{A} = \frac{3{,}239}{0.390625} = 8{,}292 \text{ psi}.$$

Combining the effects of the shear and tensile stresses to form the principal stresses yields (Reference 2-16):

$$\sigma_{p1,p2} = \frac{\sigma_t}{2} \pm \left[\left(\frac{\sigma_t}{2}\right)^2 + (\tau)^2\right]^{\frac{1}{2}}$$

$$\sigma_{p1} = \frac{8{,}292}{2} + \left[\left(\frac{8{,}292}{2}\right)^2 + (14{,}362)^2\right]^{\frac{1}{2}} = 19{,}094\,\text{psi}$$

$$\sigma_{p2} = \frac{8{,}292}{2} - \left[\left(\frac{8{,}292}{2}\right)^2 + (14{,}362)^2\right]^{\frac{1}{2}} = -10{,}803\,\text{psi}$$

The maximum shear stress is found to be:

$$\tau_{maximum} = \frac{\sigma_{p1} - \sigma_{p2}}{2} = 14{,}948\,\text{psi.}$$

The top impact limiter lift lugs are fabricated from ASTM A240 316 SS material with minimum yield stress of 30,000 psi. Therefore allowable shear stress:

$$\tau_{allowable} = 0.6 \times 30{,}000 = 18{,}000\ \text{psi.}$$

This translates into a factor of safety of:

$$F.S. = \frac{\tau_{allowable}}{\tau_{maximum}} = \frac{18{,}000}{14{,}948} = 1.2$$

2.5.1.4.6 Top Impact Limiter Lifting Lug Stress Summary

The results of the top impact limiter lifting lug stress analysis are summarized as follows:

Case	Max. Shear Stress Membr. + Bending (psi)	Factor of Safety
Lug tear-out	16,584	1.1
Base weld	8,471	2.1
Bearing	16,585	2.08
Pin hole	14,948	1.2

2.5.2 Tie-Down Devices

The WMG-150B cask is equipped with four tie-down lugs. They are used for the tie-down of the WMG-150B cask during transportation. The transportation of the packages in the United States is controlled under the provisions of 49 CFR 393. 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 WMG-150B cask for the transportation conditions. This section demonstrates the compliance with the requirements of 10CFR71. The details of the analyses are documented in Reference 2-21.

2.5.2.1 Description of the Tie-Down Devices

The WMG-150B cask has four 3-1/4 inch thick tie-down lugs, which are welded to the external shell of the cask body (see Figure 2-5). The steel lugs are used for tying the package down. chock-blocks are used for securing the package on the trailer. In the analyses that follows, the chock-block reactions have been incorporated.

2.5.2.2 Tie-Down Stress Analysis

2.5.2.2.1 Tie-Down Forces

The analytical model for determining the loads required for preventing rotation and translation of the package due to the applied loads is shown in Figure 2-6. The chock-block reactions are represented by the orthogonal components of a single force vector, S, making an angle of θ with the global y-axis.

The lengths of tie-down cables are:

L_1=98.2768 in; L_2=100.9 in; L_3=110.1046 in; L_4=115.0994 in.

Based on the direction of the applied loading, Cable 3 will be slack. Therefore, T3 force is assumed to be zero.

The six equations of equilibrium for the free body diagrams of Figure 2-6 yield the following for the six unknowns:

$$\sum F_x = 0$$

$$+T_1\frac{x_1+x_2}{L_1} - T_2\frac{x_1+x_2}{L_2} + T_4\frac{x_1+x_2}{L_4} - 1\cdot S\sin\theta + 0\cdot S\cos\theta + 0\cdot V = 5(77.5) = 387.5$$

$$\sum F_y = 0$$

$$T_1\frac{y_1-y_3}{L_1} + T_2\frac{y_1-y_3}{L_2} - T_4\frac{y_2-y_4}{L_4} + 0\cdot S\sin\theta + 1\cdot S\cos\theta + 0\cdot V = 10(77.5) = 775$$

$$\sum F_z = 0$$

$$T_1\frac{z_5-z_1}{L_1} + T_2\frac{z_5-z_2}{L_2} + T_4\frac{z_5-z_4}{L_4} + 0\cdot S\sin\theta + 0\cdot S\cos\theta - 1\cdot V = 2(77.5) = 155$$

$$\sum M_x = 0$$

$$T_1\left[\frac{z_5-z_1}{L_1}y_3+\frac{y_1-y_3}{L_1}\left(z_6+z_5\right)\right]+T_2\left[\frac{z_5-z_2}{L_2}y_3+\frac{y_1-y_3}{L_2}\left(z_6+z_5\right)\right]-$$

$$-T_4\left[\frac{z_5-z_4}{L_4}y_4+\frac{y_2-y_4}{L_4}\left(z_6+z_5\right)\right]+0\cdot S\sin\theta+5\cdot S\cos\theta+0\cdot V=10\cdot 77.5\cdot\left(z_7+z_6\right)=50{,}568.75$$

$$\sum M_y=0$$

$$T_1\left[\frac{\left(x_1+x_2\right)}{L_1}\left(z_5+z_6\right)-\frac{z_5-z_1}{L_1}x_1\right]-T_2\left[\frac{\left(x_1+x_2\right)}{L_2}\left(z_5+z_6\right)-\frac{\left(z_5-z_2\right)}{L_2}x_1\right]+$$

$$+T_4\left[\frac{\left(x_1+x_2\right)}{L_4}\left(z_5+z_6\right)-\frac{\left(z_5-z_4\right)}{L_4}x_1\right]-5\cdot S\sin\theta+0\cdot S\cos\theta+0\cdot V=5\cdot 77.5\cdot\left(z_7+z_6\right)=25{,}284.375$$

$$\sum M_z=0$$

$$-T_1\left[\frac{\left(y_1-y_3\right)}{L_1}x1+\frac{\left(x_1+x_2\right)}{L_1}y_3\right]+T_2\left[\frac{\left(y_1-y_3\right)}{L_2}x_1+\frac{\left(x_1+x_2\right)}{L_2}y_3\right]+$$

$$+T_4\left[\frac{\left(y_2-y_4\right)}{L_4}x_1+\frac{x_1+x_2}{L_4}y_4\right]+0\cdot S\sin\theta+0\cdot S\cos\theta+0\cdot V=0$$

In matrix notation the equations appear as:

$$\begin{bmatrix} 0.49732 & -0.484388 & 0.424633 & -1 & 0 & 0 \\ 0.855365 & 0.833123 & -0.80528 & 0 & 1 & 0 \\ 0.144999 & 0.266971 & 0.413773 & 0 & 0 & -1 \\ 64.38943 & 66.21239 & -68.3308 & 0 & 5 & 0 \\ 30.42498 & -25.58652 & 16.64485 & -5 & 0 & 0 \\ -41.3638 & 40.28821 & 37.73012 & 0 & 0 & 0 \end{bmatrix} \times \begin{vmatrix} T_1 \\ T_2 \\ T_4 \\ S\sin\theta \\ S\cos\theta \\ V \end{vmatrix} = \begin{vmatrix} 387.5 \\ 775 \\ 155 \\ 50{,}568.75 \\ 25{,}284.375 \\ 0 \end{vmatrix}$$

Simultaneous solution of the six equations is:

$T_1 = 911.120$ kips

$T_2 = 429.616$ kips

$T_4 = 540.125$ kips

$S\times sin\theta = 86.872$ kips

$S\times cos\theta = 72.688$ kips

$V = 315.295$ kips

2.5.2.2.2 Tie-Down Lug Tear-Out Stress Analysis

The critical section for the tie-down lug tear-out was determined to be as shown in the following sketch. Numerically, the square of tear-out cross section is:

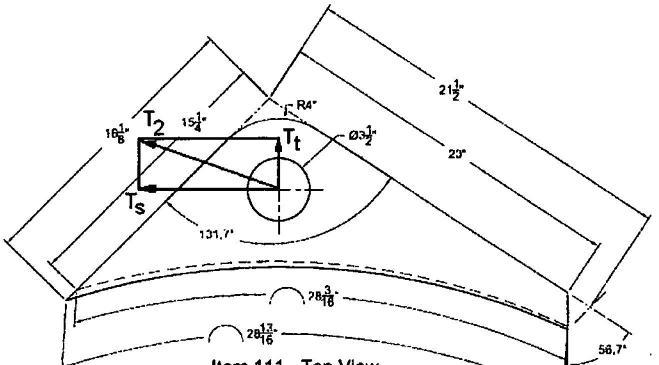
$$A_{shear} = 2 \times L \times t = 2 \times 3.133 \times 3.25 = 20.3645\,\text{in}^2,$$

where:

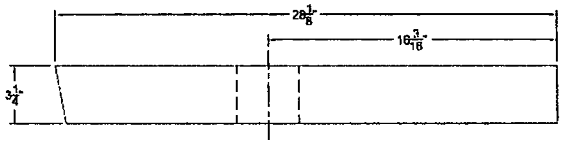
L =3.133 in - length of tear-out section,

t = 3.25 in - section thickness.

As determined above, the maximum tie-down lug load is T_l=911,120 lbs. This results in a shear stress due to tear-out of:



Item 111 - Top View
Tie Down Lug 1



Item 111 - Elevation

$$\tau = \frac{T_1}{A_{shear}} = \frac{911{,}120}{20.36} = 44{,}750 \text{ psi}$$

The tie-down lugs are fabricated from ASTM A543 Type B Class 2 material with minimum yield stress of S_y = 100,000 psi. Therefore, the allowable shear stress is:

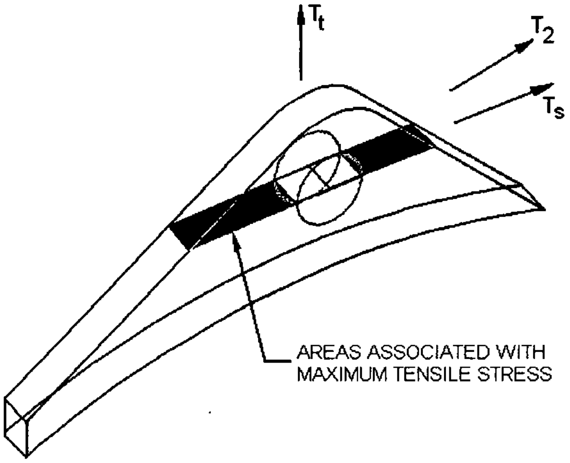
$$\tau_{allowable} = 0.6 \times S_y = 0.6 \times 100{,}000 = 60{,}000 \text{ psi}$$

This results into a factor of safety of:

$$F.S. = \frac{\tau_{allowable}}{\tau} = \frac{60{,}000}{44{,}750} = 1.34\,.$$

2.5.2.2.3 Tie-Down Lug Stress Analysis at Pin Hole

The maximum tensile stress in the tie-down lug occurs in the section of the least cross-section area, as show in following sketch.



This area is found to be:

$$A = (W - D) \times t = (13.1 - 3.5) \times 3.25 = 31.2\,\text{in}^2$$

Where:

W = 13.1 in - width of tie-down lug at the hole centerline,

D =3.5 in - diameter of hole,

t =3.25 in - plate thickness.

The shear and tensile forces are determined as:

$T_t = T_1 \times sin\beta$=911,120 ×0.1829= 166,643 lbs,

$T_s = T_1 \times cos\beta$=911,120 ×0.983127= 895,747 lbs

Where:

β=10.54° is an angle of force action.

This translates into a nominal shear and tensile stress of:

$$\tau = \frac{T_s}{A} = \frac{895{,}747}{31.2} = 28{,}709\,\text{psi},$$

$$\sigma_t = \frac{T_t}{A} = \frac{166{,}643}{31.2} = 5{,}341\,\text{psi}.$$

Combining the effects of the shear and tensile stresses to form the principal stresses yields:

$$\sigma_{p1,p2} = \frac{\sigma_t}{2} \pm \left[\left(\frac{\sigma_t}{2} \right)^2 + (\tau)^2 \right]^{\frac{1}{2}}$$

$$\sigma_{p1} = \frac{5{,}341}{2} + \left[\left(\frac{5{,}341}{2} \right)^2 + (28{,}709)^2 \right]^{\frac{1}{2}} = 31{,}503\,\text{psi}$$

$$\sigma_{p2} = \frac{5{,}341}{2} - \left[\left(\frac{5{,}341}{2} \right)^2 + (28{,}709)^2 \right]^{\frac{1}{2}} = -26{,}162\,\text{psi}$$

The maximum shear stress is found to be:

$$\tau_{maximum} = \frac{\sigma_{p1} - \sigma_{p2}}{2} = 28{,}832\,\text{psi}$$

Using an allowable shear =0.6×S_y and a yield stress of S_y=100,000 psi, the allowable shear stress is:

$$\tau_{allowable} = 0.6 \times S_y = 0.6 \times 100{,}000 = 60{,}000\,\text{psi}$$

This translates into a factor of safety of:

$$F.S. = \frac{\tau_{allowable}}{\tau_{maximum}} = \frac{60{,}000}{28{,}832} = 2.08$$

2.5.2.2.4 Tie-Down Lug Bearing Stress Analysis

The critical section for the tie-down lug bearing was determined to be as

$$A_{bearing} = d \times t = 3.375 \times 3.25 = 10.969\,\text{in}^2$$

Where:

d = 3.375 in - shackle pin diameter.

t = 3.25 in - section thickness.

As determined above in Section 2.1, the total cable force is T_2= 911.120 kips. This results in a shear stress due to tear-out of:

$$\sigma = \frac{T_1}{A_{bearing}} = \frac{911{,}120}{10.969} = 83{,}063\,\text{psi}$$

The tie-down lugs are fabricated from ASTM A543 Type B Class 2 material with minimum yield stress of S_y=100,000 psi. Therefore, the allowable bearing stress is:

$$\sigma_{allowable} = k \times \sigma_y = 1.15 \times 100{,}000 = 115{,}000\ \text{psi}$$

Where k=1.15 is an empirical coefficient of a compression stress (Reference 2-17, Page 976).

This results into a factor of safety of:

$$F.S. = \frac{\sigma_{allowable}}{\sigma} = \frac{115{,}000}{83{,}063} = 1.38.$$

2.5.2.2.5 Tie-Down Lug Base Stresses Analysis

The tie-down lug is welded to the outer shell. The length of weld is about 28 inch. (Please see sketch above) The base of tie-down lug is not flat. Only the center part of the base weld is loaded. We conservatively use the work part length of the base weld equal 20 inch.

The tensile stress in the weld at the bottom of the tie-down lug as shown in in the sketch is:

$$\sigma_{tensile} = \frac{T_t}{A_b} = \frac{166{,}643}{100} = 1{,}666 \text{ psi}$$

$$A_b = 4 \cdot l \cdot t_w = 4 \cdot 20 \cdot 1.25 = 100 \,\text{in}^2,$$

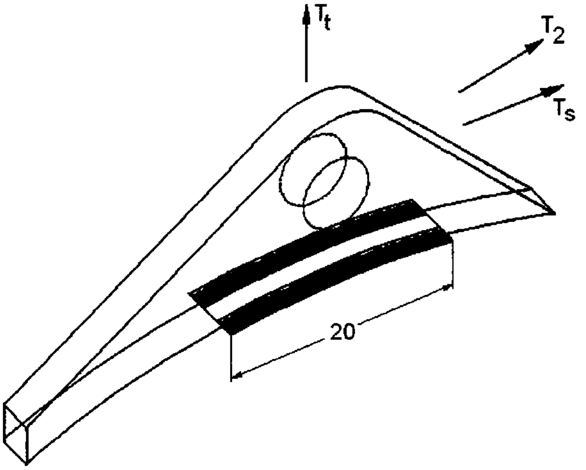
where:

A_b = 100in^2 -base area,

l =20 in - weld length,

t_w =1.25 in - weld thickness,

T_t =166,643 lbs – tensile force.



The bending stress, maximum at the bottom outer edge of each of lug, is:

$$\sigma_{bending} = \frac{M \times c}{I} = \frac{3{,}582{,}988 \times 10}{3333.33} = 10{,}749 \,\text{psi}$$

$$M = 4 \times T_S = 4 \times 895{,}747 = 3{,}582{,}988 \,\text{in·lbs}$$

$$I = \frac{(4 \times t_w) \times (l)^3}{12} = \frac{5 \times 20^3}{12} = 3333.33 \text{ in}^4,$$

where:

M = 3,582,988 in-lbs- bending moment,

c =10 in - distance to neutral axis,

I = 3333.33 in^4 - moment of inertia,

l= 20 in – weld length,

t_w =1.25 in - weld thickness.

At the outer edge of the tie-down lug, the bending stress will add to the tensile stress to produce a total tensile stress of:

$$\sigma_{total} = \sigma_{bending} + \sigma_{tensile} = 10{,}749 + 1{,}666 = 12{,}415 \text{ psi}$$

The shear stress at the bottom of the tie-down lug is:

$$\tau = \frac{T_S}{A_b} = \frac{895{,}747}{100} = 8{,}957 \text{ psi},$$

where:

T_S= 895,747 lbs - shear force,

A_b=100 in^2 - base area.

The effect of the shear and total tensile stresses are combined to form the principal stress for the lifting lugs as follows (Reference 2-16):

$$\sigma_{p1,p2} = \frac{\sigma_{total}}{2} \pm \left[\left(\frac{\sigma_{total}}{2} \right)^2 + (\tau)^2 \right]^{\frac{1}{2}}$$

Thus,

$$\sigma_{p1} = \frac{12{,}415}{2} + \left[\left(\frac{12{,}415}{2} \right)^2 + (8{,}957)^2 \right]^{\frac{1}{2}} = 17{,}105 \text{psi}$$

$$\sigma_{p2} = \frac{12{,}415}{2} - \left[\left(\frac{12{,}415}{2} \right)^2 + (8{,}957)^2 \right]^{\frac{1}{2}} = -4{,}690 \text{psi}$$

The maximum shear stress will be:

$$\tau_{maximum} = \frac{\sigma_{p1} - \sigma_{p2}}{2} = 10{,}897 \text{ psi}$$

Using an allowable shear =0.6×S_y and a yield stress of S_y=100,000 psi, the allowable shear stress is:

$$\tau_{allowable} = 0.6 \times S_y = 0.6 \times 100{,}000 = 60{,}000 \text{psi}$$

The factor of safety will be:

$$F.S. = \frac{\tau_{allowable}}{\tau_{maximum}} = \frac{60{,}000}{10{,}897} = 5.5$$

2.5.2.3 Outer Shell Stresses Analysis

The outer shell stress analysis is performed numerically using ANSYS software (Reference 2-22). Details of ANSYS verification and validation are presented in V&V report (Reference 2-23). The detailed description of FEM model used is presented in WMG document AR-120 (Reference 2-24). The computer model configurations of Cask Body is illustrated in Figure 2-7. The boundary conditions and loads of cask model are shown in Figures 2-8. Tie-down force is applied to the hole surface of the lug. Loading contact pressure is equal to:

$$q = \frac{T_1}{Sc} = \frac{911{,}120}{4.94} = 184{,}437 \text{ psi.}$$

Where: Sc=4.94 in^2 - contact area, T_1= 911,120 lbs – applied load.

Figure 2-9 shows the plot of stress intensity contour in the outer shell near lug. Maximum stress intensity of 79,382 psi in the shell is smaller than the yield stress of the material – 85,000 psi.

2.5.2.4 Tie-Down Lug Stress Analysis Summary

The results of the tie-down lug stress analysis are summarized as follows in the following table:

Case	Allowable S.I. (psi)	Max. Shear Stress Membrane + Bending (psi)	Factor of Safety
Lug Tear-out	60,000	44,750	1.34
Pin Hole	60,000	28,832	2.08
Bearing	115,000	83,063	1.38
Base Weld	60,000	10,897	5.5
Outer shell	85,000	79,382	1.1

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 (Reference 2-3).

The structural analyses of the WMG 150B Cask under NCT events have been performed through the use of finite element models. ANSYS finite element analysis code (References 2-22 and 2-23) has been employed to perform the analyses.

Full (360°) 3D finite element model is developed to obtain the structural analysis results both for normal conditions of transport (NCT) and hypothetical accident conditions (HAC). The model represents all the major components of the cask, including the inner and the outer shells, the top flange, the primary and the secondary lids, the lift lugs, the tie-down lugs, the bottom plate, the lead shields and the closure bolts.

The finite element model of the cask consists of 953,244 3-dimensional 8-node structural solid elements (ANSYS SOLID185) and of 209,316 contact elements. 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-dimensional 8 node contact (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 typical size of the finite solid elements is (0.53x0.63x0.37) inch for the shells and the lids. For the closure bolts and the small parts of the cask the typical size of the finite elements is (0.13x0.08x0.16) inch. This selection of the element size results in very fine finite element grids of all the components of the WMG 150B cask (see Figure 2-10). It results in several elements through the thickness of the critical components. Also because of the small aspect ratio of the elements, the dimensions of the elements along the length and circumferential directions of the cask are also very small. In addition the fully-integrated formulation option of the ANSYS SOLID185 elements has been employed in the models. Therefore, the grid size used in the model is sensitive enough for computing the bending stresses in the cask accurately.

Figure 2-10 shows the cask FE-model. The cask lid assembly model is shown in Figure 2-11.

The details of the finite element model, including the assumptions, modeling details, boundary conditions, and input and output data are included in the WMG document AR-119 (Reference 2-24).

2.6.1 Heat

The thermal evaluation of the WMG 150B package is described in Section 3.3. 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 2-12 (reproduced from Figure 3-5) 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 2-12):

Fire Shield = 149.4°F
Outer Shell = 149.3°F
Inner Shell = 153.0°F
Lead = 151.4°F
Seal = 150.9°F
Lid/Baseplate = 153.3°F

The maximum temperature of the cask cavity is under normal conditions is 155.5°F which is conservatively assumed to be the average cask cavity temperature. The gas mixture in the cavity is conservatively assumed to be 175°F. This temperature has been used for calculating the Maximum Normal Operating Pressure (MNOP) in Section 3.3.2. The MNOP of 26.36 psia is used for the evaluation of the hot and cold environment load conditions.

2.6.1.2 Differential Thermal Expansion

The structural finite element model used for the analyses of the WMG 150B 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 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 WMG Document AR-119 (Reference 2-24). The loading combination is listed in Table 2-1. Table 2-5 presents the maximum stresses in various components of the package. Figure 2-13 shows the plot of stress intensity contour in the inner and outer shells. It should be noted that the stresses caused by lead shrinkage during fabrication are small and have been neglected. AR-130S (Reference 2-41) gives the evaluation and the justification for neglecting these stresses.

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 1.42 occurs in the primary lid bolts.

2.6.2 Cold

The thermal evaluation of the WMG 150B package under cold conditions is described in Section 3.3. 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 2-14 (reproduced from Figure 3-6) shows the temperature distribution in the structural components of the package.

The structural finite element model used for the analyses of the WMG 150B 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 included in the stress calculation of the package.

The stresses in the package under the cold environment loading conditions have been performed in WMG Document AR-119 (Reference 2-24). The loading combination is listed in Table 2-1. Table 2-6 presents the maximum stresses in various component of the package. Figure 2-15 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 1.24 occurs in the primary lid bolts.

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 (Reference 2-2), this condition is associated with the minimum decay heat load.

Per regulatory Guide 7.8 (Reference 2-2), the cask must be able to resist brittle fracture failure under normal conditions of transport and hypothetical accident conditions at temperature as low as -20°F. Fracture critical parts of the cask are shown in Figure 2-16. For compliance with Category II fracture toughness requirements of NUREG/CR-1815 (Reference 2-6), the nil ductility transition temperature (T_{NDT}) of this steel with which these parts are fabricated must be less than the value determined by the equation:

T_{NDT} = LST – A

Where:

LST = Lowest service temperature (-20°F)

A = Value from Figure 7 of NUREG/CR 1815 (Reference 2-6) also shown in Figure 2-17

Table 2-7 tabulates the T_{NDT} required for the fracture critical components of the WMG 150B cask except bolting.

For the bolting NUREG/CR-1815 does not provide any guidance. ASME Section III Subsection NB is used to specify the toughness requirements of the fracture-critical bolts. The lid bolts and the bolts attaching the lifting lugs with the cask body are considered to be fracture-critical. The toughness requirements for these bolts, based on article NB-2333 of the code are:

- Energy required – None
- Lateral expansion = 25 mils

The Charpy V-Notch test must be performed at -20°F using ASTM A-370 standard.

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 WMG 150B package is 26.36 psia. The external pressure reduced to 3.5 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 AR-119 (Reference 2-24). Table 2-8 presents the maximum stresses in various components of the package. Figure 2-18 shows the plot of stress intensity in the inner and outer shells of the cask.

The stresses in the package under the reduced 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. A minimum factor of safety of 1.38 occurs in the primary lid bolts.

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 WMG 150B package is 26.36 psia. 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 AR-119 (Reference 2-24). Table 2-9 presents the maximum stresses in various components of the package. Figure 2-19 shows the plot of stress intensity in the inner and outer shells of the cask.

The stresses in the package under the increased external pressure loading conditions are compared with their allowable values in Table 2-9. 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 1.24 occurs in the primary lid bolts.

2.6.5 Vibration

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

The WMG 150B package consists of thick section materials that will be unaffected by vibration normally incident to transport, such as over the road vibrations.

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 a WMG proprietary methodology outlined in document AR-110 (Reference 2-25) that utilizes the ANSYS/LS-DYNA computer code (References 2-26, 2-27, and 2-39). The methodology was developed after a considerable amount of research and parametric studies for the accuracy of results. These studies included the choice of elements, mesh density, material damping, hourglass control, and, solution parameters and controls, etc. The methodology was successfully validated against test results, and the analyzed results of another cask. Full documentation of the benchmark analysis against the test results is provided in WMG proprietary document AR-131S (Reference 2-42) and against another analyzed cask is provided in WMG proprietary document AR-111 (Reference 2-7). The sensitivity study of the modeling technique is documented in the WMG document AR-116 (Reference 2-29). Similar methodology has also been used in recently approved cask packages Energy*Solutions* 3-60B and 8-120B.

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. All the load combinations listed in Table 2-1 are analyzed. Since the cold environment conditions result in higher impact limiter reactions than the hot environment, analyses for all drop orientations were performed for cold environment only. The details of the package dynamic analyses are documented in WMG Document AR-111 (Reference 2-7). The documentation of the detailed FEM analyses of the package is provided in WMG Document AR-119 (Reference 2-24).

The summary of the results from the package dynamic analyses of the NCT free drop are presented in Table 2-10. 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 WMG Document AR-111 (Reference 2-7). Note that the reactions listed in Reference 2-7 are for 180° model. They are multiplied by 2 to obtain the results for the complete cask package.

Bottom End $= 2\times1.6554\times10^6$ lb (see Figure 2-20)

$= 3.3108\times10^6$ lb

Top End = $2\times1.7057\times10^6$ lb (see Figure 2-21)

= 3.4114×10^6 lb

For the NCT test in the end drop orientations, the maximum of the two reactions are used in the analyses. This reaction is further increased to 3.6×10^6 lb for added conservatism (see Table 2.8 of Reference 2-7).

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. The results obtained from the detailed FEM analysis of the cask are presented in Tables 2-11 and 2-12 for the hot and cold combinations, for the bottom end drop and Tables 2-13 and 2-14 for the bottom end drop.

Of all components, a minimum safety factor of 1.24 is computed for the loading combinations involving end drop.

2.6.7.2 Side Drop

The following impact limiter reactions are obtained from WMG Document AR-111 (Reference 2-7).

Side Drop Reaction = $2\times5.6256\times10^5$ lb (see Figure 2-22)

= 1.1251×10^6 lb

For the NCT test in the side drop orientation, the reaction is further increased to 1.4×10^6 lb for added conservatism (see Table 2.8 of Reference 2-7).

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 Tables 2-15 and 2-16 for the hot and cold combinations, respectively.

Of all components, a minimum safety factor of 1.15 is computed for the loading combinations involving side drop.

2.6.7.3 Corner Drop

The following impact limiter reactions are obtained from WMG Document AR-111 (Reference 2-7).

Corner Drop = $2\times3.2066\times10^5$ lb (see Figure 2-23)

= 6.4132×10^5 lb

For the NCT test in the corner drop orientation, the reaction is further increased to 7×10^5 lb for added conservatism (see Table 2.8 of Reference 2-7).

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 Tables 2-17 and 2-18 for the hot and cold combinations, respectively.

Of all components, a minimum safety factor of 1.16 is computed for the loading combinations involving corner drop.

2.6.8 Corner Drop

Not applicable; the WMG 150B package is not a fiberboard, wood, or fissile material package.

2.6.9 Compression

Not applicable; the WMG 150B 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″ on to 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 cited in Reference 2-30. 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 WMG 150B outer shell is 1¼″, the lid is 3″, the outer baseplate is 3¼″ and the impact limiter shell is 11 gauge = 0.125″. 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 WMG 150B package is shown to comply with the hypothetical accident conditions (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 WMG 150B 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 primarily made from steel and lead, with stainless steel used for the seal rings. The fundamental periods of the two components are, therefore, sufficiently far apart that little or no interaction takes place between their dynamic responses during 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 WMG, using an explicit dynamic finite element code, ANSYS/LS-DYNA (References 2-26 and 2-27), 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 WMG 150B package. The validation of the modeling techniques have been performed with the modeling technique developed at Energy*Solutions* that has been validated with the actual drop test data. The details of the modeling techniques and the validation are documented in an WMG proprietary document AR-110 (Reference 2-2-25). The WMG 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 WMG 150B package is described in details in WMG document AR-111 (Reference 2-7). Figure 2-24 shows the finite element model. It is made of 8-node solid elements and 4-node shell elements.

In order to envelop the entire spectrum of orientations of the WMG 150B cask during various drop tests, the three customary orientations – end, side, and corner, as well as three additional orientations have been analyzed. The analyzed orientations are:

(1) Bottom End Drop – The cask axis parallel to the vertical direction (see Figure 2-25(a))

(2) Top End Drop – The cask axis parallel to the vertical direction (see Figure 2-25(b))

(3) Side Drop – The cask axis perpendicular to the vertical direction (see Figure 2-25(c))

(4) Corner Drop – The C.G. of the cask directly over the impact point. The cask axis makes an angle of 51.8° with the horizontal plane (see Figure 2-25(d))

(5) Shallow Angle Drop – In order to account for the secondary impact, 150B cask is analyzed for two shallow angle orientations. In the first, the cask axis is inclined by 5° from the horizontal plane, and in the second, the cask axis is inclined by 10° from the horizontal plane (see Figures 2-25(e) and (f)).

(6) Off-Corner Drop – In order to capture a slight deviation from the corner-over-CG orientation, an off corner orientation is also analyzed. The cask axis makes an angle of 45° with the horizontal plane (see Figure 2-25(g))

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 2-26 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 2-27 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 WMG 150B package, including the finite element model details, assumptions, boundary conditions, and the input and output data are included in the WMG document AR-111 (Reference 2-7).

The maximum acceleration results from these analyses are presented in Table 2-19. Table 2-20 presents the maximum crush depth of the impact limiter material during various drop test orientations.

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 (References 2-22 and 23) has been employed to perform the analyses. The finite element model is described briefly in Section 2.6 of the SAR. The details of the finite element model including the grid geometry, material properties, and the boundary conditions are provided in WMG document AR-120 (Reference 2-31).

To incorporate the loading combinations of Table 2-1 for various drop conditions, the analyses have been performed for two thermal conditions. These combinations have been performed per Regulatory Guide 7.8. For the hot conditions the ambient temperature is 100°F and the maximum internal decay heat load is assumed to be present in the cask. For the cold conditions the ambient temperature is -20°F and the minimum decay heat is assumed to be present in the cask. The nodal temperatures for all the thermal conditions are obtained from the analyses in Section 3 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 WMG document AR-120 (Reference 2-31).

2.7.1.1 End Drop

The following impact limiter reactions for the 180° model are obtained from WMG Document AR-111 (Reference 2-7).

Bottom End Drop (Cold)	$= 6.1305\times10^6$ lb	(Table 2-19)
Bottom End Drop (Hot)	$= 4.1458\times10^6$ lb	(Table 2-19)
Top End Drop (Cold)	$= 5.7325\times10^6$ lb	(Table 2-19)
Top End Drop (Hot)	$= 3.8171\times10^6$ lb	(Table 2-19)

The maximum of all the reactions, 2x6.1305x10^6 lb = 12.261x10^6 lb, further increased to 13x10^6 lb (see Table 2.8 of Reference 2-7), is conservatively used for the end drop 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.

Bottom End Drop Rigid Body Deceleration = 13x10^6/(77,500 – 4,540) = 178.2g

Top End Drop Rigid Body Deceleration = 13x10^6/(77,500 – 4,870) = 179.0g

The decelerations used in the bottom and top end drop analyses in Reference 2-31 are 179.56g and 180.31g, respectively. These values are slightly conservative.

The distribution of reactions and inertia loads used in the quasi-static FEM analyses are shown in Figure 2-28. The plot of the stress intensities (S.I.) in the cask shells are shown in Figures 2-29 for the top end drop under hot conditions. The S.I. plots for all the components are included in Reference 2-31). The results obtained from the detailed FEM analysis of the cask are presented in Tables 2-21 and 2-22 for the hot and cold combinations for top end drop and in Tables 2-23 and 2-24 for bottom end drop.

Of all components, a minimum safety factor of 1.17 is computed for the loading combinations involving end drop.

2.7.1.2 Side Drop

The following impact limiter reactions for the 180° model are obtained from WMG Document AR-111 (Reference 2-7).

Side Drop (Cold)	= 1.7804x10^6 lb	(Table 2-19)
Side Drop (Hot)	= 1.5509x10^6 lb	(Table 2-19)
Shallow-1 (Cold)	= 2.081x10^6 lb	(Table 2-19)
Shallow-2 (Cold)	= 2.1384x10^6 lb	(Table 2-19)

The maximum of all the reactions, 2x2.1384x10^6 lb = 4.2768x10^6 lb, further increased to 4.6x10^6 lb (see Table 2.8 of Reference 2-7), is conservatively used for the side drop 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 impact limiters.

Side Drop Rigid Body Deceleration = 4.6x10^{6}x2/(77,500 – 4,540 – 4,870) = 135.1g

The deceleration used in the side drop analyses in Reference 2-31 is 136.5g. This value is slightly conservative.

The distribution of reactions and inertia loads used in the quasi-static FEM analyses are shown in Figure 2-30. The plot of the stress intensities (S.I.) in the cask shells are shown in Figures 2-31 for the side drop under hot conditions. The S.I. plots for all the components are included in Reference 2-31). The results obtained from the detailed FEM analysis of the cask are presented in Tables 2-25 and 2-26 for the hot and cold combinations, respectively.

Of all components, a minimum factor of safety on the containment boundary components is 1.05.

2.7.1.3 Corner Drop

The following impact limiter reactions for the 180° model are obtained from WMG Document AR-111 (Reference 2-7).

Corner Drop (Cold)	$= 2.1821\times10^6$ lb	(Table 2-19)
Corner Drop (Hot)	$= 2.0684\times10^6$ lb	(Table 2-19)
Off-Corner (Cold)	$= 2.0933\times10^6$ lb	(Table 2-19)

The maximum of all the reactions, $2\times2.1821\times10^6$ lb $= 4.3642\times10^6$ lb, further increased to 4.6×10^6 lb (see Table 2.8 of Reference 2-7), is conservatively used for the corner drop 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.

Corner Drop Rigid Body Deceleration $= 4.6\times10^6/(77{,}500 - 4{,}540) = 63g$

The decelerations used in the corner drop analyses in Reference 2-31 are 63.8g for top corner and 63.5g. These values are slightly conservative.

The distribution of reactions and inertia loads used in the quasi-static FEM analyses are shown in Figure 2-32. The plot of the stress intensities (S.I.) in the cask shells are shown in Figures 2-33 for the top corner drop under hot conditions. The S.I. plots for all the components are included in Reference 2-31). The results obtained from the detailed FEM analysis of the cask are presented in Tables 2-27 and 2-28 for the hot and cold combinations, respectively.

Of all components, a minimum safety factor of 1.03 is computed for the loading combinations involving corner drop.

2.7.1.4 Oblique Drop

The diameter of the WMG 150B package impact limiter is 106.5 inches and the overall package height is 129 inches. The following analysis indicates that for the WMG 150B package with the diameter approximately equal to its length, there is no slapdown effect. That is, the impact is not more severe than a side drop.

This section represents an analysis demonstrating that oblique impacts are not worst-case for casks having length-to-diameter ratios less than 1.37. Figure 2-34 illustrates a cask of length (l), and mass (M), dropped at an angle (α) measured from the horizontal plane. No energy absorption is initially assumed from the impact limiter of cask during primary impact (first contact of the lower end of the cask with the impact surface). This assumption results in the worst case (greatest) impact velocity of the higher end of the cask.

The angular momentum before and after impact can be estimated based on the following assumptions:

- The impact point does not slide along the horizontal impact surface.

- The rotational inertia of the cask can be approximated assuming a uniform density solid cylinder, i.e. : $I_{CG} = \frac{1}{4} \times M \times \left(r^2 + \frac{l^2}{3} \right)$
- The gravitational acceleration of the cask is neglected after the initial impact.

Then, before impact,

$$L_1 = M \times \mathrm{v}_1 \times \left(\frac{1}{2} \times l - r \times \tan\alpha \right) \times \cos\alpha$$

And, after impact:

$$L_2 = I_i \times \omega_2$$

Where:

L_1 = angular momentum before impact

M = mass of cask

v_1 = impact velocity

I_i = rotational inertia of cask about impact point

$$= I_{CG} + M \times R^2$$

$$= M \times \left(\frac{1}{4} \times r^2 + \frac{1}{12} \times l^2 + R^2 \right)$$

ω_2 = angular velocity of cask following impact

Since no moments are applied to the cask, angular momentum is conserved, and $L_1 = L_2$:

$$M \times \mathrm{v}_1 \times \left(\frac{1}{2} \times l - r \times \tan\alpha \right) \times \cos\alpha = M \times \left(\frac{1}{4} \times r^2 + \frac{1}{12} \times l^2 + R^2 \right) \times \omega_2$$

Solving for angular velocity:

$$\omega_2 = \mathrm{v}_1 \times \frac{\left(\frac{1}{2} \times l - r \times \tan\alpha \right) \times \cos\alpha}{\frac{1}{4} \times r^2 + \frac{1}{12} \times l^2 + R^2}$$

In general, maximum angular velocity occurs when the impact angle equals zero.

The velocity of the secondary impact is given by:

$$\mathrm{v}_S = l \times \omega_2$$

Then:

$$v_S = l \times v_1 \times \frac{\left(\frac{1}{2} \times l - r \times \tan\alpha\right) \times \cos\alpha}{\frac{1}{4} \times r^2 + \frac{1}{12} \times l^2 + R^2}$$

The limiting case can be taken as that for which the secondary impact velocity equals the initial impact velocity for the worst case angular velocity. Then,

$$v_S = v_1 \text{ at } a = 0$$

And:

$$\frac{\frac{1}{2} \times l^2}{\frac{1}{4} \times r^2 + \frac{1}{12} \times l^2 + R^2} = 1$$

From Figure 2-34,

$$R^2 = \frac{1}{4} \times l^2 + r^2$$

Therefore,

$$\frac{1}{2} \times l^2 = \frac{1}{4} \times r^2 + \frac{1}{12} \times l^2 + \frac{1}{4} \times l^2 + r^2$$

$$\frac{l^2}{r^2} = 7.50 \qquad and, \qquad \frac{l}{r} = 2.74$$

Implying that:

$$\frac{l}{d} = \frac{l}{2 \times r} = 1.37$$

Thus, for length-to-diameter ratios greater than 1.37, slapdown impacts may be more severe than a normal side drop. Since this analysis very conservatively neglects any energy absorption of the initial impact, this ratio may be taken as a lower bound, below which one may safely assume that secondary impact will be less severe than side drop impacts. Since the WMG 150B cask has a length-to-diameter ratio of 1.21, the oblique drop is less severe than the side drop. Cask stresses in an oblique drop will be less than those experienced during a side drop.

2.7.1.5 Lead Slump Evaluation

The WMG 150B package experiences the largest acceleration during the end drop orientation. Analyses of the WMG 150B package under various environmental conditions in this drop orientation have been performed in Section 2.7.1.1. A finite element model analysis, using a 2-dimensional axi-symmetrical model, has been performed in WMG document AR-125 (Reference 2-32) to conservatively estimate the lead slump in the WMG 150B cask. The total relative displacement of the lead column of 3/8 inch is reported as the lead-slump. However, it should be noted that the analysis uses several very conservative assumptions to predict this value. Nonetheless, this value has been used in the shielding analysis to address the lead slump scenario.

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 2-29. The maximum load in an individual attachment under any of the HAC events is 38,569 lb (WMG document AR-111, Reference 2-7). A detail evaluation of the impact limiter attachment components is performed in WMG document AR-115 (Reference 2-33), which shows that the assembly is capable of sustaining this load with a large margin of safety.

2.7.1.7 Shell Buckling

Buckling, per Regulatory Guide 7.6 (Reference 2-3), is an unacceptable failure mode for the containment vessel. The intent of this guideline is to make large deformations unacceptable because they would compromise the validity of linear assumptions and quasi-linear allowable stresses as given in Paragraph C.6 of NRC Regulatory Guide 7.6.

Evaluation of the WMG 150B cask for buckling has been performed in WMG document AR-114 (Reference 2-34). The analyses in Reference 2-34 address both elastic and inelastic stability of the shells. The results of the analyses show that there is a large margin of safety against the buckling of the WMG 150B cask shells under all the possible loading scenarios.

2.7.1.8 Pressurization Port Evaluation

The WMG 150B package has one penetration through the containment boundary that is closed with a bolt. This is the pressurization port. The port is recessed into the cask lid. It is completely covered by the foam of the impact limiter. Therefore, during the HAC drop tests the pressurization port does not make contact with the impact surface.

2.7.1.9 Closure Bolt Evaluation

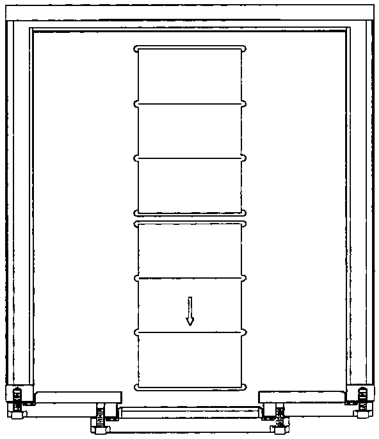
The primary and secondary lid bolt stresses under various loading combinations that were obtained from the FEM analyses have been provided in the appropriate sections of the SAR. They have been compared with the corresponding design allowable values and typically show that a large factor of safety exists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

Evaluation of the closure bolts for the combined tension and shear loading has been performed for all the HAC drop test orientations in WMG document AR-120 (Reference 2-31). The analyses have been performed using the approach outlined in NUREG-6007 (Reference 2-18) and it is shown that both the primary and secondary lid bolts meet the design criteria listed in Section 2.1.2 of this SAR.

2.7.1.10 Payload Shoring

In order to conveniently place the payload into the cask, the payload dimensions will be smaller than the cask cavity dimensions. However, since the drop analyses performed in this SAR assume the payload to be uniformly distributed in the cavity, restrictions are applied to the maximum amount of gap that can exist between the payload and the cask cavity. Shoring will be provided around the payload that will keep this gap to be within ½" in the radial and axial directions. This will make the payload inertia load distribution to be reasonably uniform in the cavity which will match the analyses assumptions. Nonetheless, an unlikely scenario in which a pair of drums dislodge from the pallet and apply the inertia load to the secondary lid is analyzed here to show that the bolting provided in the design is sufficient to preclude opening of the lid in this scenario.

When the payload is in the form of drums, the WMG 150B cask can carry up to 10 drums. The total payload is 15,500 lb. Thus the drums will have a maximum average mass of 1,550 lb each. Conservatively consider that the mass of the two drums is 5,000 lb. The secondary lid mass is estimated to be 1,790 lb (see Reference 2-20). The maximum deceleration of the package occurs during the top end drop and its value is 179g (see Section 2.7.1.1). Thus the maximum inertia load that the secondary lid bolts will have to resist is:



$$P = (5{,}000 + 1{,}790) \times 179 = 1.22\times10^{6}\ \text{lb}$$

The secondary lid is fastened with 15 1½"-6UNC bolts, made of ASTM A-540 Gr. B24 material. The bolts have a stress area of 1.4041 in^2 (Reference 2-19) and have the tensile stress allowable of 115,500 psi (Table 2-2). Thus the bolts are capable of sustaining an axial load of:

$$P_{max} = 15\times115{,}500\times1.4041 = 2.43\times10^{6}\ \text{lb}$$

Since the bolts are capable of resisting much larger load than the drum inertia can apply, it is concluded that the secondary lid will remain attached to the primary lid in this scenario.

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 detail puncture drop analysis of the WMG 150B cask has been performed in WMG document AR-121 (Reference 2-35). A supplemental analysis that addresses the puncture drop on the cask sidewall is performed in WMG document AR-126 (Reference 2-36). The following summarizes the results of the analyses performed in these references.

For the side drop of a lead-steel cask, Nelm's equation provides a relation of total weight of the package to the thickness of the outer shell that can sustain the puncture drop loading. This relation is given in Reference 2-37, Page 18) as follows:

$$t = (W/S)^{0.71}$$

Where:

t = shell thickness = 1¼ inch

W = cask weight, lb

S_u = ultimate tensile strength of outer shell

= 105,000 psi

The package weight causing puncture is:

$$W = S \times t^{1.4}$$

The corresponding weight to cause puncture of the 1¼ inch outer shell is:

$$W_s = 70{,}000 \times 1.25^{1.4} = 143{,}504\,lb$$

The actual package weight is 77,500 lbs; therefore, the factor of safety for puncture resistance on an energy basis is:

$$F.S. = \frac{143{,}504}{77{,}500} = 1.85$$

When the package impacts the puncture pin, the force imposed upon the package is estimated as:

$$F_I = K_S \times A_I$$

K_s = Dynamic flow pressure of steel = 45,000 psi (Reference 2-37, Page 64)

R_c = Pin diameter = 6.0 inches

$$A_I = \frac{\pi}{4} \times (R_c)^2 = \frac{\pi}{4} \times (6.0)^2 = 28.27\ in.^2$$

$$F_I = (45{,}000) \times (28.27)$$

$$= 1.272 \times 10^6 lbs.$$

This force induces a moment at the midsection of the package. The moment is estimated as:

$$M = \frac{F \times l}{8} = \frac{(1.272 \times 10^6) \times (87)}{8} = 13.83 \times 10^6\ in\text{-}lb$$

Calculating the section properties of the outer shell at the midsection:

$$I = \frac{\pi(d_o^4 - d_i^4)}{64} = \frac{\pi(76.75^4 - 74.25^4)}{64} = 2.113 \times 10^5\ in^4$$

Using these section properties gives a bending stress of:

$$S_b = \frac{M \times c}{I} = \frac{(13.83 \times 10^6) \times (38.375)}{2.113 \times 10^5} = \pm 2{,}512\ psi$$

Conservatively assuming that the tensile and compressive stresses appear at the same location, the stress intensity is 5,024 psi and the safety factor is:

$$F.S. = \frac{105{,}000}{5{,}024} = 20.9$$

To evaluate the ability of the cask to withstand puncture from a 40-inch bottom end drop onto a 6-inch diameter pin, the bottom end of the cask will be treated as simply supported plate with a central load. Reference 2-38 gives the following equation for the deflection of a centrally loaded circular plate:

$$\frac{\omega_0}{h} + A \times \left(\frac{\omega_0}{h}\right)^3 = B \times \left(\frac{P \times a^2}{E \times h^4}\right)$$

Where:

ω_0 = deflection at center of plate, in;

h = plate thickness, in;

P = central load, lb;

E = Young's modulus, psi;

a = plate radius, in;

A = 0.272 (simply supported plate

B = 0.552 (simply supported plate

The deformation energy can be found from:

$$u = \int_0^{\delta} P d\omega_o = \frac{E \times h^4}{B \times a^2}\left[\frac{\delta^2}{2h} + \frac{A \times \delta^4}{4h^3}\right].$$

This can be equated to the drop energy, $W \times H$ to find the central deflection:

$$EhA\delta^4 + 2Eh^3\delta^2 - 4Ba^2WH = 0$$

$$\delta^2 = \frac{-2Eh^3 + \sqrt{(4E^2h^6 + 4EhA \times 4Ba^2WH)}}{2EhA}$$

$$\delta^2 = \frac{-2 + \sqrt{\left(4 + \frac{16ABa^2WH}{Eh^5}\right)}}{\frac{2A}{h^2}}$$

For:

$h = 3$ in

$E = 28.2 \times 10^6 \, psi$

$a = 38.75$ in

$W = 77{,}500$ lb

$H = 40$ in.

$$\delta^2 = \frac{-2 + \sqrt{\left(4 + \frac{16 \times 0.272 \times 0.552 \times 38.75^2 \times 77{,}500 \times 40}{28.2 \times 10^6 \times 3^5}\right)}}{\frac{2 \times 0.272}{3^2}} = 6.173 \, in^2$$

Then:

$\delta = 2.485 \, in$.

Solving for the force required to produce this deflection gives a value:

$$\frac{2.485}{3} + 0.272 \times \left(\frac{2.485}{3}\right)^3 = 0.552 \times \left(\frac{P \times 38.75^2}{28.2 \times 10^6 \times 3^4}\right)$$

$$P = 2.71\times10^{6} lb$$

However, using the dynamic flow pressure of the steel pin, the maximum force that can be exerted by the pin is given by:

$$F_I = K_S \times A_I$$

Where:

K_s = Dynamic flow pressure of steel = 45,000 psi

$$A_I = \frac{\pi}{4}\times(R_c)^2 ;$$

R_c = Pin diameter = 6.0 inches.

Then:

$$A_I = \frac{\pi}{4}\times(6.0)^2 = 28.27 in^2$$

$$F_I = (45{,}000)\times(28.27) = 1.272\times10^{6}\, lb.$$

This force will produce the maximum deflection of the plate $\delta = 1.316\ in$

Reference 2-38 gives the following equations for the maximum membrane and membrane plus bending stresses:

Membrane:

$$\sigma_1 = \frac{\alpha\times E\times\delta^2}{a^2}.$$

Membrane-plus-bending:

$$\sigma_2 = \frac{\beta\times E\times\delta\times h}{a^2}.$$

For:

$$\alpha = 0.407$$
$$\beta = 0.606$$

Then:

$$\sigma_1 = \frac{0.407\times28.2\times10^{6}\times1.316^{2}}{38.75^{2}} = 13{,}238\, psi$$

$$\sigma_2 = \frac{0.606\times28.2\times10^{6}\times1.316\times3}{38.75^{2}} = 44{,}932\, psi$$

The minimum safety factor is:

$$F.S. = \frac{105{,}000}{44{,}932} = 2.34$$

The evaluation of the puncture drop on the sidewall is performed in detail in WMG document AR-126 (Reference 2-36), using a nonlinear finite element model. The results of the analysis show that a maximum lead flattening of less than ¼" may occur during the puncture drop test on the sidewall. The effect of the loss of this shielding is addressed in Section 5 of the SAR.

2.7.4 Thermal

The thermal evaluation of the WMG 150B package for the HAC fire test specified in 10 CFR 71.73(c)(4) has been performed in Section 3.4. It has been shown in the free drop analyses that the rupture of the impact limiter skin near the point of impact is possible. The polyurethane foam is self-extinguishing and produces intumescent char when thermally degraded. The two impact limiters are assumed to provide thermal insulation.

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 WMG document AR-120 (Reference 2-31).

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 3-14. These temperatures are summarized here as follows:

Fire Shield = 1,264.8°F
Outer Shell = 552.0°F
Inner Shell = 238.3°F
Lead = 372.0°F
Primary Lid Seal = 189.3°F
Secondary Lid Seal = 190.2°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 219°F as shown in Table 2.2 of WMG document AR-123 (Reference 3-2). This 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 49.24 psia.

2.7.4.2 Differential Thermal Expansion

The structural finite element model used for the analyses of the WMG 150B 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 WMG document AR-120 (Reference 2-31). The loading combination used for the HAC fire test is listed in Table 2-1. The stress analyses of the finite element model has been performed at several time instants during the fire, including the cool-down. The maximum of the cask component stresses are presented in Table 2-30.

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 2-30. 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 1.07 occurs in the baseplate.

2.7.5 Immersion – Fissile Material

Not applicable for WMG 150B 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; WMG 150B 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 WMG 150B 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 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 fire test, the impact limiters will provide thermal insulation with a reduced efficiency. The temperature in the critical components of the cask will not vary significantly.
- 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 WMG 150B 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 WMG 150B package since it is not transported by air.

2.9 Accident Conditions for Fissile Material Packages for Air Transport

Not applicable for WMG 150B package since it is not transported by air.

2.10 Special Form

Not applicable for WMG 150B package since the package contents are not limited to special form.

2.11 Fuel Rods

Not applicable for WMG 150B package; since the contents do not include fuel rods.

2.12 Appendix

2.12.1 List of References

2-1 Code of Federal Regulations, Title 10, Part 71, *Packaging and Transportation of Radioactive Material.*

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, 2010 Edition.

2-5 U.S. NRC Regulatory Guide 7.11, *Fracture Toughness Criteria of Base Material for Ferritic Steel Shipping Cask Containment Vessel with a Maximum Wall Thickness of 4 inches (0.1 m)*, June 1991.

2-6 NUREG/CR-1815, *Recommendations for Protecting Against Failure by Brittle Fracture in Ferritic Steel Shipping Containers Up to Four Inches Thick*, August 1981.

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2-12 NUREG/CR-6407, *Classification of Transportation Packaging and Dry Spent Fuel Storage System Components Accordance to Importance to Safety*, February 1996.

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2-16 Timoshenko S., Gere J., *Mechanics of Material*, New York, Van Nostrand Reinhold Company, 1972.

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2-18 NUREG/CR-6007, *Stress Analysis of Closure Bolts for Shipping Casks*, April 1992.

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2-21 WMG-150B-AR-113-P71, Rev.0, *WMG 150B Tie-Down Analysis.*

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2-23 WMG-150B-AR-099-P71, Rev.1, *SAEC ANSYS 14.0.3 Verification and Validation Report.*

2-24 WMG-150B-AR-119-P71, Rev.0, *WMG 150B Cask NCT Analyses.*

2-25 WMG-150B-AR-110-P71, Rev.0, *Drop Analyses of Casks at WMG Using LS-DYNA Software Code.*

2-26 ANSYS/LS-DYNA Version 15.0, ANSYS Inc., Canonsburg, PA.

2-27 WMG Document 14-040-IH-AR-109-P71, Rev.0, *ANSYS/LS-DYNA Verification and Validation Report* for Windows 8.0.

2-28 *Effect of Gamma Radiation on the Integrity of Viton*, Steve Sims, Central Virginia Governor's School, Lynchburg, VA, 2003.
http://www.cvgs.k12.va.us:81/research/paper/parts/papereng1.pdf

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2-32 WMG-150B-AR-125-P71, Rev.0, *WMG 150B Cask Lead Slump Analysis.*

2-33 WMG-150B-AR-115-P71, Rev.0, *WMG 150B Cask Misc. Structural Analyses.*

2-34 WMG-150B-AR-114-P71, Rev.0, *Buckling Analyses of the WMG 150B Cask Shells.*

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2-38 *Formulas for Stress and Strain*, Roark, Raymond J. and Warren C. Young, Fifth Edition, McGraw Hill Book Company, 1975.

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2-40 WMG-150B-AR-129S-P71, Rev.0, *WMG 150B Cask – Liquid Metal Embrittlement.*

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Table 2-1
Summary of NCT and HAC Loads

Loading Conditions	Ambient Temperature (°F)	Insolation	Heat Load (Watt)	Pressure (psi)		Stress Table(2) or Reference
				Internal	External	
NORMAL CONDITIONS (1)						
Hot Environment	100	Yes	200	26.36	14.7	2-5
Cold Environment	-40	No	0	12.59	14.7	2.6
Increased External Pressure	-20	No	0	13.19	20	2-8
Minimum External Pressure	100	Yes	200	26.36	3.5	2-9
Free Drop + Max Internal Pressure	100	Yes	200	26.36	14.7	2-11, 2-13, 2-15, 2-17
Free Drop + Min Internal Pressure (3)	-20	No	0	13.19	14.7	2-12, 2-14, 2-16, 2-18
ACCIDENT CONDITIONS (1)						
Free Drop + Max Internal Pressure	100	Yes	200	26.36	14.7	2-21, 2-23, 2-25, 2-27
Free Drop + Min Internal Pressure	-20	No	0	13.19	14.7	2-22, 2-24, 2-26, 2-28
Puncture	-	-	-	-	-	Section 2.7.3
Fire	1475	-	200	49.24	14.7	2-30

Notes:

1. The loading combinations have been derived from the NRC Regulatory Guide 7.8 (Reference 2-2).
2. The Stress Tables present the results for corresponding cases.

Table 2-2

Allowable Stresses

Material		**ASTM A240-A666** Type 304 (1)	**ASTM A240-A666** Type 316 (2)	**ASTM A540** Gr. B24 Class1 (3)	**ASTM A543** Type B Class 1 (4)	**ASTM A543** Type B Class 2 (5)
Yield Stress, S_y (ksi)		30.0(1)	30.0(1)	150.0(1)	85.0(1)	100.0(1)
Ultimate Stress, S_u (ksi)		75.0(1)	75.0(1)	165.0(1)	105.0(1)	115.0(1)
Design Stress Intensity, S_m (ksi)		20.0(1)	20.0(1)	50.0(1)	35.0(1)	-
Normal Conditions	Membrane Stress	20.0(2)	20.0(2)	50.0(2)	35.0(2)	-
	Membrane Stress+ Bending Stress	30.0(2)	30.0(2)	75.0(2)	52.5(2)	-
Accident Conditions	Membrane Stress	48.0(3)	48.0(3)	115.5(4)	73.5(3)	-
	Membrane Stress+ Bending Stress	72.0(3)	72.0(3)	165.0(4)	105.0(3)	-

Notes:

1. From ASME Boiler and Pressure Vessel Code, Section II Part A, pages 372, 991, 1010, 1094 (Reference 2-4).
2. Established from U.S. NRC Regulatory Guide 7.6 (Reference 2-3), Position 2;
3. Established from Regulatory Guide 7.6 (Reference 2-3) Position 6.
4. Regulatory Guide 7.6 [Ref. 120-9] does not provide any criteria. ASME B&PV Code, Section III, Appendix F (Reference 2-4) has been used to establish these criteria.

Table 2-3
Stress Component Definition

Component	ASME Definition	WMG 150B Cask Incorporation
Primary (General) Membrane, P_m [RG 7.6, B-2&B-4, Ref. 2-3, WB-3213.6 & WB-3213.8 ,Ref. 2-4]	Average primary stress across solid section. Excludes discontinues and concentrations	The stress caused by thermal expansion (contraction) are also included besides those caused by pressure and mechanical loads. The total stress over a section if meeting the allowable of membrane stress has been categorized as primary stress. Otherwise, then stress obtained from FEA have been linearized to obtain the membrane component.
Primary Bending, P_b [RG 7.6, B-2&B-4, Ref. 2-3, WB-3213.6 & WB-3213.8, Ref. 2-4]	Component of Primary stress proportional to distance from centroid of solid section Excluding discontinues and concentrations. Produced by pressure and mechanical load.	The stress 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 FEA have been linearized to obtain the membrane plus bending component.
Secondary Membrane Plus Bending, Q [RG 7.6, B-3, Ref. 2-3, WB-3213.9, Ref. 2-4]	Self-equilibrating stress necessary to satisfy continuity of structure. Occurs in structural discontinues concentrations. Can be caused by mechanical loads of by thermal expansion. Excludes local stress concentration.	The total stress over a section if meeting the allowable stress membrane plus bending stress has been categorized as secondary membrane plus bending stress. Otherwise, the stresses obtained from FEA have been linearized to obtain the membrane plus bending component.

Table 2-4

Material Properties

Material	T (°F)	S_y (ksi)	S_u (ksi)	S_m (ksi)	E (10^6 psi)	α (10^{-6} in/in °F)	ν	δ %
ASTM A240-A666 Type 304	-20	30.0	75.0	20.0	28.7	-	0.31	-
	70	30.0	75.0	20.0	28.3	8.5	0.31	40
	100	30.0	75.0	20.0	28.4	8.6	0.31	-
	200	25.0	71.0	20.0	27.5	8.9	0.31	-
	300	22.4	66.2	20.0	27.0	9.2	0.31	-
	400	20.7	64.0	18.6	26.4	9.5	0.31	-
	500	19.4	63.4	17.5	25.9	9.7	0.31	-
ASTM A240-A666 Type 316	-20	30.0	75.0	20.0	28.7	-	0.31	-
	70	30.0	75.0	20.0	28.3	8.5	0.31	40
	100	30.0	75.0	20.0	28.1	8.6	0.31	-
	200	25.9	75.0	20.0	27.5	8.9	0.31	-
	300	23.4	72.9	20.0	27.0	9.2	0.31	-
	400	21.4	71.9	19.3	26.4	9.5	0.31	-
	500	20.0	71.8	18.0	25.9	9.7	0.31	-
ASTM A540 Gr. B24 Class1	-20	150.0	165.0	50.0	28.2	-	0.30	-
	70	150.0	165.0	50.0	27.8	6.4	0.30	35
	100	150.0	165.0	50.0	27.6	6.5	0.30	-
	200	144.0	165.0	47.8	27.1	6.7	0.30	-
	300	140.3	165.0	46.2	26.7	6.9	0.30	-
	400	137.9	165.0	44.8	26.2	7.1	0.30	-
	500	136.0	165.0	43.4	25.7	7.3	0.30	-

Table 2-4

Material Properties

(Continuation)

Material	T (°F)	S_y (ksi)	S_u (ksi)	S_m (ksi)	E (10^6 psi)	α (10^{-6} in/in °F)	ν	δ %
ASTM A543 Type B Class 1	-20	85.0	105.0	35.0	28.2	-	0.30	-
	70	85.0	105.0	35.0	27.8	6.4	0.30	14
	100	85.0	105.0	35.0	27.6	6.5	0.30	-
	200	80.1	105.0	35.0	27.1	6.7	0.30	-
	300	77.5	105.0	35.0	26.7	6.9	0.30	-
	400	75.8	103.9	34.6	26.2	7.1	0.30	-
	500	74.5	103.3	34.4	25.7	7.3	0.30	-
ASTM A543 Type B Class 2	-20	100.0	115.0	-	28.2	-	0.30	-
	70	100.0	115.0	-	27.8	6.4	0.30	14
	100	100.0	115.0	-	27.6	6.5	0.30	-
	200	94.2	115.0	-	27.1	6.7	0.30	-
	300	91.2	115.0	-	26.7	6.9	0.30	-
	400	98.2	113.8	-	26.2	7.1	0.30	-
	500	87.7	113.1	-	25.7	7.3	0.30	-
ASTM B29 Chemical Lead	-20	-	-	-	2.49	15.5	0.44	-
	70	0.8	1.733	-	2.34	15.9	0.44	-
	100	-	1.625	-	2.31	16.1	0.44	-
	200	-	1.053	-	2.13	16.7	0.44	-
	300	-	0.696	-	2.10	17.4	0.44	-
	400	-	-	-	1.81	18.2	0.44	-
	500	-	-	-	1.60	19.1	0.44	-

Notes:

1. The material properties presented in the Table 2.1 are from ASME Boiler and Pressure Vessel Code (Reference 2-4), Section II Part A.

Table 2-5

Maximum Stress Intensities in the Cask Under the Hot Environment Loading[(1)]

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I. (psi)[(2)]	F.S.[(3)]
Primary Lid	P_m	35,000	8,097	4.32
	P_m+P_b	52,500	19,601	2.67
Secondary Lid	P_m	35,000	16,938	2.07
	P_m+P_b	52,500	16,938	3.1
Bolting Ring	P_m	35,000	12,307	2.84
	P_m+P_b	52,500	22,442	2.34
Inner Shell	P_m	35,000	5,979	5.85
	P_m+P_b	52,500	5,979	8.78
Outer Shell	P_m	35,000	16,968	2.06
	P_m+P_b	52,500	28,736	1.83
Baseplate	P_m	35,000	10,514	3.32
	P_m+P_b	52,500	10,514	4.99
Primary Lid Bolts	P_m	95,600	25,382	3.77
	P_m+P_b	143,400	101,112	1.42
Secondary Lid Bolts	P_m	95,600	24,715	3.87
	P_m+P_b	143,400	88,534	1.62

Notes:

1. The stress intensity values presented here have been obtained from AR-119 (Reference 2-24), Table 3.2. See the reference table for additional notes.
2. Unless otherwise indicated the maximum stress intensity values have been conservatively reported as P_m and P_m+P_b stress intensities.
3. Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.).

Table 2-6

Maximum Stress Intensities in Cask Under Cold Environment Loading[1] (-40°F)

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I. (psi)[2]	F.S.[3]
Primary Lid	P_m	35,000	13,941	2.51
	P_m+P_b	52,500	34,346	1.53
Secondary Lid	P_m	35,000	14,873	2.35
	P_m+P_b	52,500	37,018	1.42
Bolting Ring	P_m	35,000	18,816	1.86
	P_m+P_b	52,500	18,816	2.79
Inner Shell	P_m	35,000	9,167	3.82
	P_m+P_b	52,500	9,167	5.73
Outer Shell	P_m	35,000	5,610	6.23
	P_m+P_b	52,500	5,610	9.36
Baseplate	P_m	35,000	508	69
	P_m+P_b	52,500	508	103
Primary Lid Bolts	P_m	100,000	80,372	1.24
	P_m+P_b	150,000	80,372	1.87
Secondary Lid Bolts	P_m	100,000	80,087	1.25
	P_m+P_b	150,000	80,087	1.87

Notes:

1. The stress intensity values presented here have been obtained from AR-119 (Reference 2-24), Table 3.4 and 3.6. See the reference table for additional notes.
2. Unless otherwise indicated the maximum stress intensity values have been conservatively reported as P_m and P_m+P_b stress intensities.
3. Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.).

Table 2-7

Nil Ductility Temperature Requirements for Fracture Critical Components of the WMG 150B Cask

Component[1]	Thickness (in)	A[2] (°F)	T_{NDT} Req[3] (°F)
End Plate (Outside)	3.25	43	-63
End Plate (Inside)	0.75	-20	0
Inner Shell	0.75	-20	0
Outer Shell	1.25	3	-23
Bolting Ring	3.5	45	-65
Primary Lid (Outside)	3.0	40	-60
Primary Lid (Inside)	2.25	29	-49
Secondary Lid (Outside)	3.0	40	-60
Secondary Lid (Inside)	0.75	-20	0
Secondary Lid Skirt	0.75	-20	0

Notes:

1. See Figure 2-16 for the component sketch.
2. From Figure 2-17.
3. T_{NDT} determined per ASTM E208-81.

Table 2-8

Maximum Stress Intensities in Cask Under Reduced External Pressure(1) (3.5 psi)

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I. (psi)(2)	F.S.(3)
Primary Lid	P_m	35,000	12,557	2.79
	P_m+P_b	52,500	19,409	2.70
Secondary Lid	P_m	35,000	11,167	3.13
	P_m+P_b	52,500	17,394	3.02
Bolting Ring	P_m	35,000	12,684	2.76
	P_m+P_b	52,500	23,279	2.26
Inner Shell	P_m	35,000	6,251	5.6
	P_m+P_b	52,500	6,251	8.4
Outer Shell	P_m	35,000	17,988	1.95
	P_m+P_b	52,500	30,193	1.73
Baseplate	P_m	35,000	11,169	3.13
	P_m+P_b	52,500	11,169	4.7
Primary Lid Bolts	P_m	95,600	25,403	3.76
	P_m+P_b	143,400	63,021	1.38
Secondary Lid Bolts	P_m	95,600	24,739	3.86
	P_m+P_b	143,400	90,789	1.58

Notes:

1. The stress intensity values presented here have been obtained from AR-119 (Reference 2-24), Table 3.10. See the reference table for additional notes.
2. Unless otherwise indicated the maximum stress intensity values have been conservatively reported as P_m and P_m+P_b stress intensities.
3. Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.).

Table 2-9

Maximum Stress Intensities in Cask Under Increased External Pressure(1) (20 psia)

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I. (psi)(2)	F.S.(3)
Primary Lid	P_m	35,000	13,233	2.65
	P_m+P_b	52,500	31,844	1.65
Secondary Lid	P_m	35,000	14,049	2.49
	P_m+P_b	52,500	34,410	1.53
Bolting Ring	P_m	35,000	19,349	1.81
	P_m+P_b	52,500	19,349	2.71
Inner Shell	P_m	35,000	7,449	4.70
	P_m+P_b	52,500	7,449	7.05
Outer Shell	P_m	35,000	4,321	8.10
	P_m+P_b	52,500	4,321	12.15
Baseplate	P_m	35,000	249	141
	P_m+P_b	52,500	249	211
Primary Lid Bolts	P_m	100,000	80,995	1.24
	P_m+P_b	150,000	80,995	1.85
Secondary Lid Bolts	P_m	100,000	79,578	1.26
	P_m+P_b	150,000	79,578	1.89

Notes:

1. The stress intensity values presented here have been obtained from AR-119 (Reference 2-24), Table 3.10. See the reference table for additional notes.
2. Unless otherwise indicated the maximum stress intensity values have been conservatively reported as P_m and P_m+P_b stress intensities.
3. Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.).

Table 2-10

WMG 150B Cask Impact Limiter Reactions 1-ft Drop Analyses - Various Orientations and Conditions

Drop Orientation[(1),(2)]	Impact Limiter Reaction (lb) (180^0 Model)	Reference
Bottom End	1.6554×10^6	Figure 2-21
Top End	1.7057×10^6	Figure 2-22
Side	5.6256×10^5	Figure 2-23
Corner	3.2066×10^5	Figure 2-24

NOTES:

1. See Figure 2-25 for graphical depiction of various orientations.
2. Since the cold environment conditions result in higher impact limiter reactions than the hot environment, analyses for all drop orientations were performed for cold environment only.

Table 2-11

Maximum Stress Intensities(1) in Cask during 1-ft Bottom End Drop (Hot)

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I. (psi)(2)	F.S.(3)
Primary Lid	P_m	35,000	9,589	3.65
	P_m+P_b	52,500	27,158	1.93
Secondary Lid	P_m	35,000	18,567	1.89
	P_m+P_b	52,500	18,567	2.83
Bolting Ring	P_m	35,000	9,515	3.68
	P_m+P_b	52,500	20,537	2.56
Inner Shell	P_m	35,000	11,676	2.99
	P_m+P_b	52,500	11,676	4.49
Outer Shell	P_m	35,000	15,842	2.21
	P_m+P_b	52,500	22,995	2.28
Baseplate	P_m	35,000	12,311	2.84
	P_m+P_b	52,500	12,311	4.26
Primary Lid Bolts	P_m	95,600	25,253	3.79
	P_m+P_b	143,400	87,313	1.64
Secondary Lid Bolts	P_m	95,600	24,611	3.88
	P_m+P_b	143,400	95,733	1.49

Notes:

1. The stress intensity values presented here have been obtained from AR-120 (Reference 2-31), Table 3.2. See the reference table for additional notes.
2. Unless otherwise indicated the maximum stress intensity values have been conservatively reported as P_m and P_m+P_b stress intensities.
3. Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.).

Table 2-12
Maximum Stress Intensities(1) in Cask during 1-ft Bottom End Drop (Cold)

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I. (psi)(2)	F.S.(3)
Primary Lid	P_m	35,000	16,105	2.17
	P_m+P_b	52,500	42,103	1.25
Secondary Lid	P_m	35,000	26,004	1.35
	P_m+P_b	52,500	26,004	2.02
Bolting Ring	P_m	35,000	19,081	1.83
	P_m+P_b	52,500	19,081	2.75
Inner Shell	P_m	35,000	18,312	1.91
	P_m+P_b	52,500	18,312	2.87
Outer Shell	P_m	35,000	21,686	1.61
	P_m+P_b	52,500	21,686	2.42
Baseplate	P_m	35,000	9,390	3.72
	P_m+P_b	52,500	9,390	5.59
Primary Lid Bolts	P_m	95,600	77,060	1.24
	P_m+P_b	143,400	77,060	1.86
Secondary Lid Bolts	P_m	95,600	25,327	3.77
	P_m+P_b	143,400	95,432	1.50

Notes:

1. The stress intensity values presented here have been obtained from AR-120 (Reference 2-31), Table 3.12. See the reference table for additional notes.
2. Unless otherwise indicated the maximum stress intensity values have been conservatively reported as P_m and P_m+P_b stress intensities.
3. Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.).

Table 2-13

Maximum Stress Intensities(1) in the Cask during 1-ft Top End Drop (Hot)

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I. (psi)(2)	F.S.(3)
Primary Lid	P_m	35,000	11,118	3.14
	P_m+P_b	52,500	23,596	2.22
Secondary Lid	P_m	35,000	17,935	1.95
	P_m+P_b	52,500	17,935	2.93
Bolting Ring	P_m	35,000	19,542	1.79
	P_m+P_b	52,500	19,542	2.68
Inner Shell	P_m	35,000	12,655	2.77
	P_m+P_b	52,500	12,655	4.15
Outer Shell	P_m	35,000	15,787	2.22
	P_m+P_b	52,500	15,787	3.32
Baseplate	P_m	35,000	6,837	5.12
	P_m+P_b	52,500	6,837	7.68
Primary Lid Bolts	P_m	95,600	23,517	4.07
	P_m+P_b	143,400	84,740	1.69
Secondary Lid Bolts	P_m	95,600	24,992	3.82
	P_m+P_b	143,400	92,499	1.55

Notes:

1. The stress intensity values presented here have been obtained from AR-120 (Reference 2-31), Table 3.4. See the reference table for additional notes.
2. Unless otherwise indicated the maximum stress intensity values have been conservatively reported as P_m and P_m+P_b stress intensities.
3. Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.).

Table 2-14
Maximum Stress Intensities(1) in the Cask during 1-ft Top End Drop (Cold)

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I. (psi)(2)	F.S.(3)
Primary Lid	P_m	35,000	13,451	2.60
	P_m+P_b	52,500	32,479	1.62
Secondary Lid	P_m	35,000	14,443	2.42
	P_m+P_b	52,500	37,492	1.4
Bolting Ring	P_m	35,000	12,613	2.77
	P_m+P_b	52,500	24,441	2.15
Inner Shell	P_m	35,000	14,470	2.42
	P_m+P_b	52,500	14,470	3.63
Outer Shell	P_m	35,000	7,467	4.69
	P_m+P_b	52,500	7,467	7.03
Baseplate	P_m	35,000	11,024	3.17
	P_m+P_b	52,500	11,024	4.76
Primary Lid Bolts	P_m	95,600	24,272	3.94
	P_m+P_b	143,400	93,327	1.54
Secondary Lid Bolts	P_m	95,600	24,110	3.97
	P_m+P_b	143,400	104,428	1.37

Notes:

1. The stress intensity values presented here have been obtained from AR-120 (Reference 2-31), Table 3.14. See the reference table for additional notes.
2. Unless otherwise indicated the maximum stress intensity values have been conservatively reported as P_m and P_m+P_b stress intensities.
3. Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.).

Table 2-15
Maximum Stress Intensities(1) in the Cask during 1-ft Side Drop (Hot)

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I. (psi)(2)	F.S.(3)
Primary Lid	P_m	35,000	14,784	2.37
	P_m+P_b	52,500	31,244	1.68
Secondary Lid	P_m	35,000	19,071	1.84
	P_m+P_b	52,500	19,071	2.75
Bolting Ring	P_m	35,000	22,539	1.55
	P_m+P_b	52,500	40,790	1.29
Inner Shell	P_m	35,000	18,963	1.85
	P_m+P_b	52,500	18,963	2.77
Outer Shell	P_m	35,000	20,119	1.73
	P_m+P_b	52,500	33,144	1.58
Baseplate	P_m	35,000	12,312	2.84
	P_m+P_b	52,500	12,312	4.26
Primary Lid Bolts	P_m	95,600	22,719	4.2
	P_m+P_b	143,400	79,069	1.81
Secondary Lid Bolts	P_m	95,600	22,955	4.16
	P_m+P_b	143,400	100,006	1.43

Notes:

1. The stress intensity values presented here have been obtained from AR-120 (Reference 2-31), Table 3.6. See the reference table for additional notes.
2. Unless otherwise indicated the maximum stress intensity values have been conservatively reported as P_m and P_m+P_b stress intensities.
3. Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.).

Table 2-16

Maximum Stress Intensities(1) in the Cask during 1-ft Side Drop (Cold)

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I. (psi)(2)	F.S.(3)
Primary Lid	P_m	35,000	15,970	2.19
	P_m+P_b	52,500	39,153	1.34
Secondary Lid	P_m	35,000	14,860	2.35
	P_m+P_b	52,500	36,067	1.45
Bolting Ring	P_m	35,000	23,726	1.48
	P_m+P_b	52,500	37,832	1.39
Inner Shell	P_m	35,000	20,868	1.68
	P_m+P_b	52,500	20,868	2.52
Outer Shell	P_m	35,000	28,634	1.22
	P_m+P_b	52,500	37,309	1.41
Baseplate	P_m	35,000	10,221	3.42
	P_m+P_b	52,500	10,221	5.14
Primary Lid Bolts	P_m	95,600	24,671	3.87
	P_m+P_b	143,400	125,048	1.15
Secondary Lid Bolts	P_m	95,600	24,262	3.94
	P_m+P_b	143,400	98,939	1.45

Notes:

1. The stress intensity values presented here have been obtained from AR-120 (Reference 2-31), Table 3.16. See the reference table for additional notes.
2. Unless otherwise indicated the maximum stress intensity values have been conservatively reported as P_m and P_m+P_b stress intensities.
3. Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.).

Table 2-17

Maximum Stress Intensities(1) in the Cask during 1-ft Top Corner Drop (Hot)

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I. (psi)(2)	F.S.(3)
Primary Lid	P_m	35,000	24,315	1.44
	P_m+P_b	52,500	24,315	2.16
Secondary Lid	P_m	35,000	19,307	1.81
	P_m+P_b	52,500	19,307	2.72
Bolting Ring	P_m	35,000	15,192	2.3
	P_m+P_b	52,500	29,040	1.81
Inner Shell	P_m	35,000	10,030	3.49
	P_m+P_b	52,500	10,030	5.23
Outer Shell	P_m	35,000	11,303	3.1
	P_m+P_b	52,500	30,126	1.74
Baseplate	P_m	35,000	9,330	3.75
	P_m+P_b	52,500	9,330	5.63
Primary Lid Bolts	P_m	95,600	25,192	3.79
	P_m+P_b	143,400	123,993	1.16
Secondary Lid Bolts	P_m	95,600	23,062	4.15
	P_m+P_b	143,400	99,943	1.43

Notes:

1. The stress intensity values presented here have been obtained from AR-120 (Reference 2-31), Table 3.8. See the reference table for additional notes.
2. Unless otherwise indicated the maximum stress intensity values have been conservatively reported as P_m and P_m+P_b stress intensities.
3. Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.).

Table 2-18

Maximum Stress Intensities(1) in the Cask during 1-ft Top Corner Drop (Cold)

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I. (psi)(2)	F.S.(3)
Primary Lid	P_m	35,000	14,390	2.43
	P_m+P_b	52,500	35,495	1.47
Secondary Lid	P_m	35,000	14,698	2.38
	P_m+P_b	52,500	36,164	1.45
Bolting Ring	P_m	35,000	13,504	2.59
	P_m+P_b	52,500	23,340	2.25
Inner Shell	P_m	35,000	11,597	3.02
	P_m+P_b	52,500	11,597	4.53
Outer Shell	P_m	35,000	12,564	2.79
	P_m+P_b	52,500	23,776	2.21
Baseplate	P_m	35,000	3,447	10.1
	P_m+P_b	52,500	3,447	15.2
Primary Lid Bolts	P_m	95,600	25,519	3.75
	P_m+P_b	143,400	95,107	1.51
Secondary Lid Bolts	P_m	95,600	24,259	3.94
	P_m+P_b	143,400	92,043	1.56

Notes:

1. The stress intensity values presented here have been obtained from AR-120 (Reference 2-31), Table 3.18. See the reference table for additional notes.
2. Unless otherwise indicated the maximum stress intensity values have been conservatively reported as P_m and P_m+P_b stress intensities.
3. Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.).

Table 2-19

Hypothetical Accident Conditions Drop Test Reactions

Drop Orientation[(1)]	Thermal Environment	Impact Limiter Reaction (lb) (180^0 Model)	Reference
Bottom End	Cold	6.1305×10^6	Figure 16 of Ref. 2-7
	Hot	4.1458×10^6	Figure 19 of Ref. 2-7
Top End	Cold	5.7325×10^6	Figure 22 of Ref. 2-7
	Hot	3.8171×10^6	Figure 25 of Ref. 2-7
Side	Cold	1.7804×10^6	Figure 28 of Ref. 2-7
	Hot	1.5509×10^6	Figure 31 of Ref. 2-7
Corner	Cold	2.1821×10^6	Figure 34 of Ref. 2-7
	Hot	2.0684×10^6	Figure 37 of Ref. 2-7
Shallow-1	Cold	2.081×10^6	Figure 39 of Ref. 2-7
Shallow-2	Cold	2.1384×10^6	Figure 40 of Ref. 2-7
Off-Corner	Cold	2.0933×10^6	Figure 41 of Ref. 2-7

NOTES:

(1) See Figure 2-19 for graphical depiction of various orientations.

Table 2-20

Hypothetical Accident Conditions Drop Test Maximum Crush

Drop Orientation[1]	Thermal Environment	Maximum Deformation (in)	Original Thickness (in)	Percentage Crush (%)	Reference
Bottom End	Cold	3.087	20.25	15.24	Figure 17 of Ref. 2-7
	Hot	4.517	20.25	22.31	Figure 20 of Ref. 2-7
Top End	Cold	3.308	20.25	16.34	Figure 23 of Ref. 2-7
	Hot	4.775	20.25	23.58	Figure 26 of Ref. 2-7
Side	Cold	3.917	11.25	34.82	Figure 29 of Ref. 2-7
	Hot	6.260	11.25	55.64	Figure 32 of Ref. 2-7
Corner	Cold	12.558	23.165	54.21	Figure 35 of Ref. 2-7
	Hot	14.693	23.165	63.43	Figure 38 of Ref. 2-7

NOTES:

(1) See Figure 1 for graphical depiction of various orientations.

Table 2-21

Maximum Stress Intensities(1) in the Cask during 30-ft Top End Drop (Hot)

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I. (psi)(2)	F.S.(3)
Primary Lid	P_m	73,500	53,931	1.36
	P_m+P_b	105,000	53,931	1.95
Secondary Lid	P_m	73,500	41,014	1.79
	P_m+P_b	105,000	41,014	2.56
Bolting Ring	P_m	73,500	29,724	2.47
	P_m+P_b	105,000	29,724	3.53
Inner Shell	P_m	73,500	33,838	2.17
	P_m+P_b	105,000	33,838	3.10
Outer Shell	P_m	73,500	26,241	2.8
	P_m+P_b	105,000	26,241	4.0
Baseplate	P_m	73,500	25,701	2.86
	P_m+P_b	105,000	25,701	4.09
Primary Lid Bolts	P_m	115,500	68,585	1.68
	P_m+P_b	165,000	68,585	2.41
Secondary Lid Bolts	P_m	115,500	40,232	2.87
	P_m+P_b	165,000	131,887	1.25

Notes:

1. The stress intensity values presented here have been obtained from AR-120 (Reference 2-31), Table 4.2. See the reference table for additional notes.
2. Unless otherwise indicated the maximum stress intensity values have been conservatively reported as P_m and P_m+P_b stress intensities.
3. Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.).

Table 2-22

Maximum Stress Intensities[1] in the Cask during 30-ft Top End Drop (Cold)

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I. (psi)[2]	F.S.[3]
Primary Lid	P_m	73,500	24,896	2.95
	P_m+P_b	105,000	65,937	1.59
Secondary Lid	P_m	73,500	45,813	1.60
	P_m+P_b	105,000	45,813	2.29
Bolting Ring	P_m	73,500	48,097	1.53
	P_m+P_b	105,000	48,097	2.18
Inner Shell	P_m	73,500	55,259	1.33
	P_m+P_b	105,000	85,696	1.23
Outer Shell	P_m	73,500	43,597	1.69
	P_m+P_b	105,000	66,476	1.58
Baseplate	P_m	73,500	28,736	2.55
	P_m+P_b	105,000	28,736	3.65
Primary Lid Bolts	P_m	115,500	66,094	1.75
	P_m+P_b	165,000	66,094	2.50
Secondary Lid Bolts	P_m	115,500	42,636	2.71
	P_m+P_b	165,000	140,956	1.17

Notes:

1. The stress intensity values presented here have been obtained from AR-120 (Reference 2-31), Table 4.12. See the reference table for additional notes.
2. Unless otherwise indicated the maximum stress intensity values have been conservatively reported as P_m and P_m+P_b stress intensities.
3. Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.).

Table 2-23

Maximum Stress Intensities(1) in the Cask during 30-ft Bottom End Drop (Hot)

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I. (psi)(2)	F.S.(3)
Primary Lid	P_m	73,500	43,400	1.69
	P_m+P_b	105,000	43,400	2.42
Secondary Lid	P_m	73,500	32,525	2.26
	P_m+P_b	105,000	32,525	3.23
Bolting Ring	P_m	73,500	23,285	3.16
	P_m+P_b	105,000	55,047	1.91
Inner Shell	P_m	73,500	26,788	2.74
	P_m+P_b	105,000	26,788	3.92
Outer Shell	P_m	73,500	32,335	2.27
	P_m+P_b	105,000	32,335	3.25
Baseplate	P_m	73,500	40,394	1.82
	P_m+P_b	105,000	40,394	2.6
Primary Lid Bolts	P_m	115,500	26,101	4.42
	P_m+P_b	165,000	95,452	1.73
Secondary Lid Bolts	P_m	115,500	22,948	5.03
	P_m+P_b	165,000	121,779	1.35

Notes:

1. The stress intensity values presented here have been obtained from AR-120 (Reference 2-31), Table 4.4. See the reference table for additional notes.
2. Unless otherwise indicated the maximum stress intensity values have been conservatively reported as P_m and P_m+P_b stress intensities.
3. Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.).

Table 2-24

Maximum Stress Intensities(1) in the Cask during 30-ft Bottom End Drop (Cold)

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I. (psi)(2)	F.S.(3)
Primary Lid	P_m	73,500	51,500	1.42
	P_m+P_b	105,000	51,500	2.04
Secondary Lid	P_m	73,500	53,444	1.38
	P_m+P_b	105,000	53,444	1.96
Bolting Ring	P_m	73,500	47,710	1.54
	P_m+P_b	105,000	47,710	2.2
Inner Shell	P_m	73,500	35,203	2.08
	P_m+P_b	105,000	35,203	2.98
Outer Shell	P_m	73,500	25,960	2.83
	P_m+P_b	105,000	25,960	4.04
Baseplate	P_m	73,500	38,540	1.91
	P_m+P_b	105,000	38,540	2.72
Primary Lid Bolts	P_m	115,500	24,479	4.71
	P_m+P_b	165,000	120,248	1.37
Secondary Lid Bolts	P_m	115,500	24,509	4.71
	P_m+P_b	165,000	122,206	1.35

Notes:

1. The stress intensity values presented here have been obtained from AR-120 (Reference 2-31), Table 4.14. See the reference table for additional notes.
2. Unless otherwise indicated the maximum stress intensity values have been conservatively reported as P_m and P_m+P_b stress intensities.
3. Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.).

Table 2-25

Maximum Stress Intensities(1) in the Cask during 30-ft Side Drop (Hot)

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I. (psi)(2)	F.S.(3)
Primary Lid	P_m	73,500	27,266	2.69
	P_m+P_b	105,000	78,471	1.34
Secondary Lid	P_m	73,500	28,198	2.61
	P_m+P_b	105,000	28,198	3.72
Bolting Ring	P_m	73,500	64,592	1.14
	P_m+P_b	105,000	78,916	1.33
Inner Shell	P_m	73,500	61,716	1.19
	P_m+P_b	105,000	67,819	1.55
Outer Shell	P_m	73,500	67,339	1.09
	P_m+P_b	105,000	77,370	1.35
Baseplate	P_m	73,500	31,589	2.33
	P_m+P_b	105,000	64,479	1.63
Primary Lid Bolts	P_m	115,500	36,881	3.13
	P_m+P_b	165,000	126,814	1.30
Secondary Lid Bolts	P_m	115,500	24,567	4.7
	P_m+P_b	165,000	131,630	1.25

Notes:

1. The stress intensity values presented here have been obtained from AR-120 (Reference 2-31), Table 4.6. See the reference table for additional notes.
2. Unless otherwise indicated the maximum stress intensity values have been conservatively reported as P_m and P_m+P_b stress intensities.
3. Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.).

Table 2-26

Maximum Stress Intensities(1) in the Cask during 30-ft Side Drop (Cold)

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I. (psi)(2)	F.S.(3)
Primary Lid	P_m	73,500	47,241	1.56
	P_m+P_b	105,000	47,241	2.22
Secondary Lid	P_m	73,500	48,820	1.51
	P_m+P_b	105,000	48,820	2.15
Bolting Ring	P_m	73,500	42,918	1.71
	P_m+P_b	105,000	99,630	1.05
Inner Shell	P_m	73,500	64,431	1.14
	P_m+P_b	105,000	97,362	1.08
Outer Shell	P_m	73,500	67,539	1.09
	P_m+P_b	105,000	73,337	1.43
Baseplate	P_m	73,500	57,509	1.28
	P_m+P_b	105,000	57,509	1.83
Primary Lid Bolts	P_m	115,500	27,237	4.24
	P_m+P_b	165,000	93,354	1.77
Secondary Lid Bolts	P_m	115,500	23,948	4.82
	P_m+P_b	165,000	127,015	1.3

Notes:

1. The stress intensity values presented here have been obtained from AR-120 (Reference 2-31), Table 4.16. See the reference table for additional notes.
2. Unless otherwise indicated the maximum stress intensity values have been conservatively reported as P_m and P_m+P_b stress intensities.
3. Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.).

Table 2-27

Maximum Stress Intensities(1) in the Cask during 30-ft Top Corner Drop (Hot)

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I. (psi)(2)	F.S.(3)
Primary Lid	P_m	73,500	22,768	3.23
	P_m+P_b	105,000	72,343	1.45
Secondary Lid	P_m	73,500	49,715	1.48
	P_m+P_b	105,000	49,715	2.11
Bolting Ring	P_m	73,500	35,222	2.09
	P_m+P_b	105,000	71,517	1.47
Inner Shell	P_m	73,500	43,841	1.68
	P_m+P_b	105,000	43,841	2.4
Outer Shell	P_m	73,500	69,951	1.05
	P_m+P_b	105,000	95,426	1.1
Baseplate	P_m	73,500	8,684	8.46
	P_m+P_b	105,000	8,684	12.09
Primary Lid Bolts	P_m	115,500	59,070	1.96
	P_m+P_b	165,000	129,921	1.27
Secondary Lid Bolts	P_m	115,500	47,054	2.45
	P_m+P_b	165,000	106,558	1.55

Notes:

1. The stress intensity values presented here have been obtained from AR-120 (Reference 2-31), Table 4.8. See the reference table for additional notes.
2. Unless otherwise indicated the maximum stress intensity values have been conservatively reported as P_m and P_m+P_b stress intensities.
3. Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.).

Table 2-28

Maximum Stress Intensities(1) in the Cask during 30-ft Top Corner Drop (Cold)

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I. (psi)(2)	F.S.(3)
Primary Lid	P_m	73,500	48,568	1.51
	P_m+P_b	105,000	102,329	1.03
Secondary Lid	P_m	73,500	47,782	1.54
	P_m+P_b	105,000	47,782	2.2
Bolting Ring	P_m	73,500	47,098	1.56
	P_m+P_b	105,000	92,910	1.13
Inner Shell	P_m	73,500	49,492	1.48
	P_m+P_b	105,000	70,479	1.49
Outer Shell	P_m	73,500	68,592	1.07
	P_m+P_b	105,000	95,468	1.1
Baseplate	P_m	73,500	11,078	6.63
	P_m+P_b	105,000	11,078	9.48
Primary Lid Bolts	P_m	115,500	66,648	1.73
	P_m+P_b	165,000	154,943	1.06
Secondary Lid Bolts	P_m	115,500	35,730	3.23
	P_m+P_b	165,000	106,930	1.54

Notes:

1. The stress intensity values presented here have been obtained from AR-120 (Reference 2-31), Table 4.18. See the reference table for additional notes.
2. Unless otherwise indicated the maximum stress intensity values have been conservatively reported as P_m and P_m+P_b stress intensities.
3. Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.).

Table 2-29

Impact Limiter Attachment Load
30-ft Drop Analyses - Various Orientations and Conditions

Drop Orientation⁽¹⁾⁽²⁾	Impact Limiter Attachment Force (lb)	Reference
Bottom End	27,221	Figure 42 of Ref. 2-7
Top End	19,166	Figure 43 of Ref. 2-7
Side	24,345	Figure 44 of Ref. 2-7
Corner	34,141	Figure 45 of Ref. 2-7
Shallow-1	31,740	Figure 46 of Ref. 2-7
Shallow-2	35,492	Figure 47 of Ref. 2-7
Off-Corner	38,569	Figure 48 of Ref. 2-7

NOTES:

(1) See Figure 2-19 for graphical depiction of various orientations.

(2) Since the cold environment conditions result in higher impact limiter reactions than the hot environment, analyses for all drop orientations were performed for cold environment only.

Table 2-30

Maximum Stress Intensities in the Cask Under HAC Fire Test(1)

Component	Stress Category	Allowable S.I. (psi)	Calculated S.I. (psi)(2)	F.S.(3)
Primary Lid	Pm	73,500	29,090	2.53
	Pm + Pb	105,000	29,090	3.61
Secondary Lid	Pm	73,500	21,048	3.49
	Pm + Pb	105,000	21,048	4.99
Bolting Ring	Pm	73,500	35,117	2.09
	Pm + Pb	105,000	35,117	2.99
Inner Shell	Pm	73,500	31,561	2.33
	Pm + Pb	105,000	31,561	3.33
Outer Shell	Pm	73,500	56,219	1.31
	Pm + Pb	105,000	95,964	1.09
Baseplate	Pm	73,500	68,965	1.07
	Pm + Pb	105,000	79,330	1.32
Primary Lid Bolts	Pm	115,500	27,148	4.25
	Pm + Pb	165,000	146,902	1.12
Secondary Lid Bolts	Pm	115,500	25,278	4.57
	Pm + Pb	165,000	108,678	1.52

Notes:

1. The stress intensity values presented here are the maximum value obtained from the stress at time 30, 42.15, 78.28 and 366.82 min after the start of the fire reported in WMG document AR-120 (Reference 2-31) Tables 5.2, 5.4, 5.6 and 5.8. See the reference table for additional notes.
2. Unless otherwise indicated the maximum stress intensity values have been conservatively reported as P_m and P_m+P_b stress intensities.
3. Factor of Safety, F.S. = (Allowable S.I.) / (Calculated S.I.).

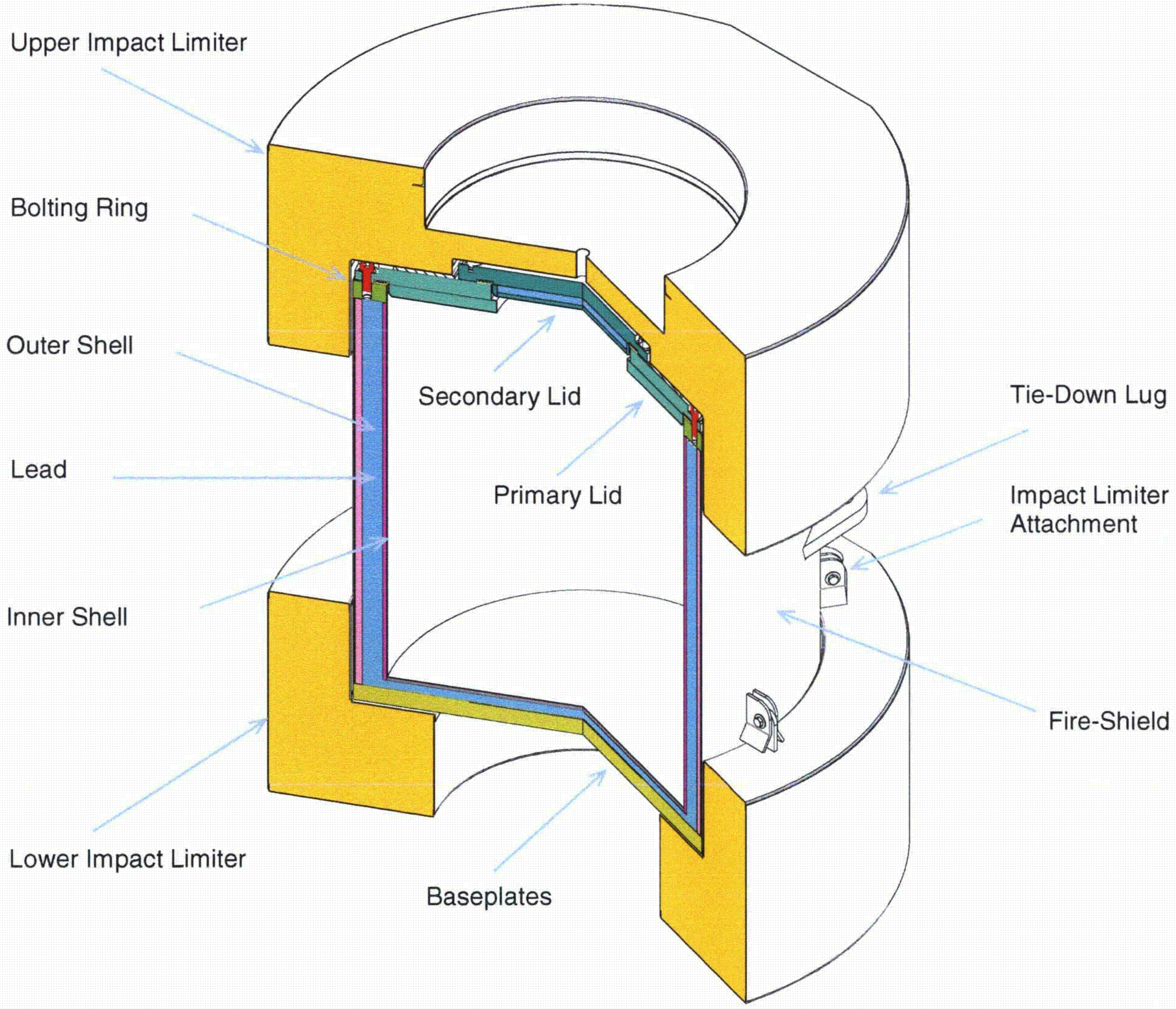


Figure 2-1 – WMG 150B Cask Component Nomenclature

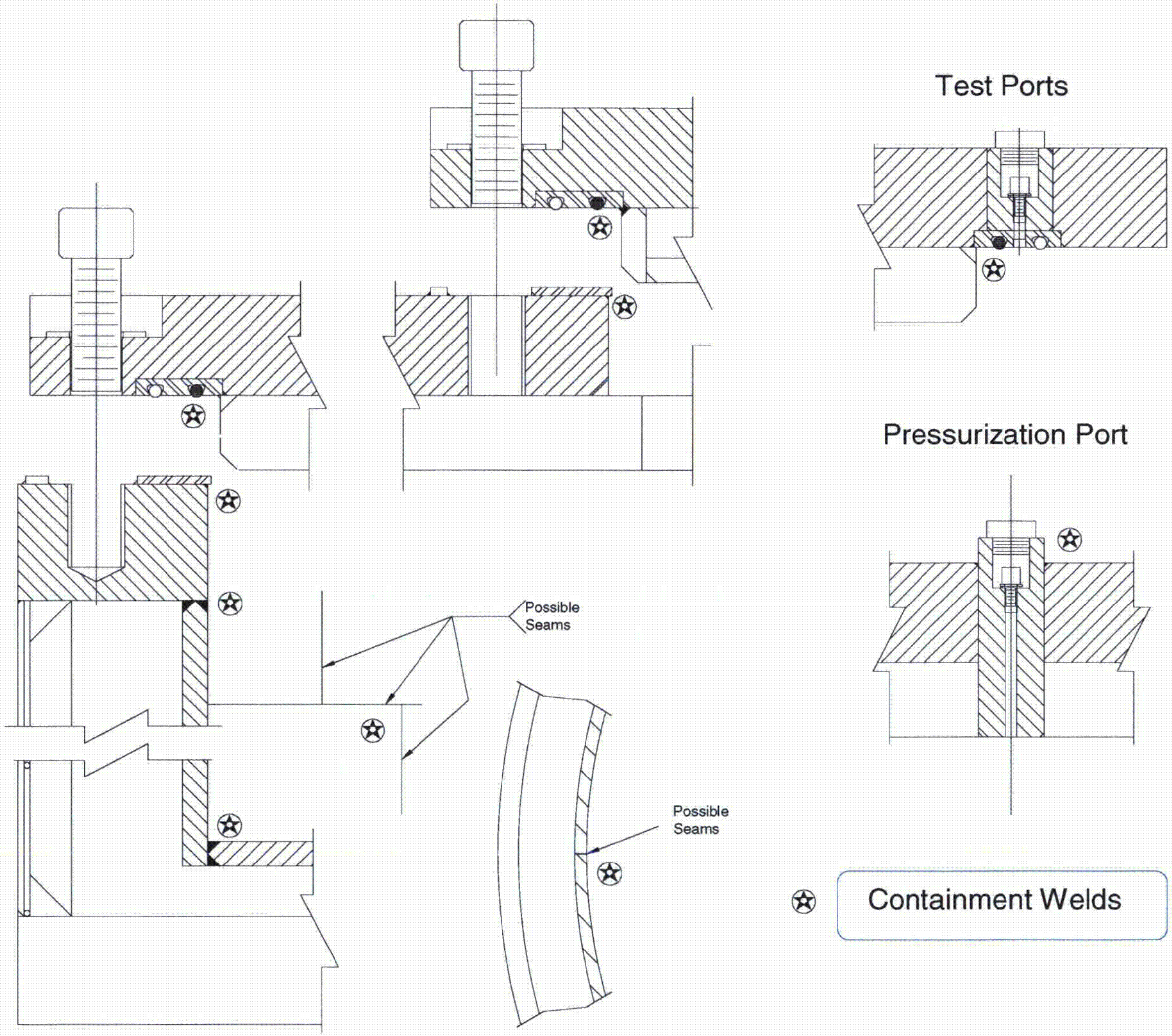


Figure 2-2 – WMG 150B Cask – Containment Boundary

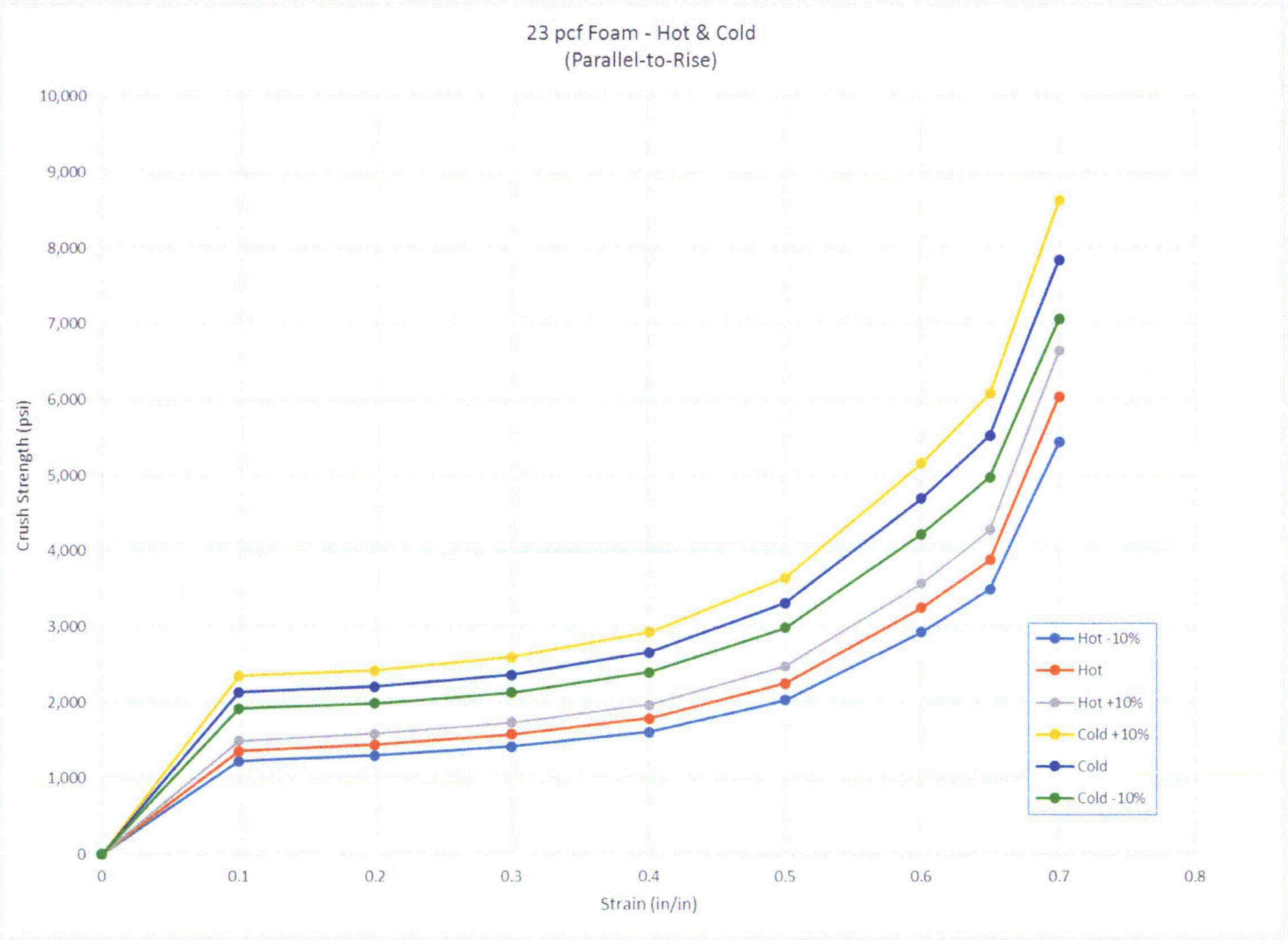


Figure 2-3 – Impact Limiter Foam Compressive Stress-Strain Plot at 100°F (Hot) and -20°F (Cold) Conditions - Parallel-to-Rise Direction
(Source: Reference 2-11)

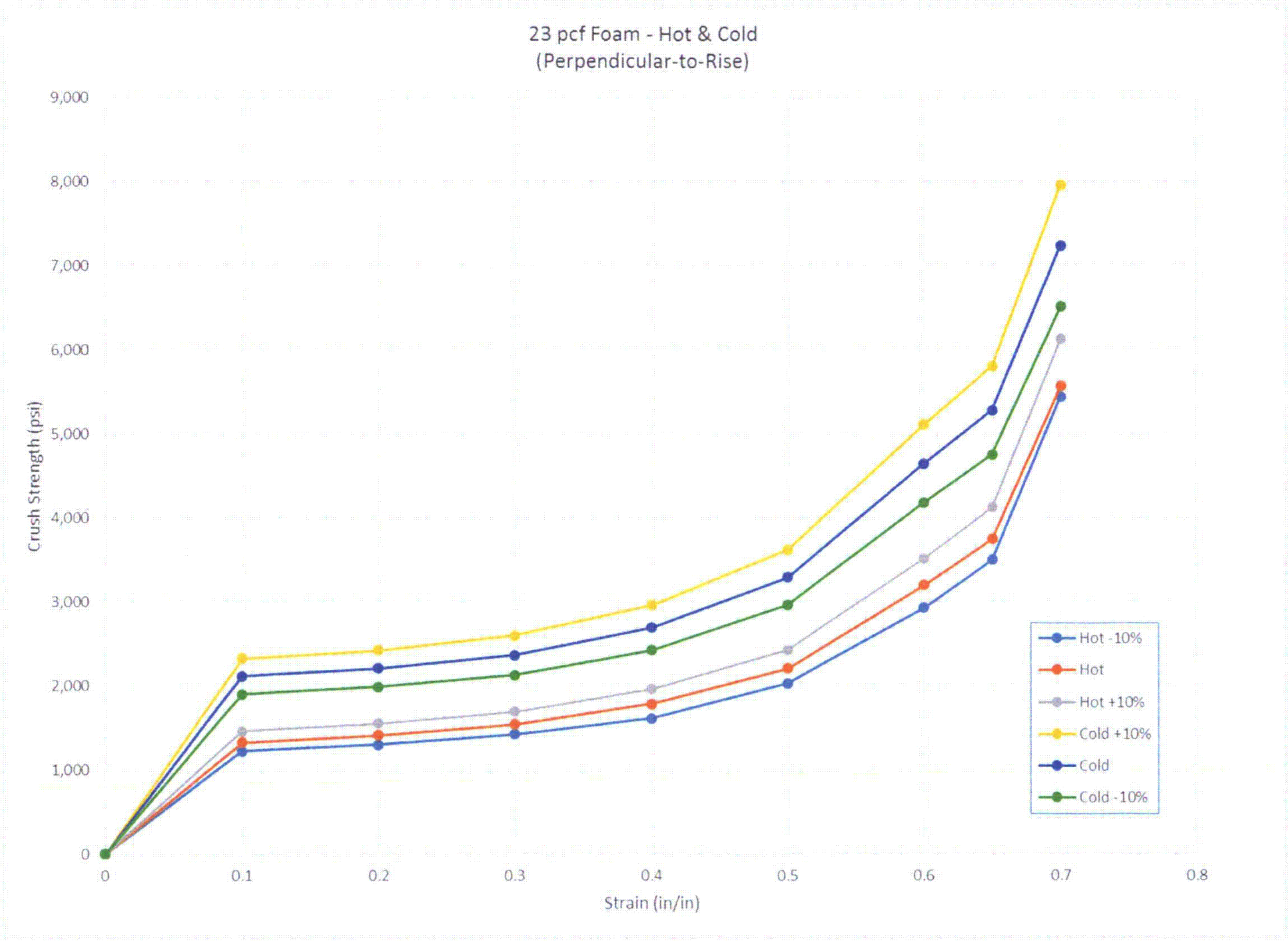


Figure 2-4 – Impact Limiter Foam Compressive Stress-Strain Plot at 100°F (Hot) and -20°F (Cold) Conditions - Perpendicular-to-Rise Direction
(Source: Reference 2-11)

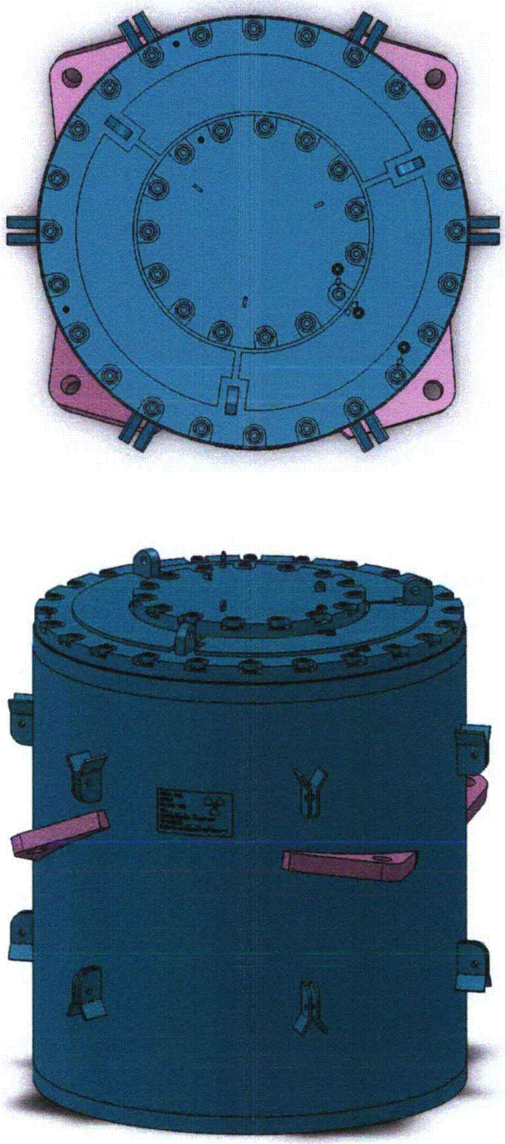
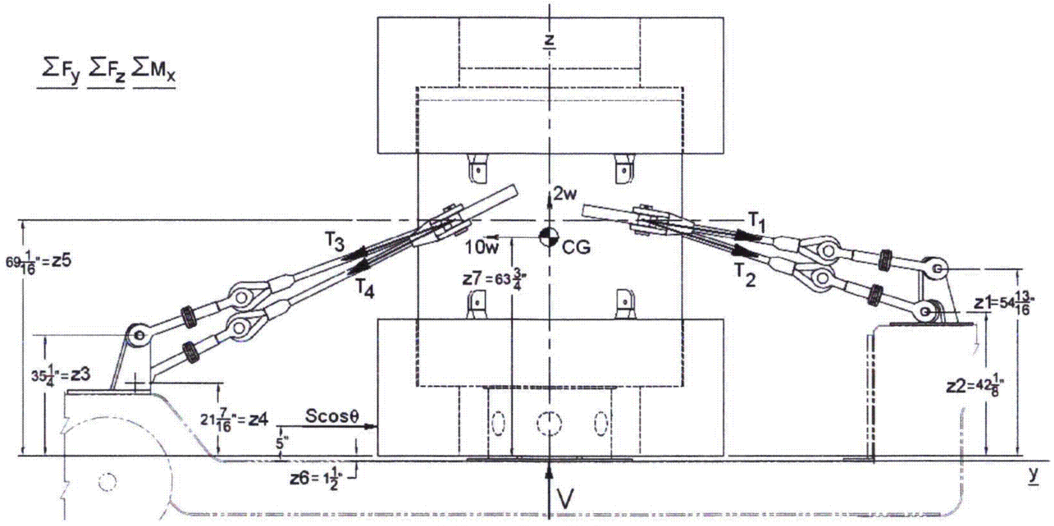
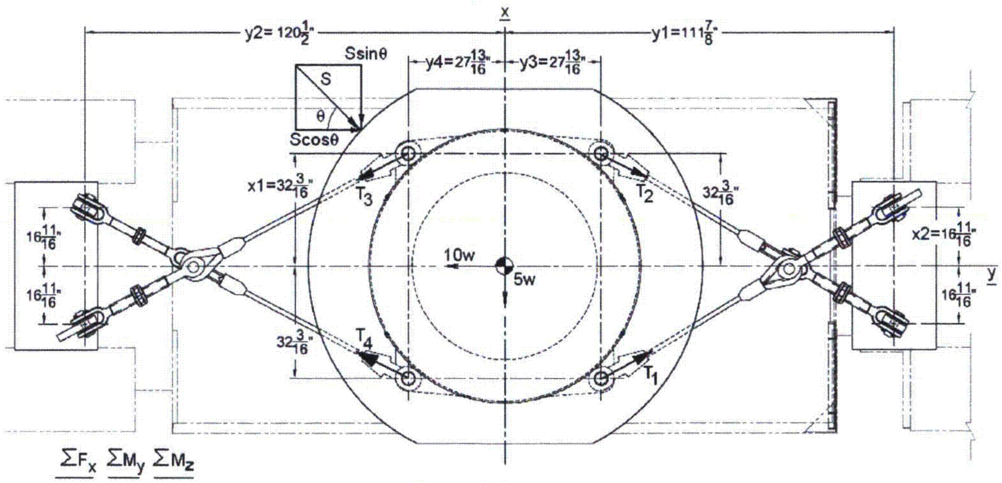


Figure 2-5 – WMG 150B Cask Tie-Down Lugs



Elevation View



Plan View

Figure 2-6 – WMG 150B Cask Package – Free Body Diagram

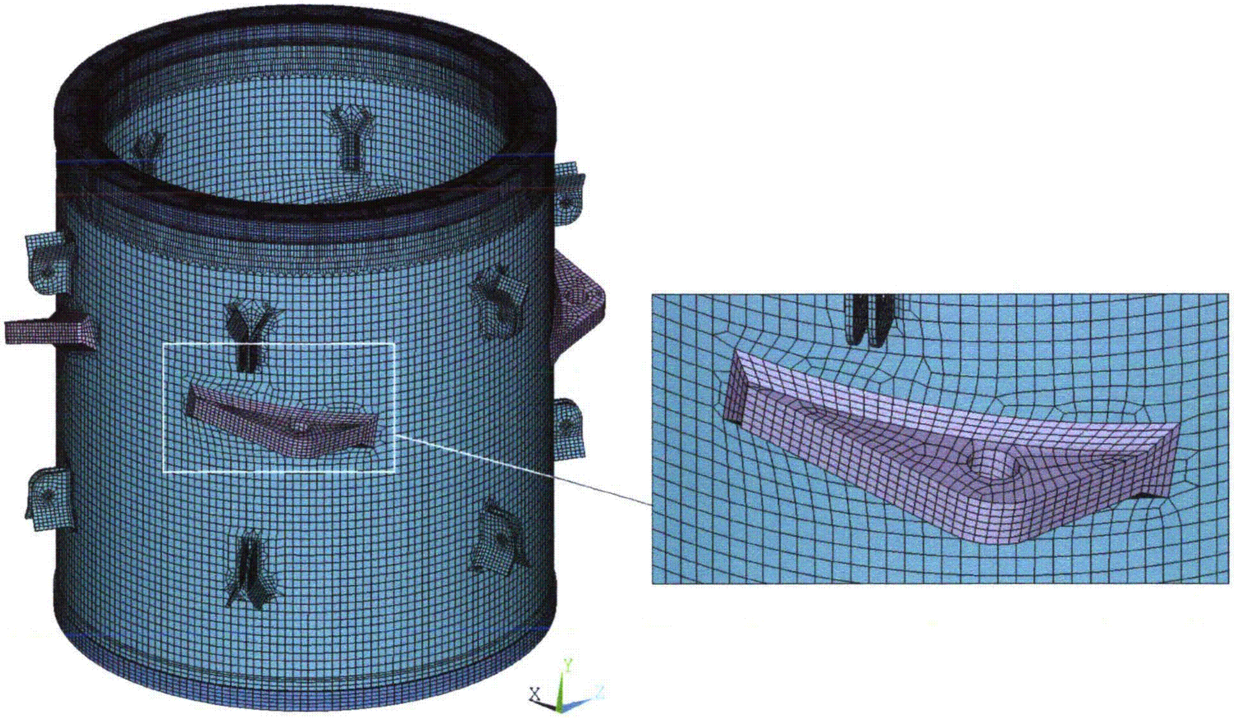


Figure 2-7 –Tie-Down Analysis Finite Element Model

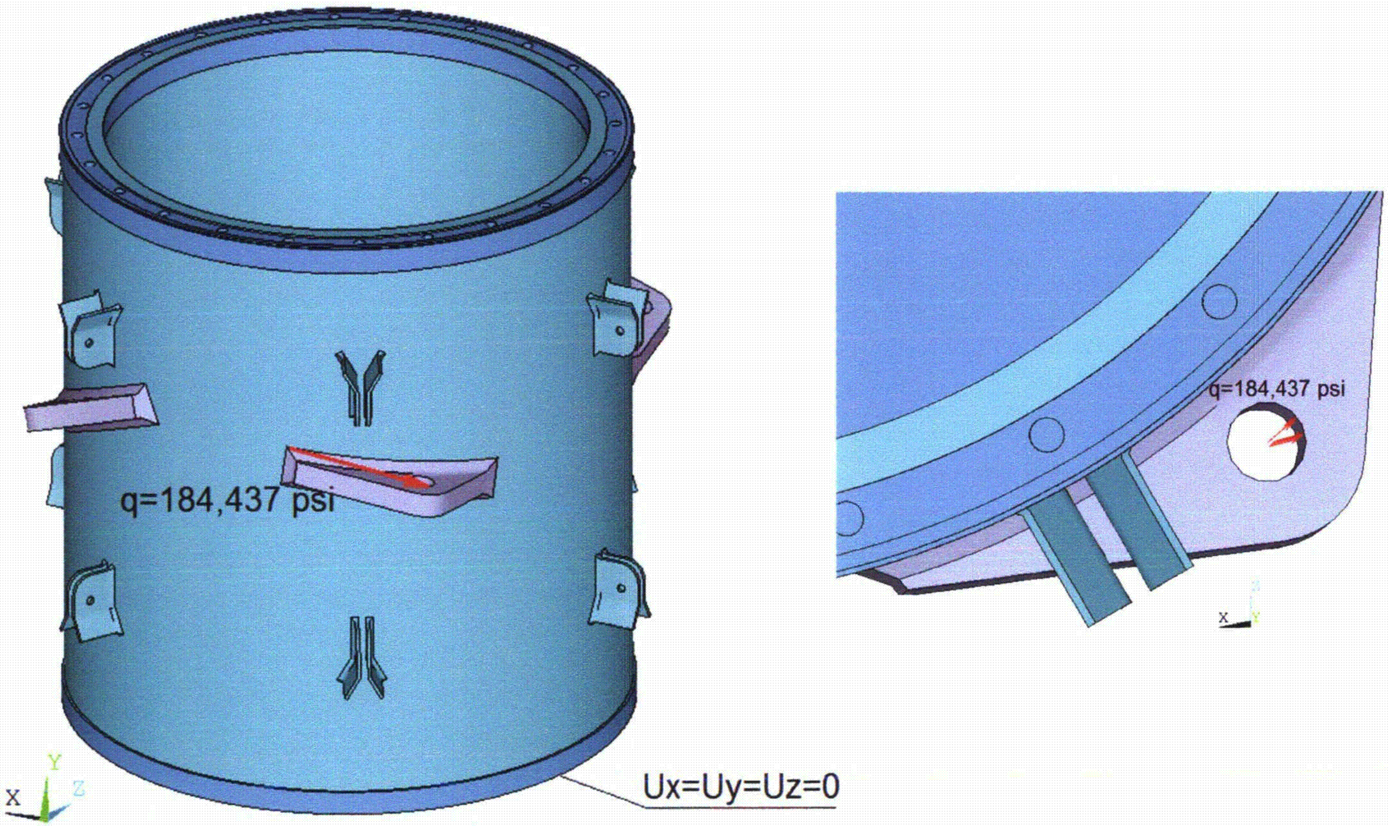


Figure 2-8 – Tie-Down FEM Boundary Conditions and Loads

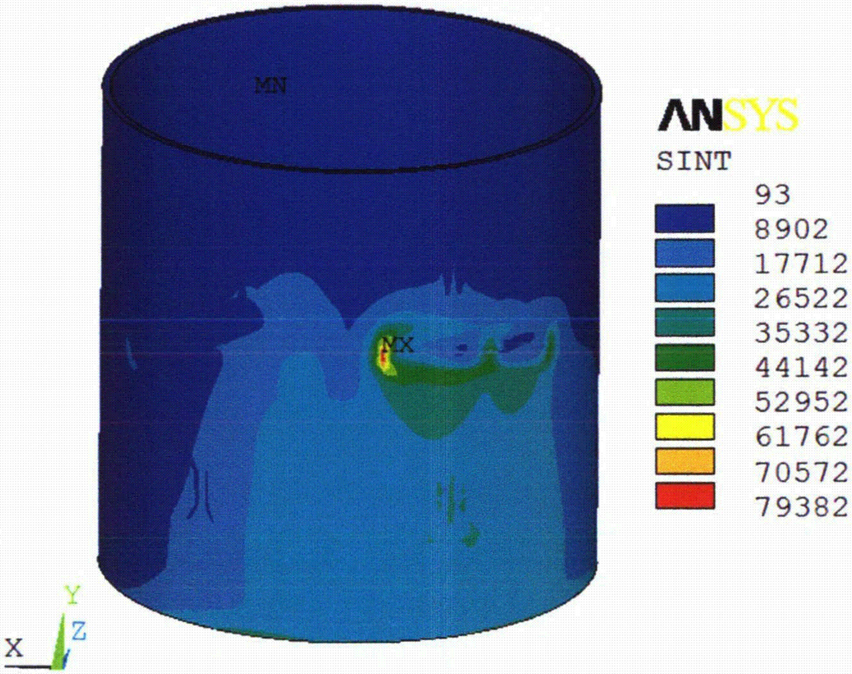
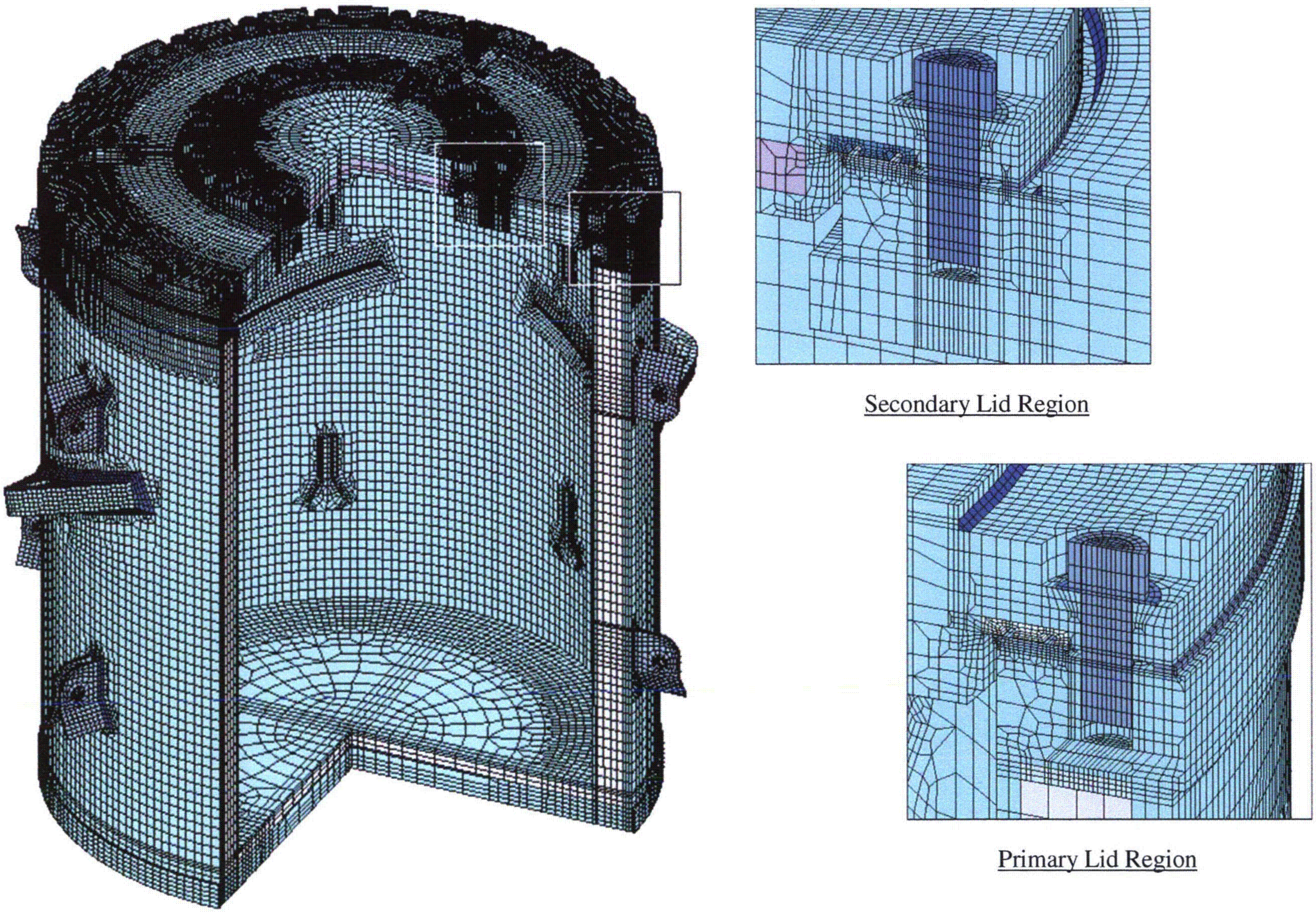


Figure 2-9 – Tie-Down FEM Analysis – Stress Intensity Contour in the Outer Shell



Secondary Lid Region

Primary Lid Region

Figure 2-10 – WMG 150B Cask Finite Element Model

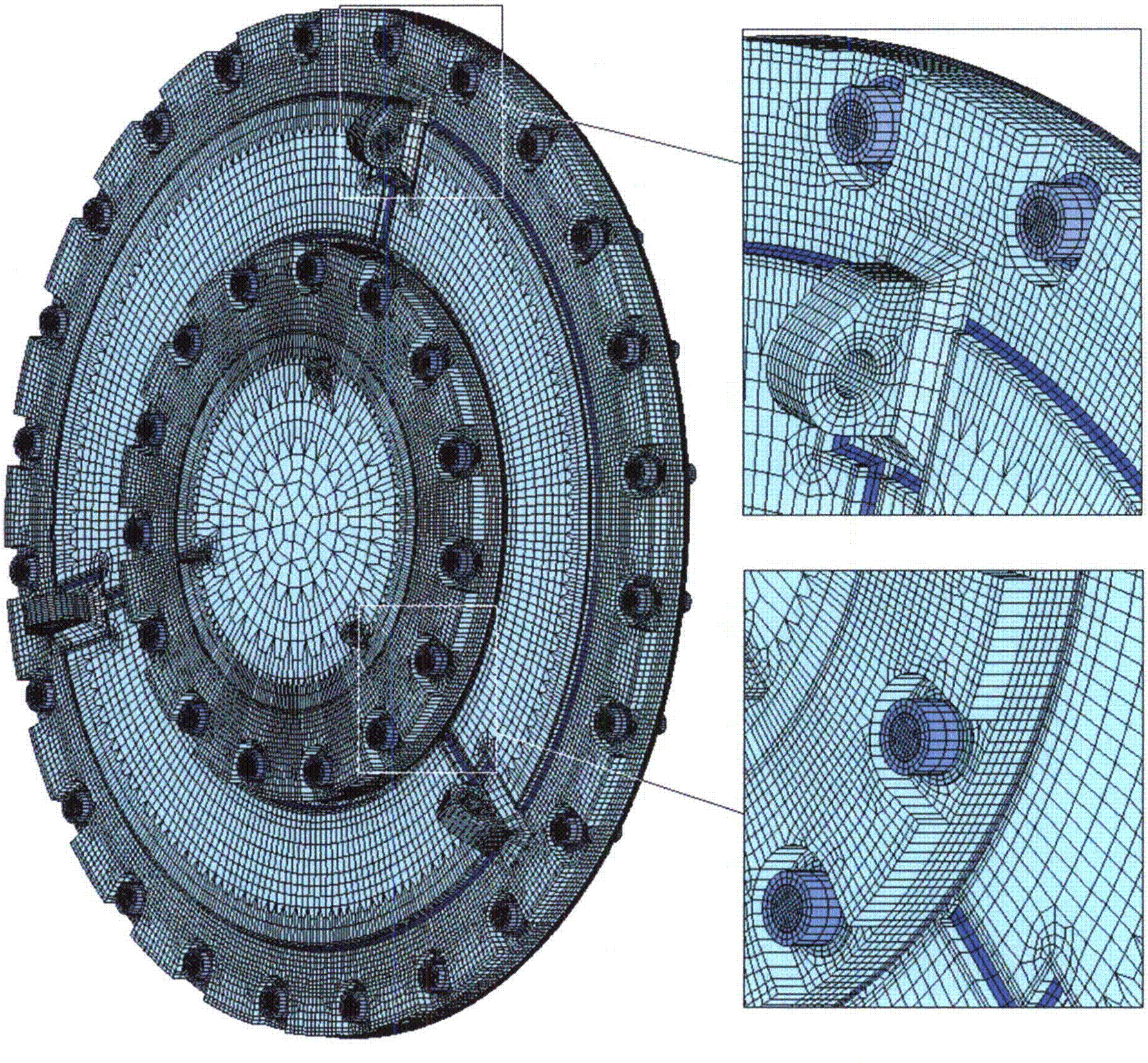


Figure 2-11 – WMG 150B Cask Lid Finite Element Model

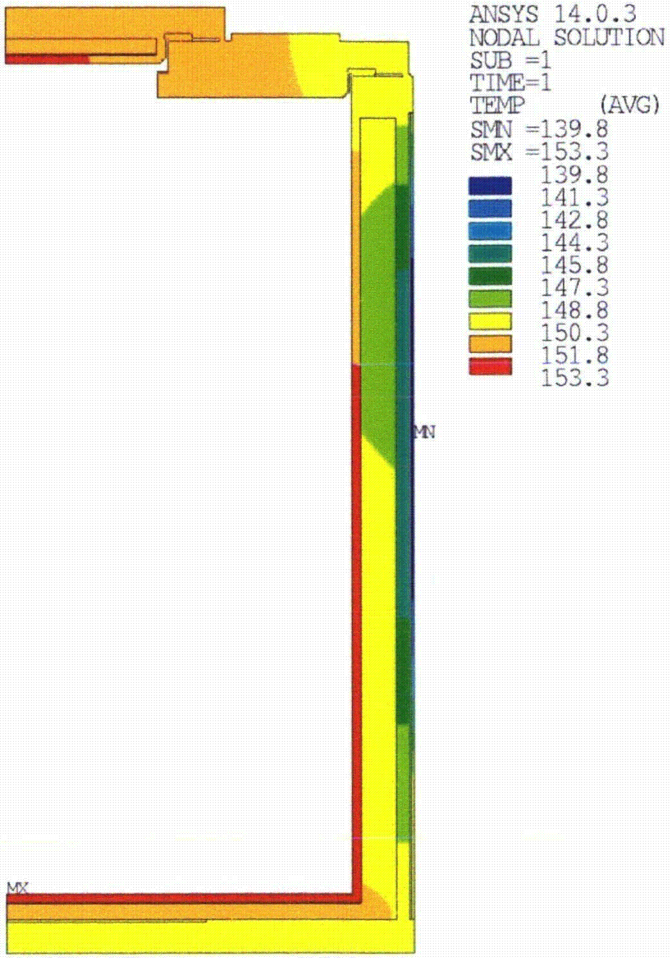
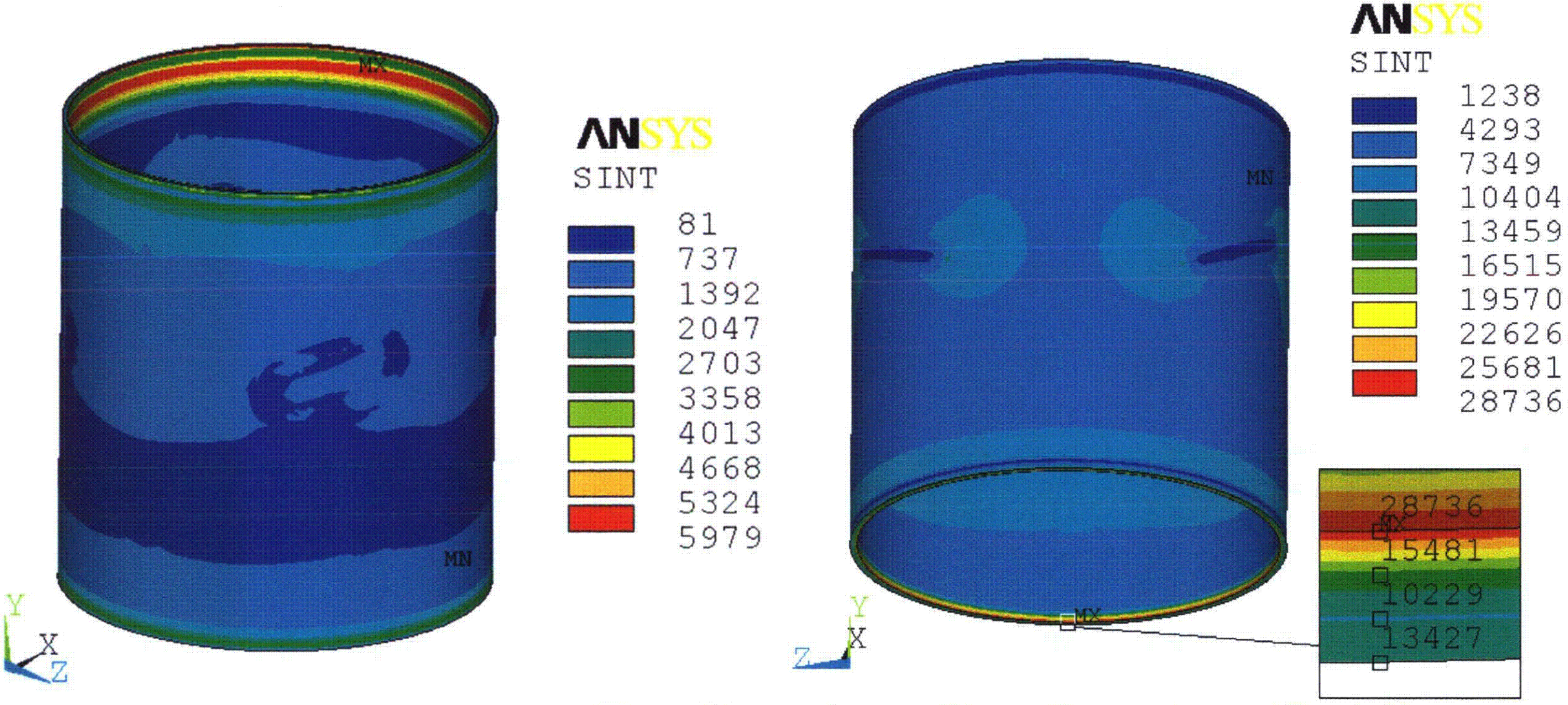


Figure 2-12 – Hot Environment Temperature Distribution

(Reproduced from Figure 3-5)



Inner Shell

Outer Shell

Figure 2-13 –Stress Intensity in the Inner & Outer Shells – Hot Environment

(Reproduced from Figures 3.4 and 3.5 of Reference 2-24)

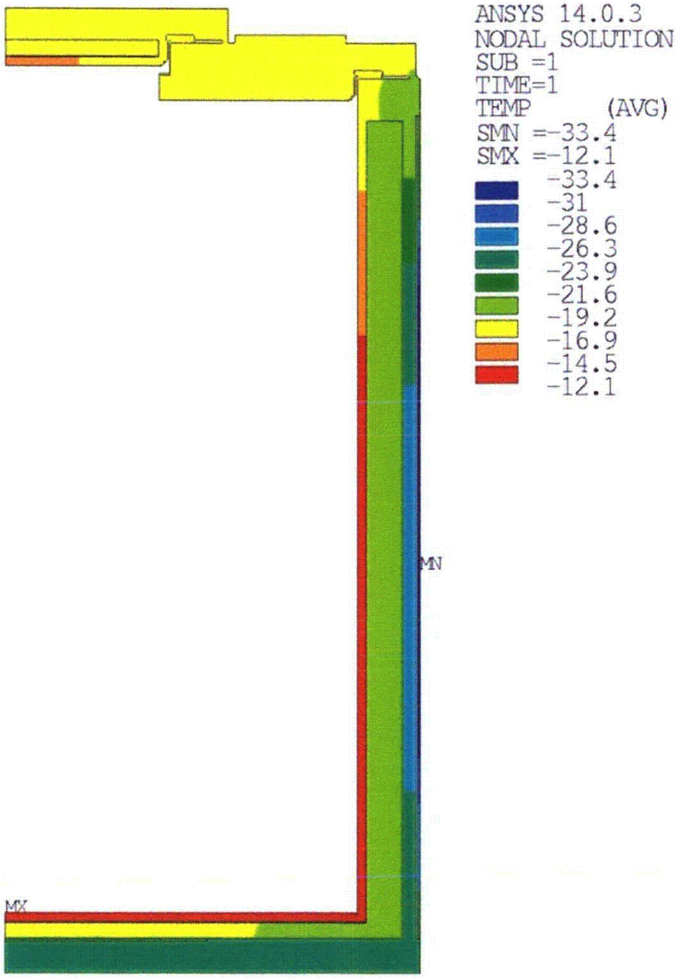
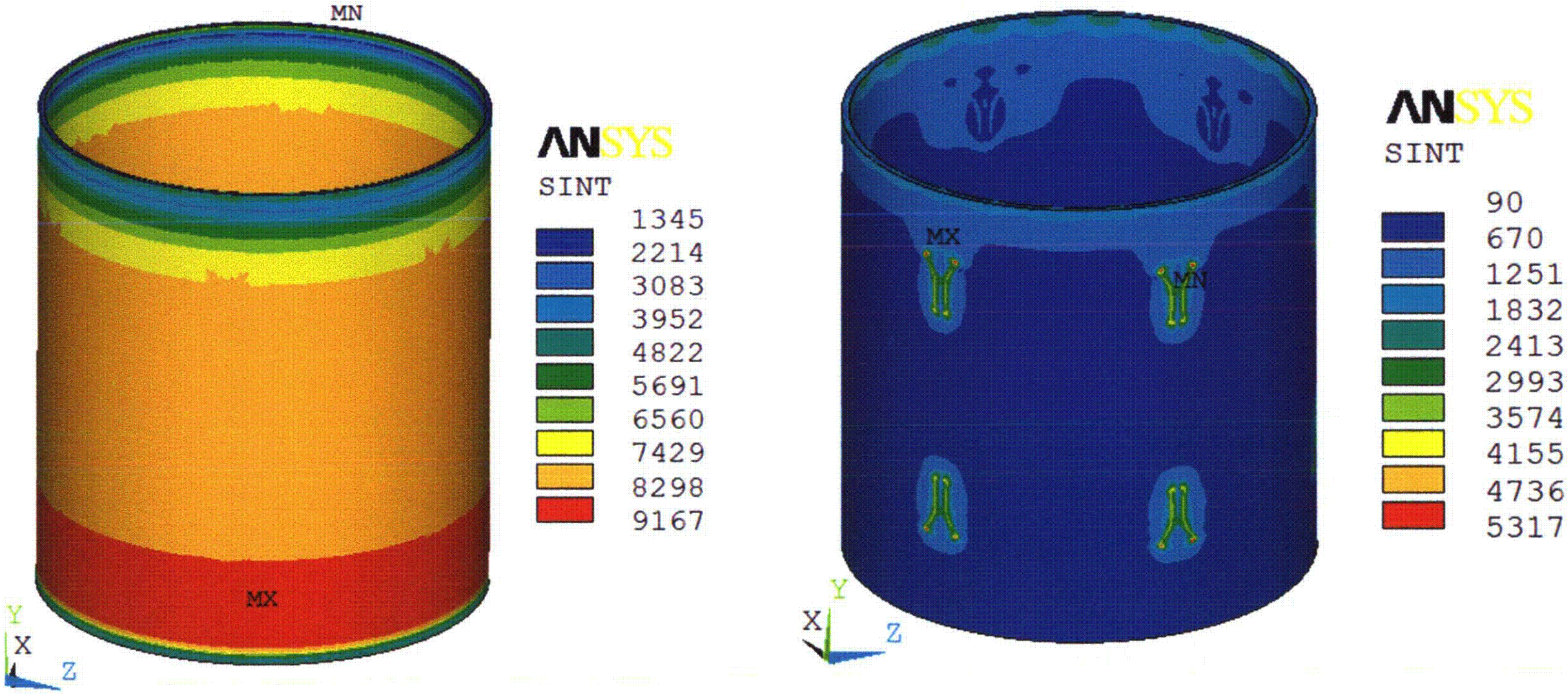


Figure 2-14 – Cold Environment Temperature Distribution

(Reproduced from Figure 3-6)



Inner Shell

Outer Shell

Figure 2-15 –Stress Intensity in the Inner & Outer Shells – Cold Environment

(Reproduced from Figures 3.28 and 3.29 of Reference 2-24)

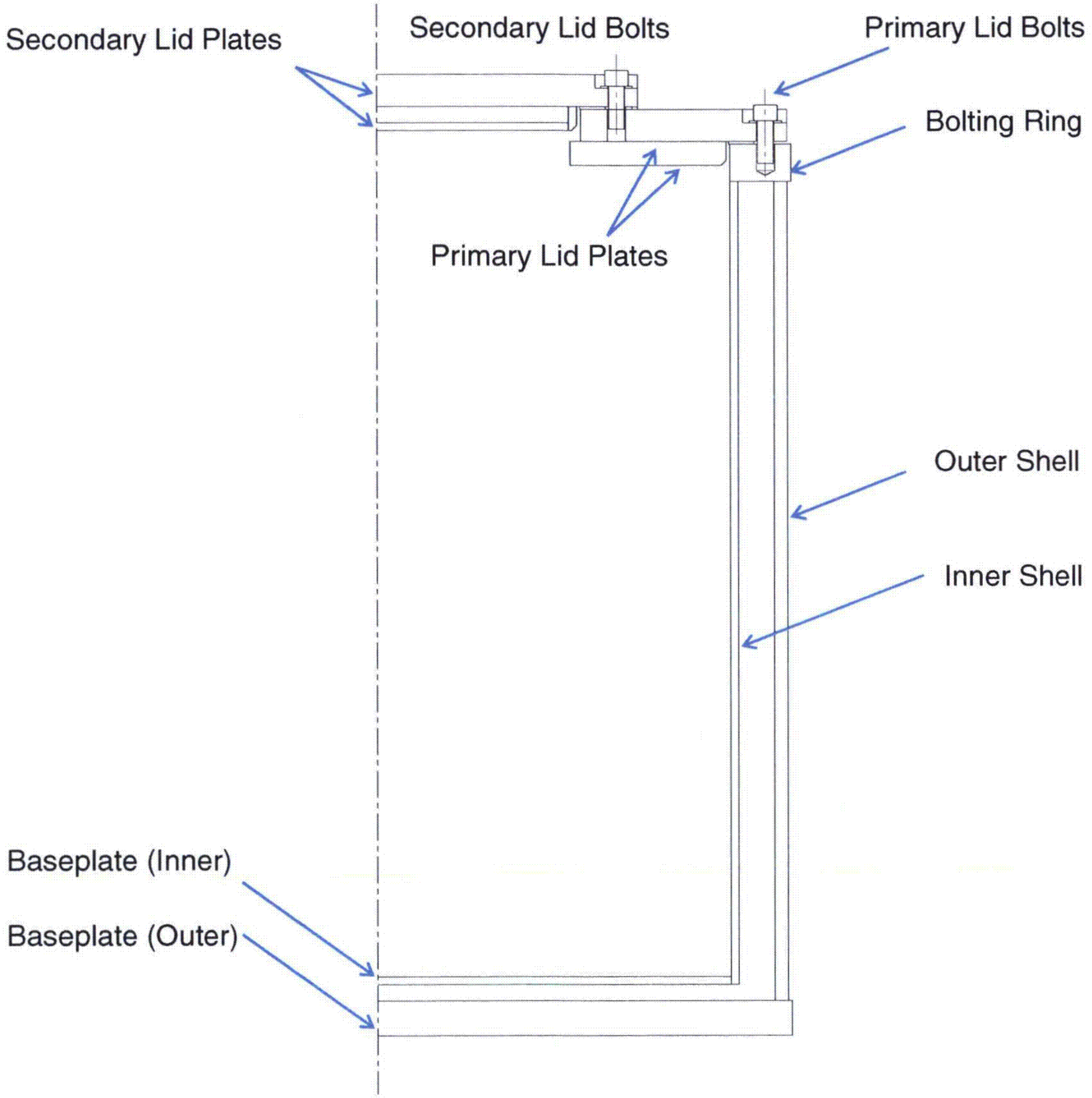


Figure 2-16 – WMG 150B Cask – Fracture Critical Components

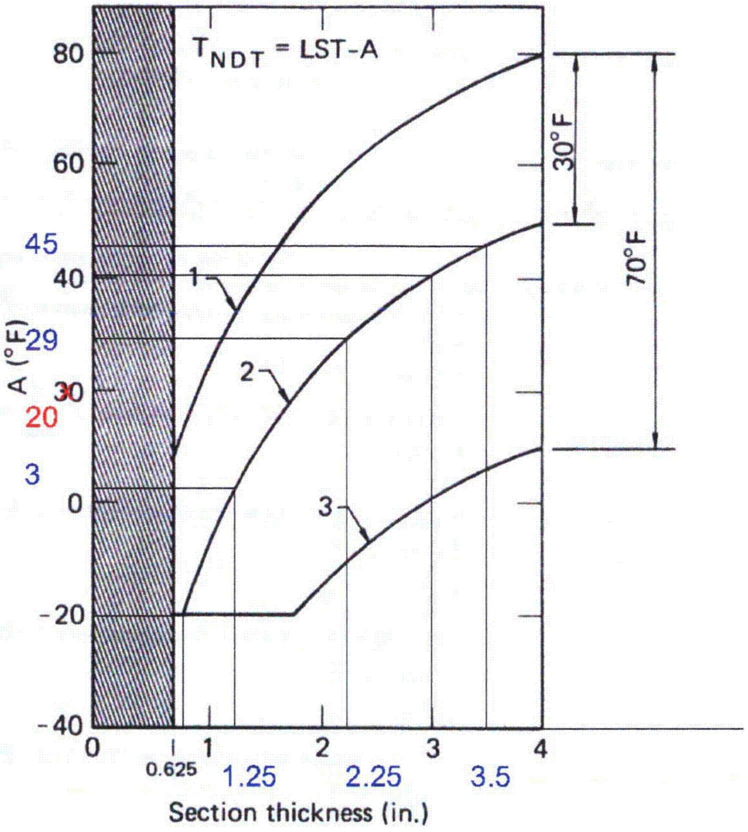
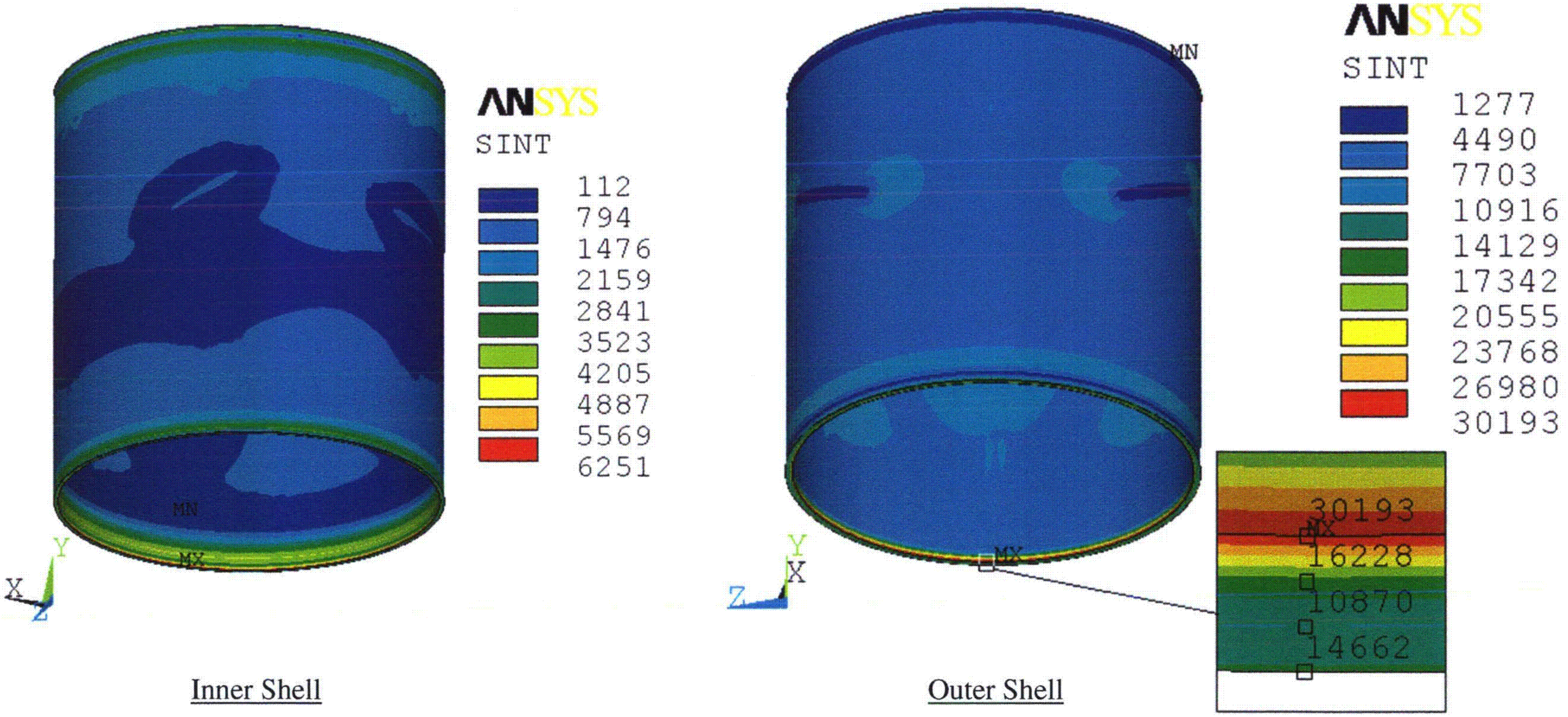


FIG. 6. Design chart for Category II fracture critical components showing reference temperature relative to NDT as a function of section thickness (derived from Fig. 7). Curve 1 is the basic K_{ID}/σ_{yd} curve for $\beta = 0.6$, and represents full dynamic loading with stresses at yield stress level. For effective g loadings of less than approximately 100 g: curve 2, shifted 30°F, may be used for steels with σ_{ys} in the range 60 ksi $\leqslant \sigma_{ys} \leqslant$ 100 ksi; curve 3, shifted 70°F, may be used for steels with σ_{ys} less than 60 ksi.

Figure 2-17 – Fracture Toughness Design Chart (Reproduced from Reference 2-6, Figure 6)

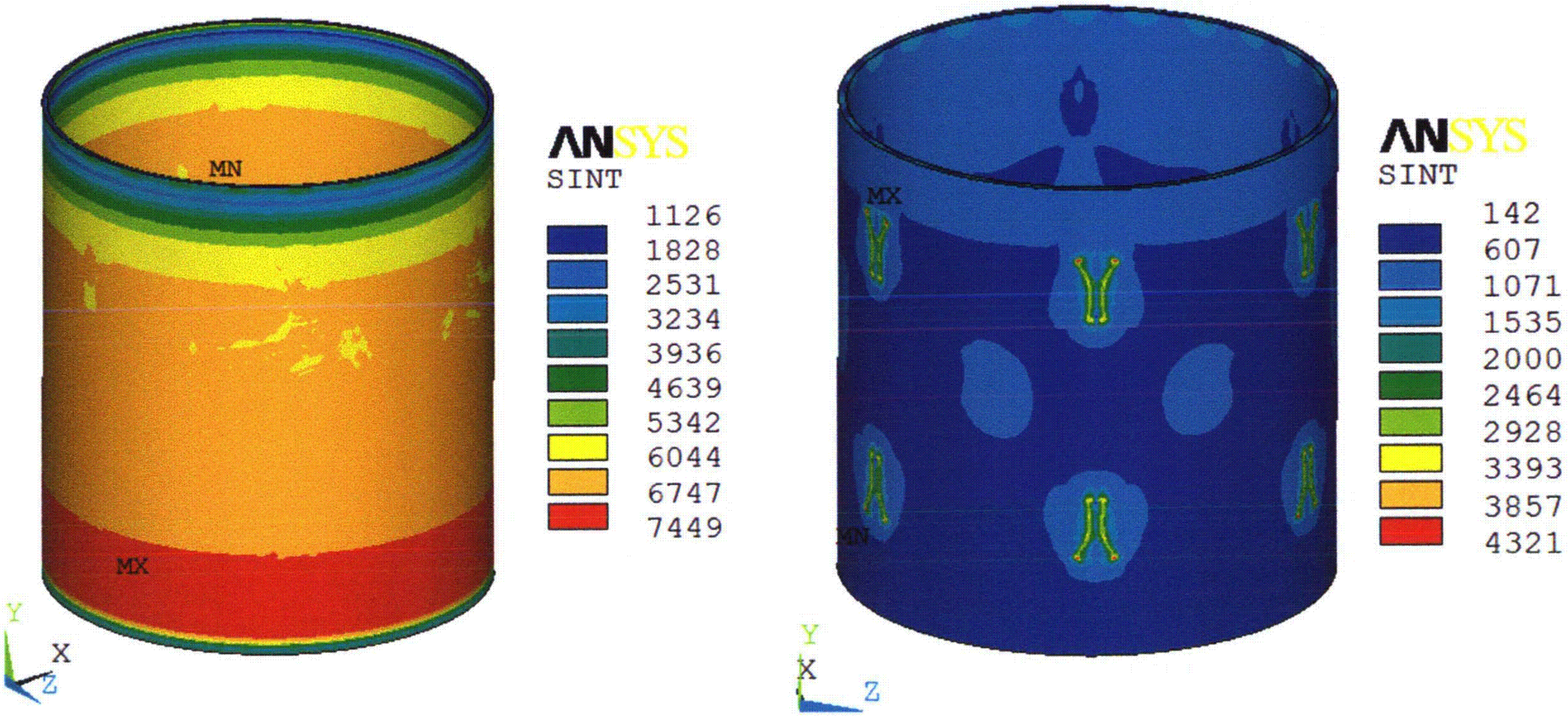


Inner Shell

Outer Shell

Figure 2-18 – Stress Intensity in the Inner & Outer Shells – Reduced External Pressure

(Reproduced from Figures 3.52 and 3.53 of Reference 2-24)



Inner Shell

Outer Shell

Figure 2-19 – Stress Intensity in the Inner & Outer Shells – Increased External Pressure

(Reproduced from Figures 3.40 and 3.41 of Reference 2-24)

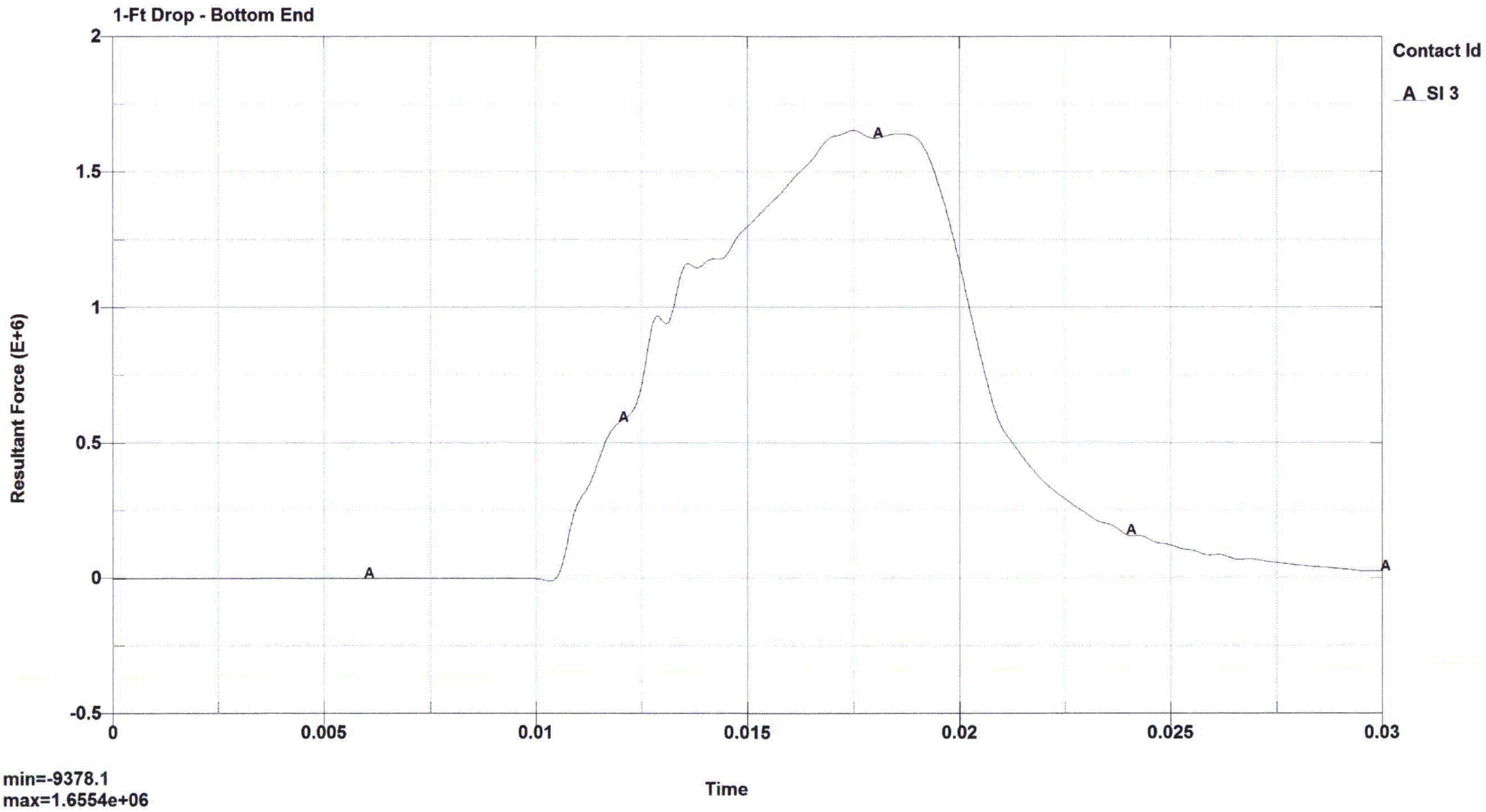


Figure 2-20 – WMG 150B Cask – 1-ft Bottom End Drop – Impact Limiter Reaction Time-History Plot
(Reproduced from Figure 49 of Reference 2-28)

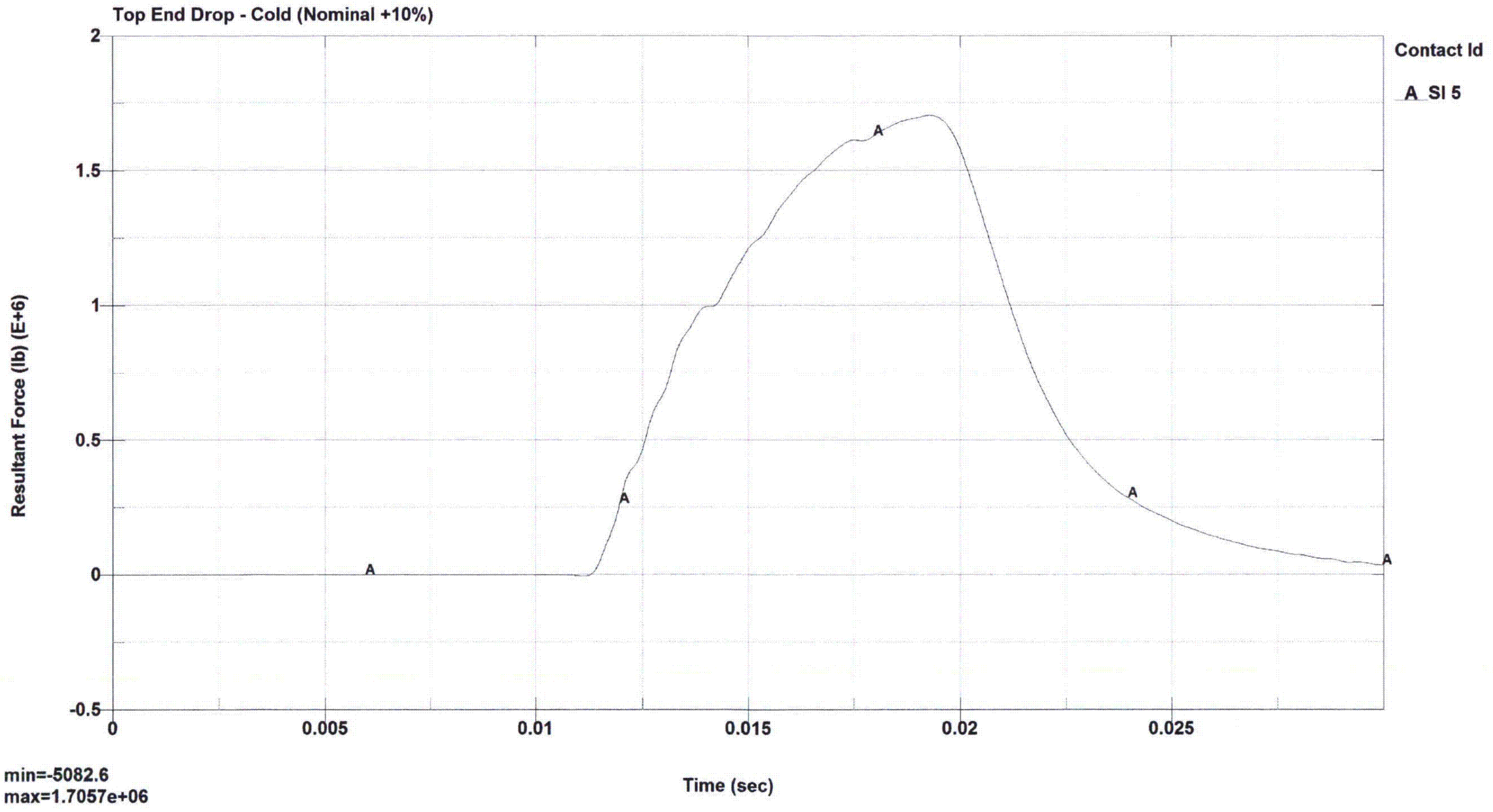


Figure 2-21 – WMG 150B Cask – 1-ft Top End Drop – Impact Limiter Reaction Time-History Plot
(Reproduced from Figure 50 of Reference 2-28)

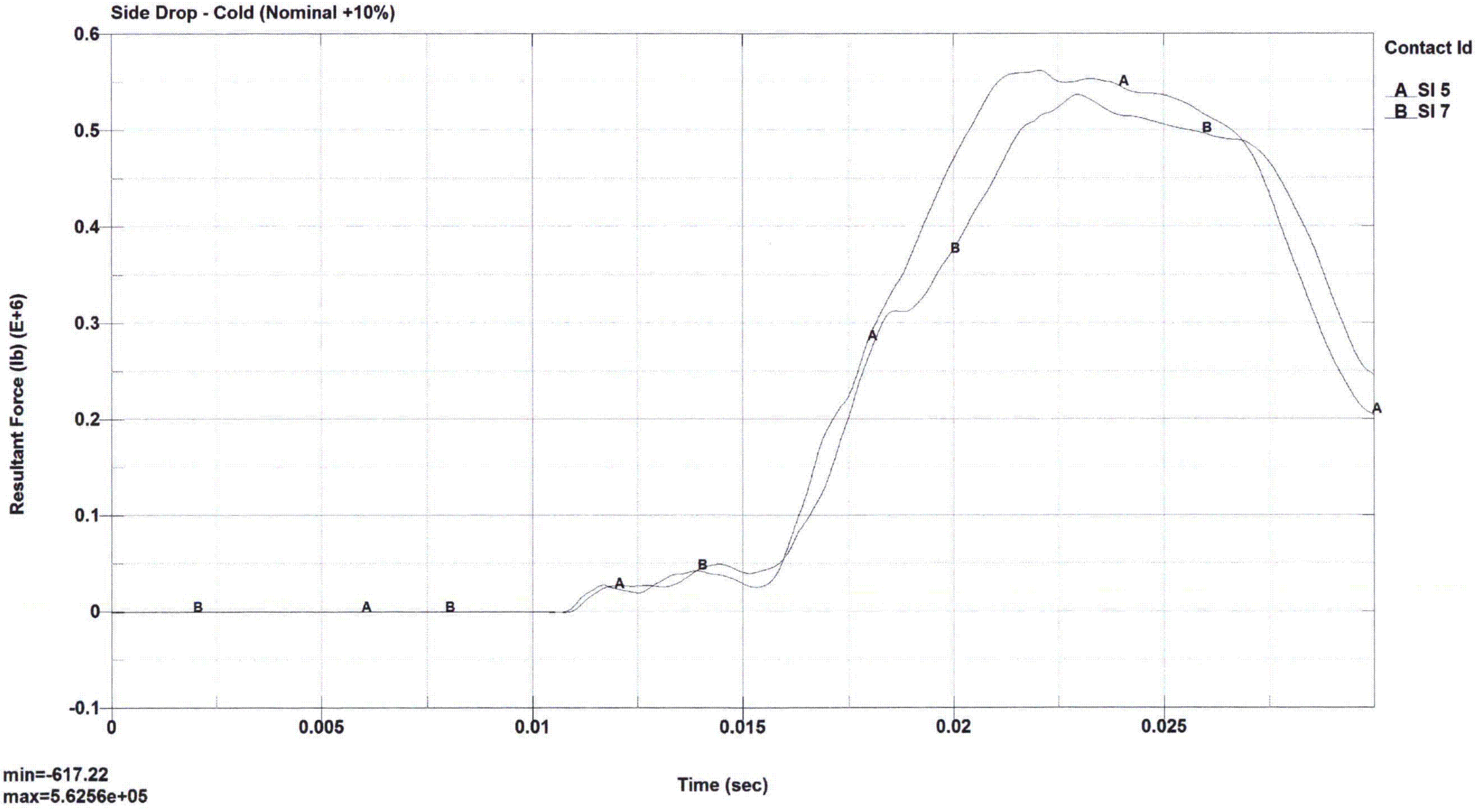


Figure 2-22 – WMG 150B Cask – 1-ft Side Drop – Impact Limiter Reaction Time-History Plot
(Reproduced from Figure 51 of Reference 2-28)

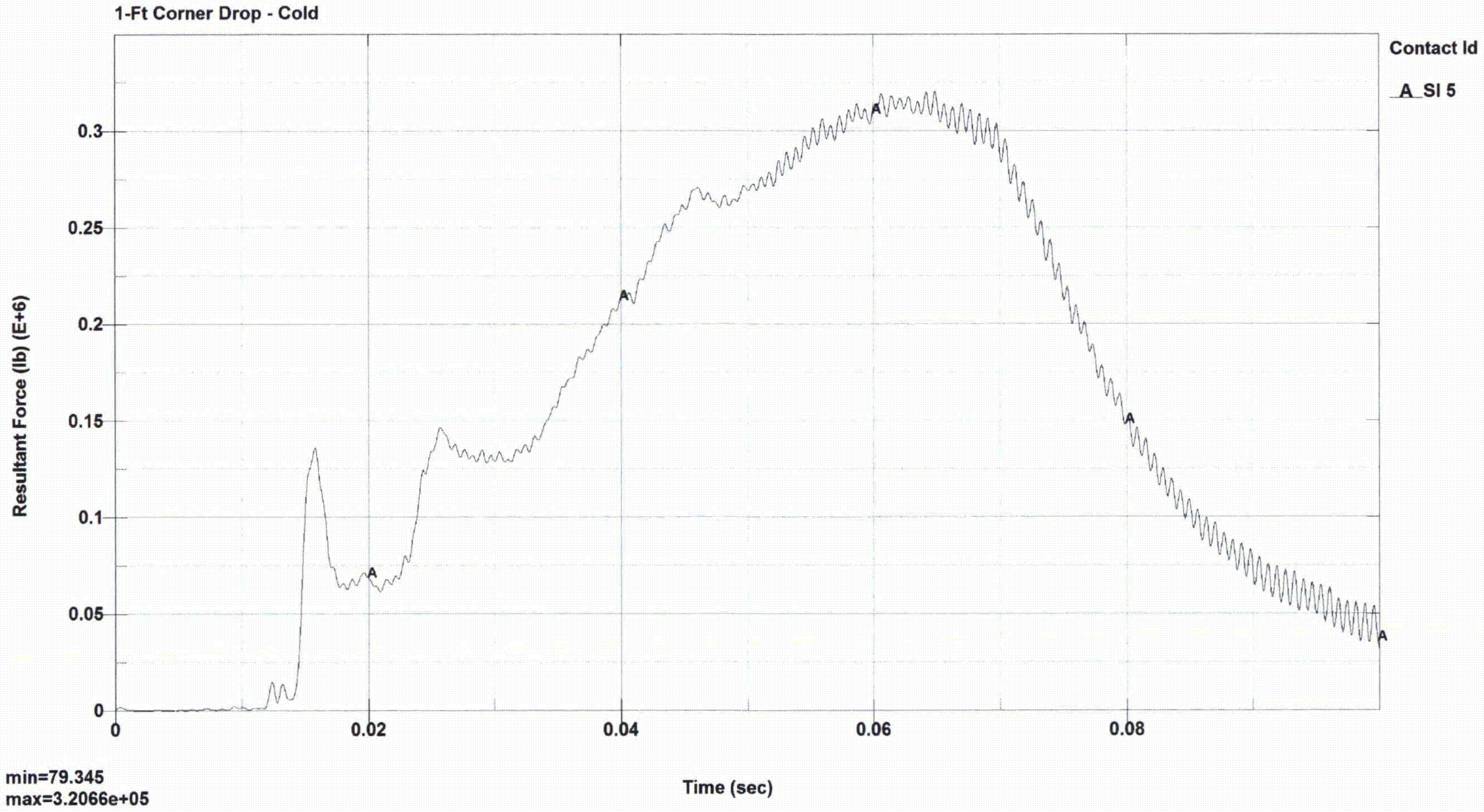


Figure 2-23 – WMG 150B Cask – 1-ft Corner Drop – Impact Limiter Reaction Time-History Plot
(Reproduced from Figure 51 of Reference 2-28)

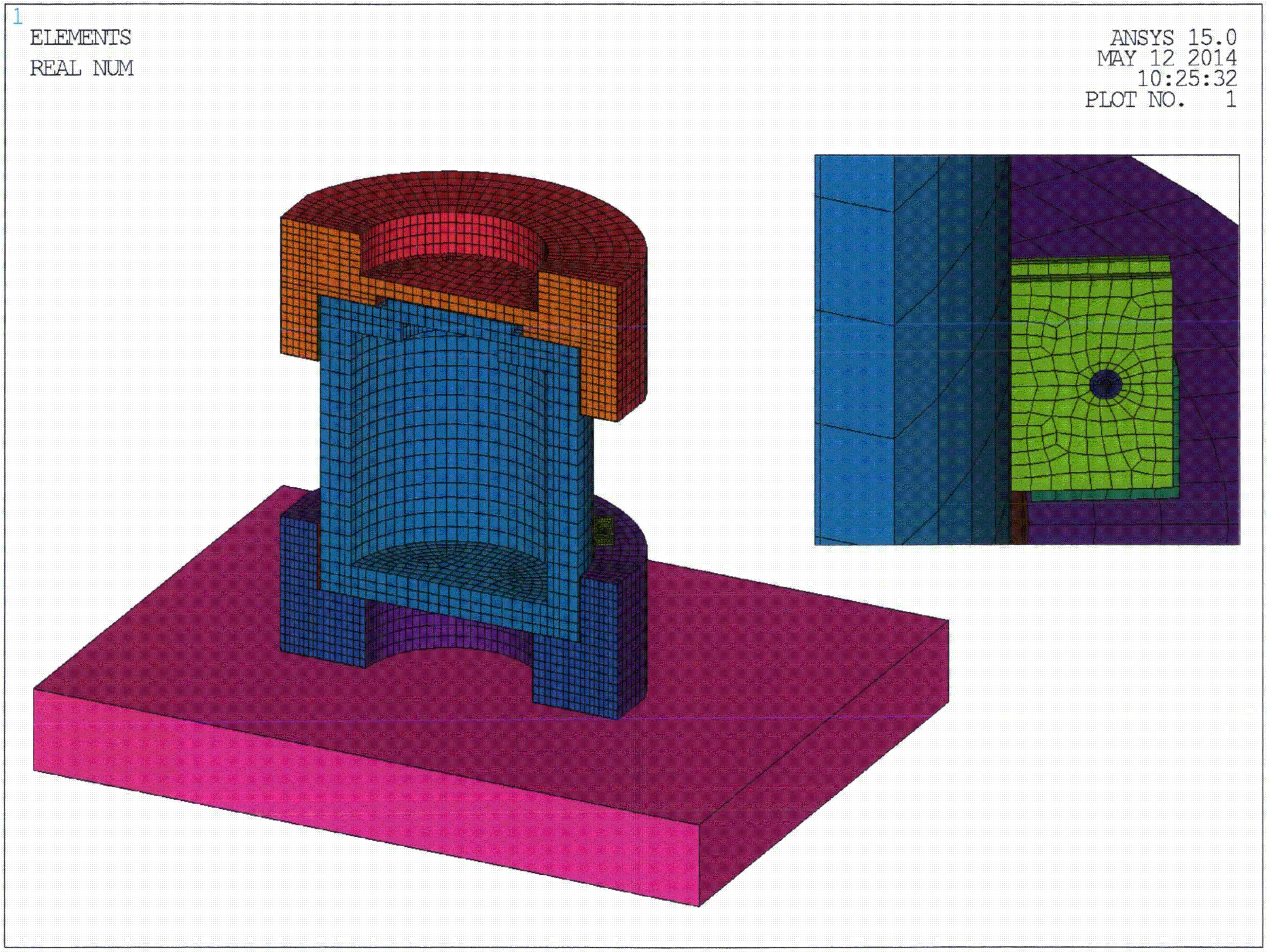
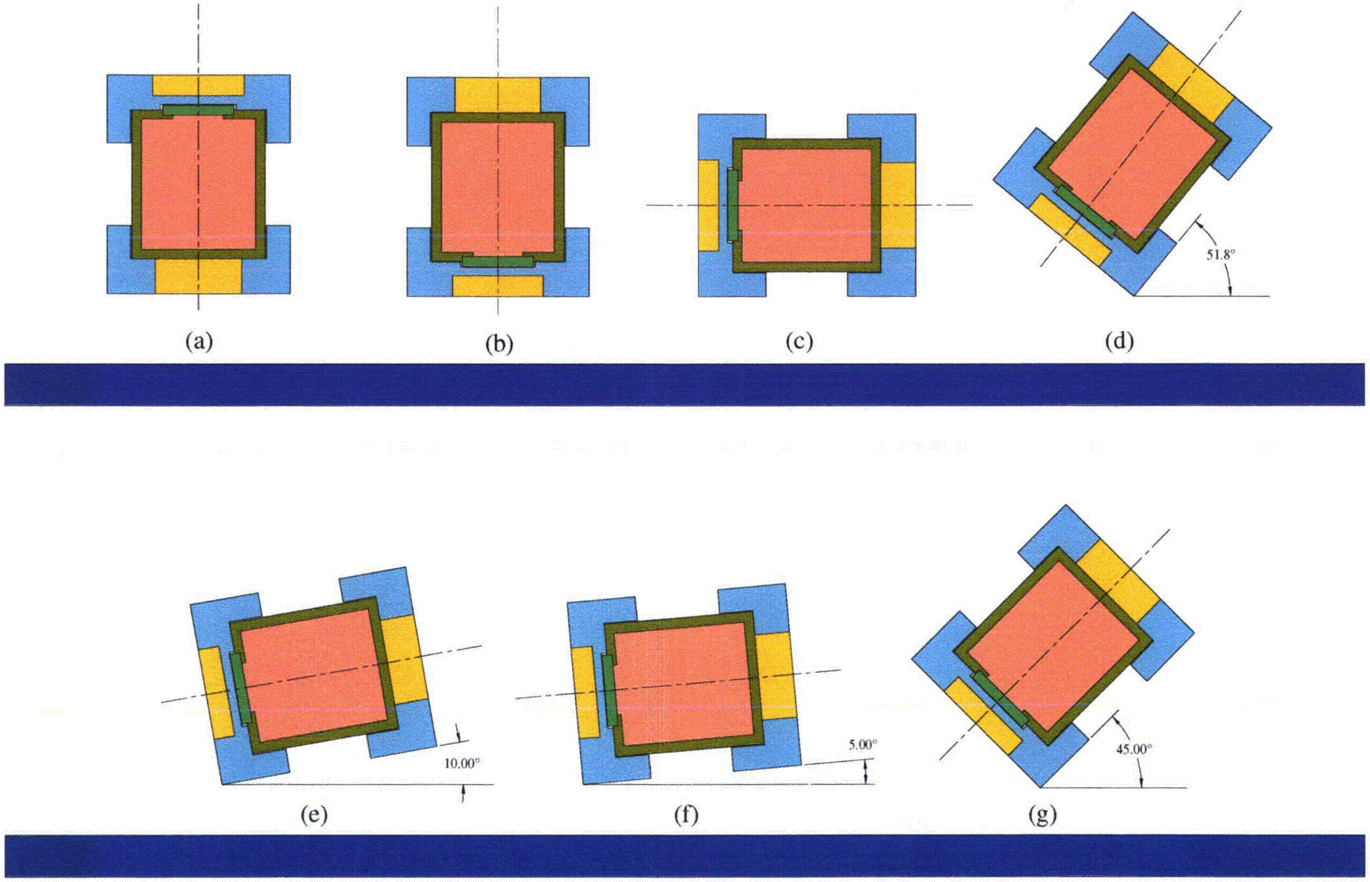


Figure 2-24 – ANSYS/LS-DYNA Finite Element Model of the WMG 150B Package
(Reproduced from Figure 5 of Reference 2-28)



(a) (b) (c) (d)

(e) (f) (g)

Figure 2-25 – WMG 150B Cask Drop Test Orientations
(Reproduced from Figure 1 of Reference 2-28)

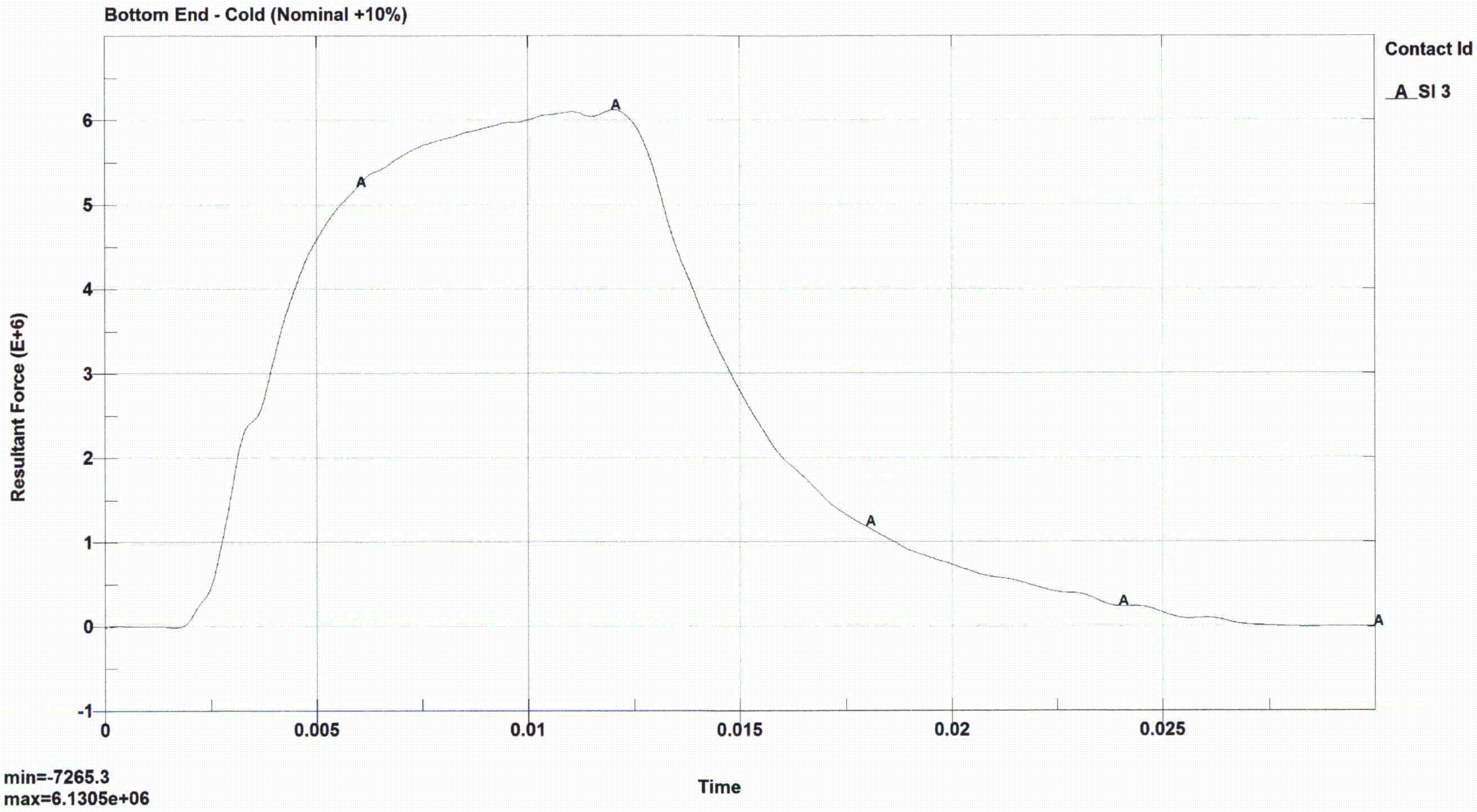


Figure 2-26 – A Typical Time-History Plot of Impact Limiter Reaction

(Reproduced from Figure 16 of Reference 2-28)

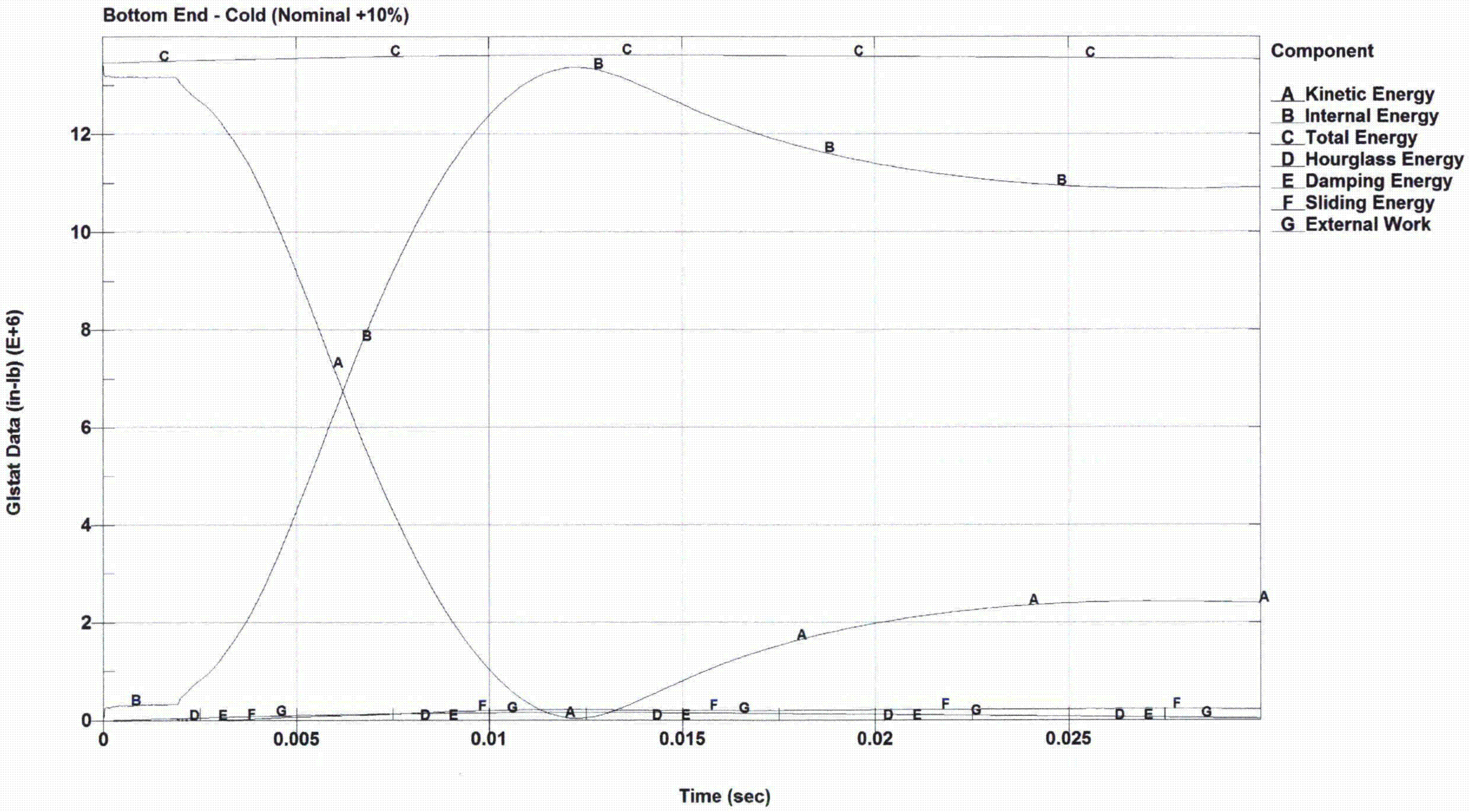


Figure 2-27 – A Typical Plot of Time-History of Various Energy Quantities Monitored for Each Drop Analysis (Reproduced from Figure 15 of Reference 2-28)

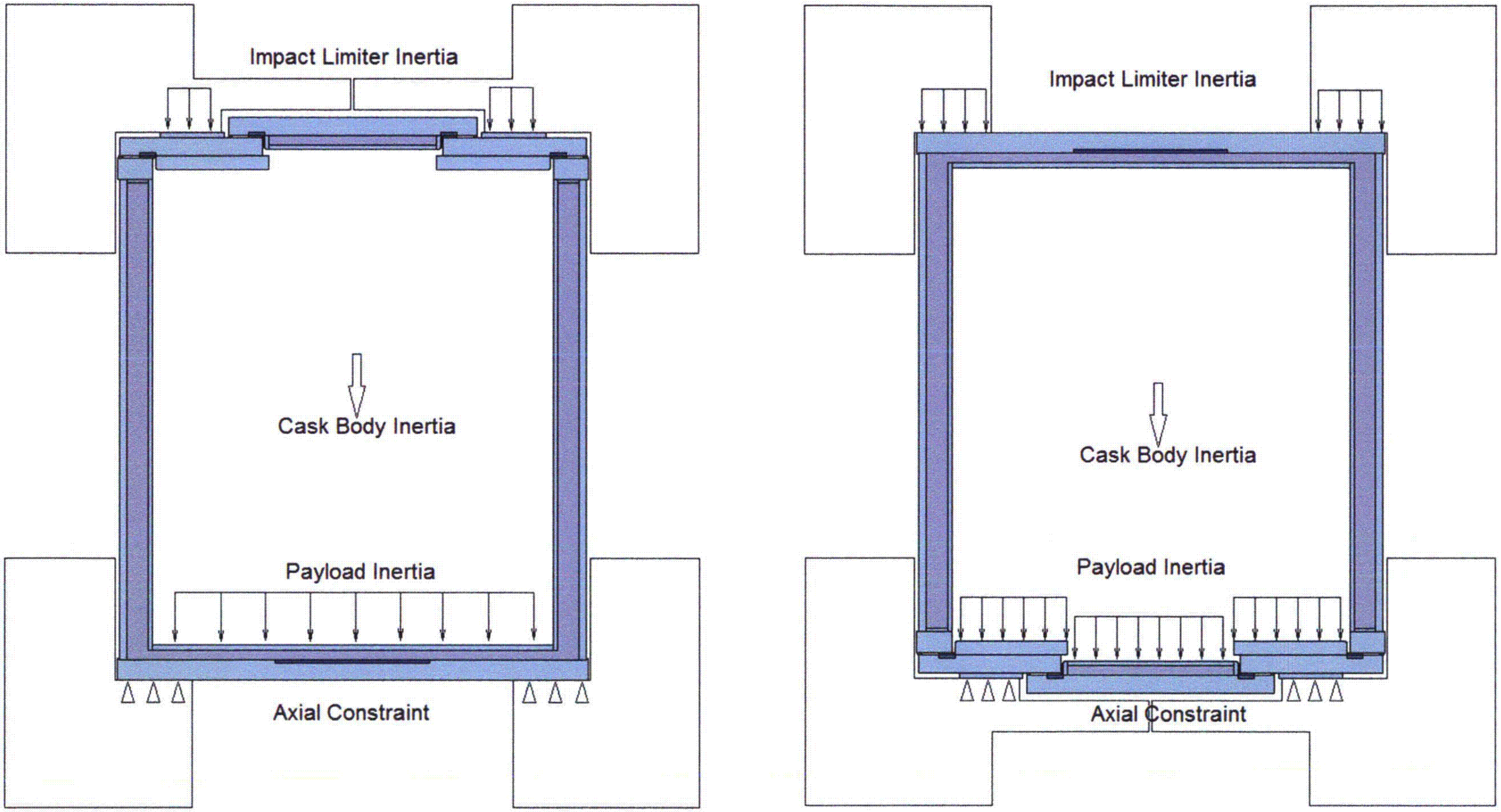
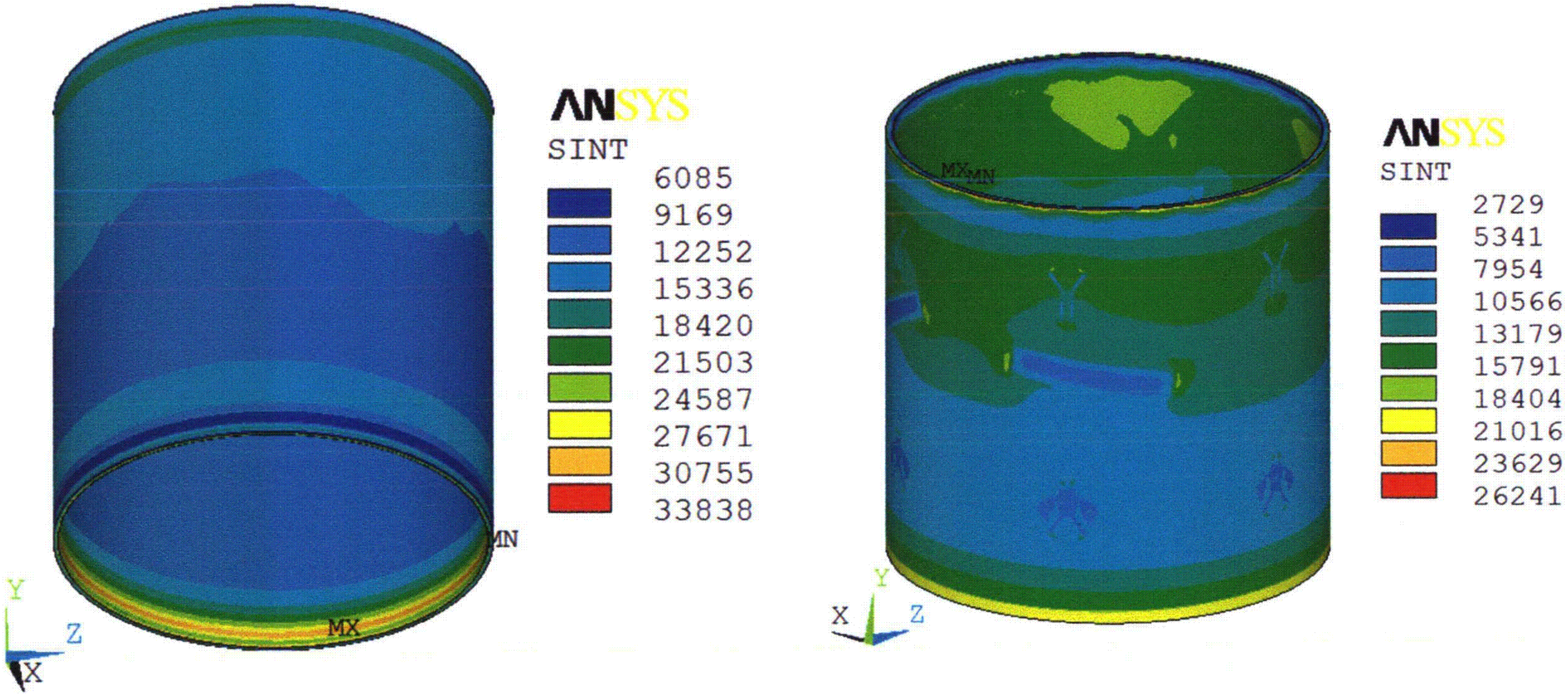


Figure 2-28 – End Drop Analyses – Load Distribution and Boundary Conditions



Inner Shell

Outer Shell

Figure 2-29 – 30-ft Top End Drop (Hot) – Stress Intensity Plot in the Shells

(S.I. plots for all components of the cask are included in Reference 2-31)

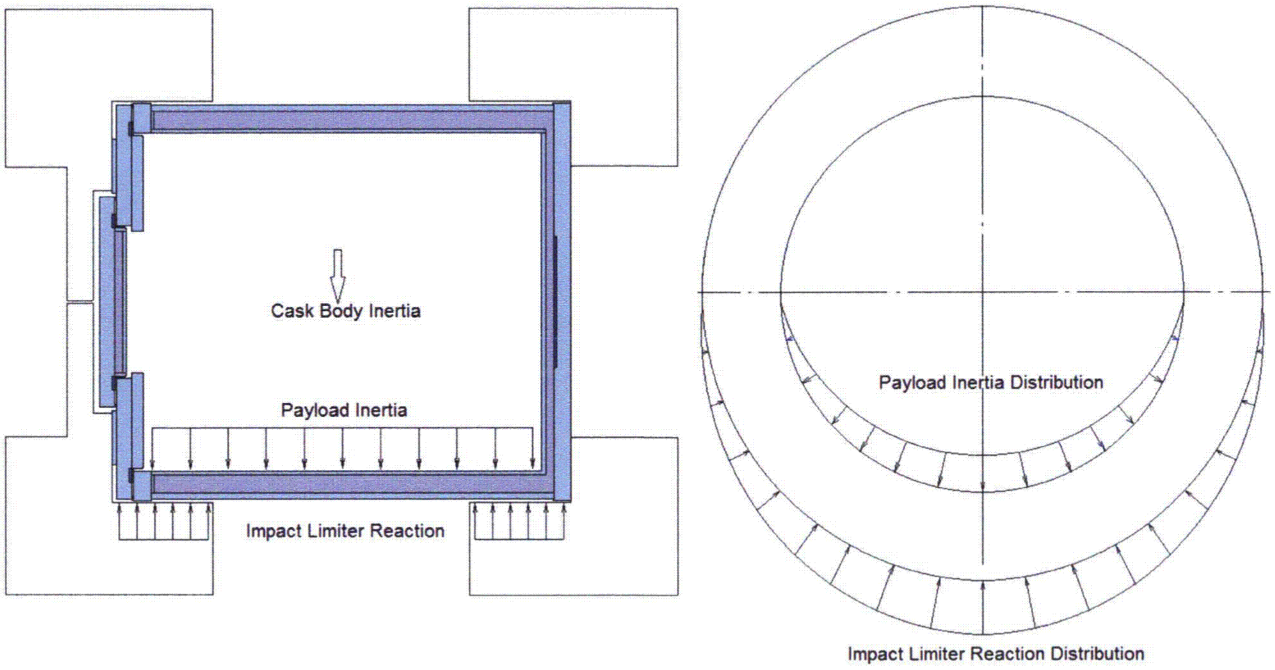
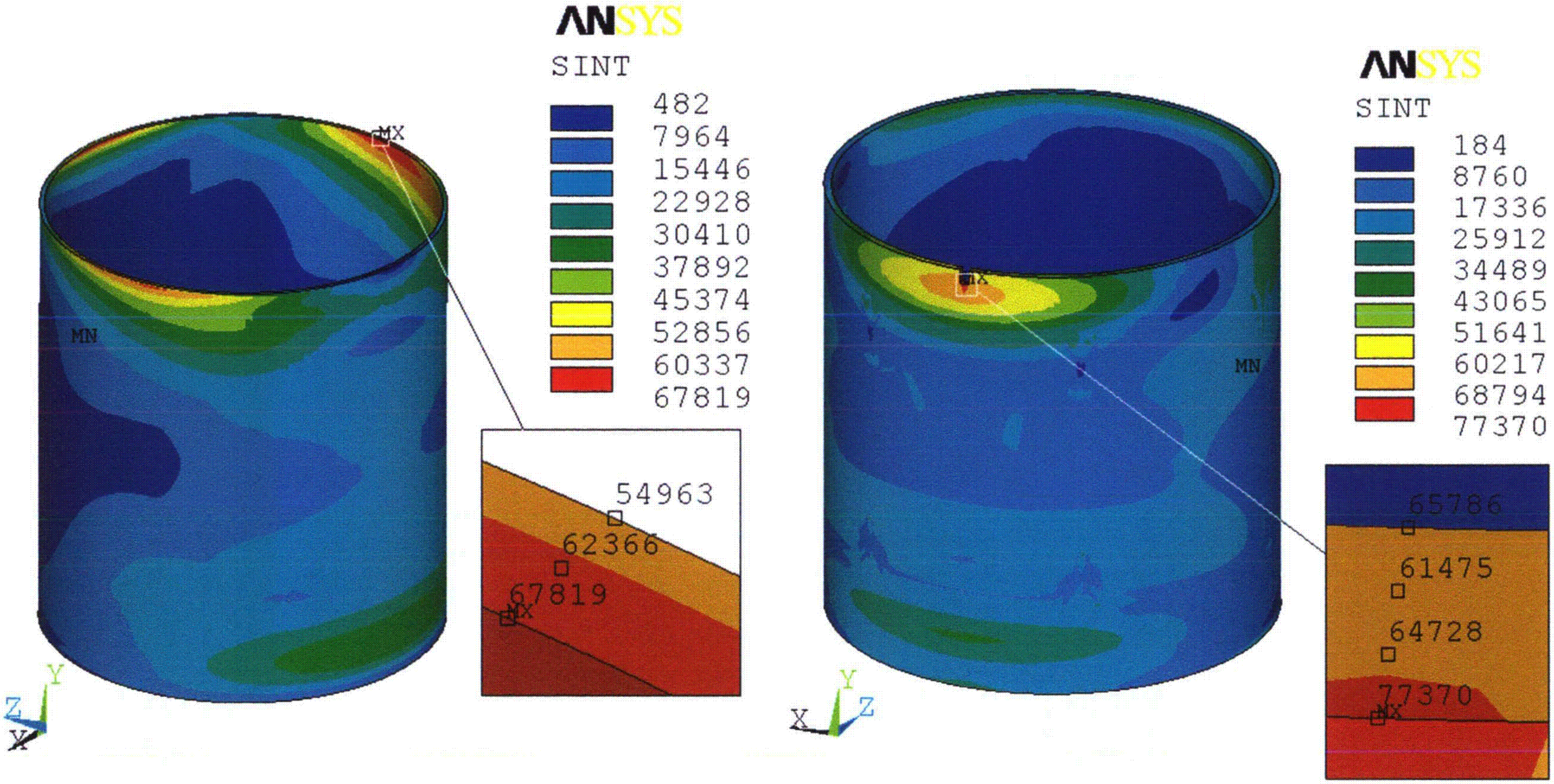


Figure 2-30 – Side Drop Analyses – Load Distribution and Boundary Conditions



Inner Shell

Outer Shell

Figure 2-30 – 30-ft Side Drop (Hot) – Stress Intensity Plot in the Shells

(S.I. plots for all components of the cask are included in Reference 2-31)

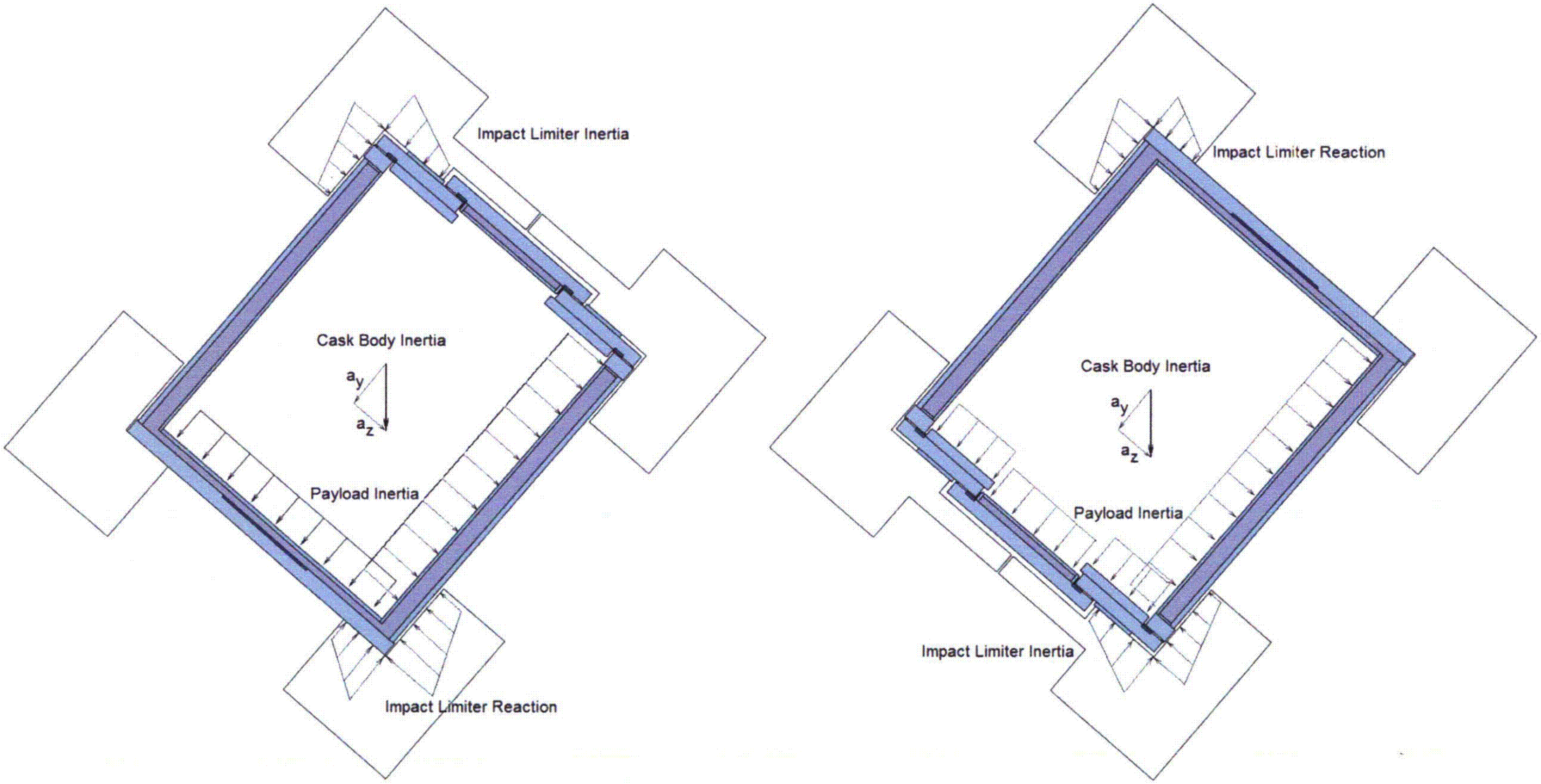
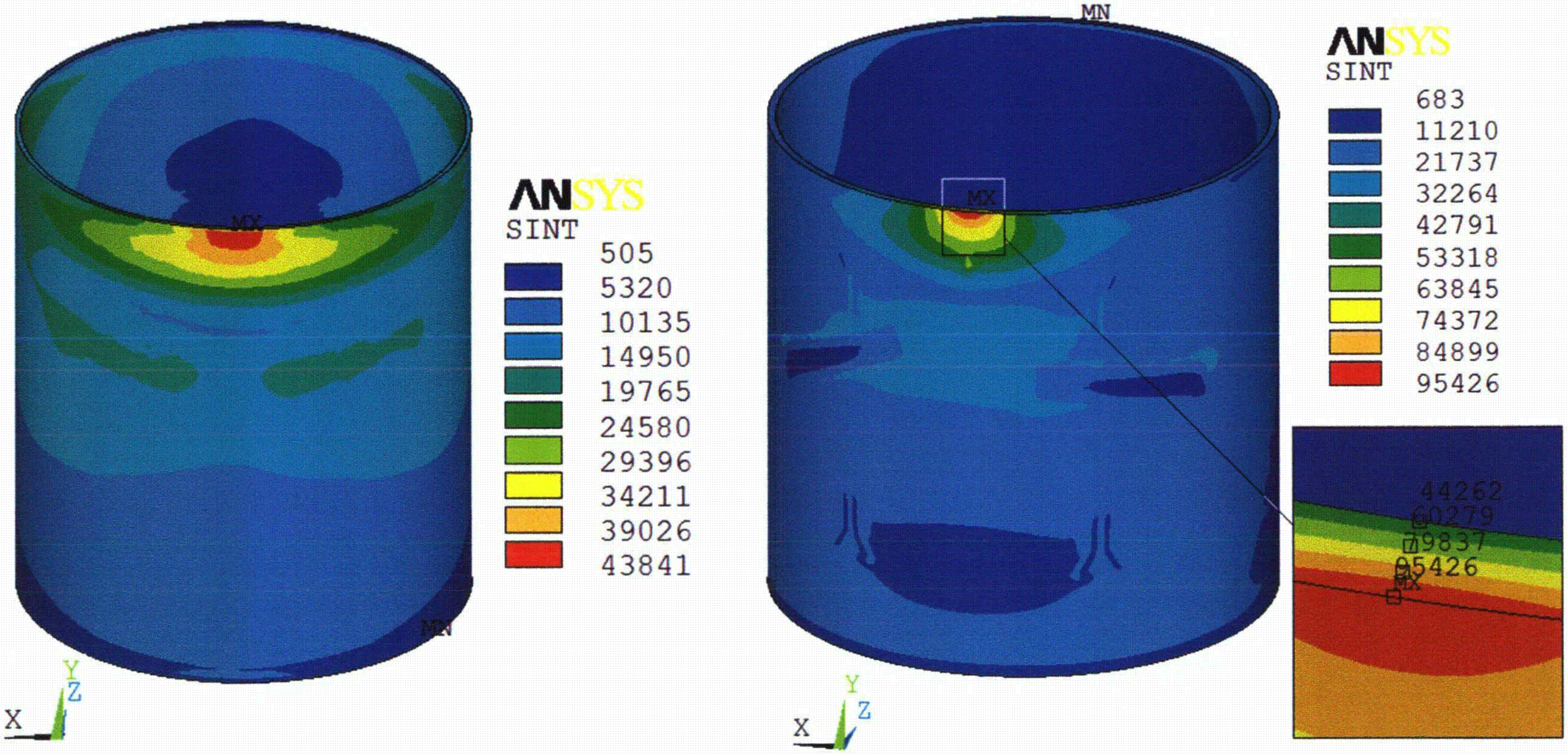


Figure 2-32 – Corner Drop Analyses – Load Distribution and Boundary Conditions



Inner Shell

Outer Shell

Figure 2-33 – 30-ft Top Corner Drop (Hot) – Stress Intensity Plot in the Shells

(S.I. plots for all components of the cask are included in Reference 2-31)

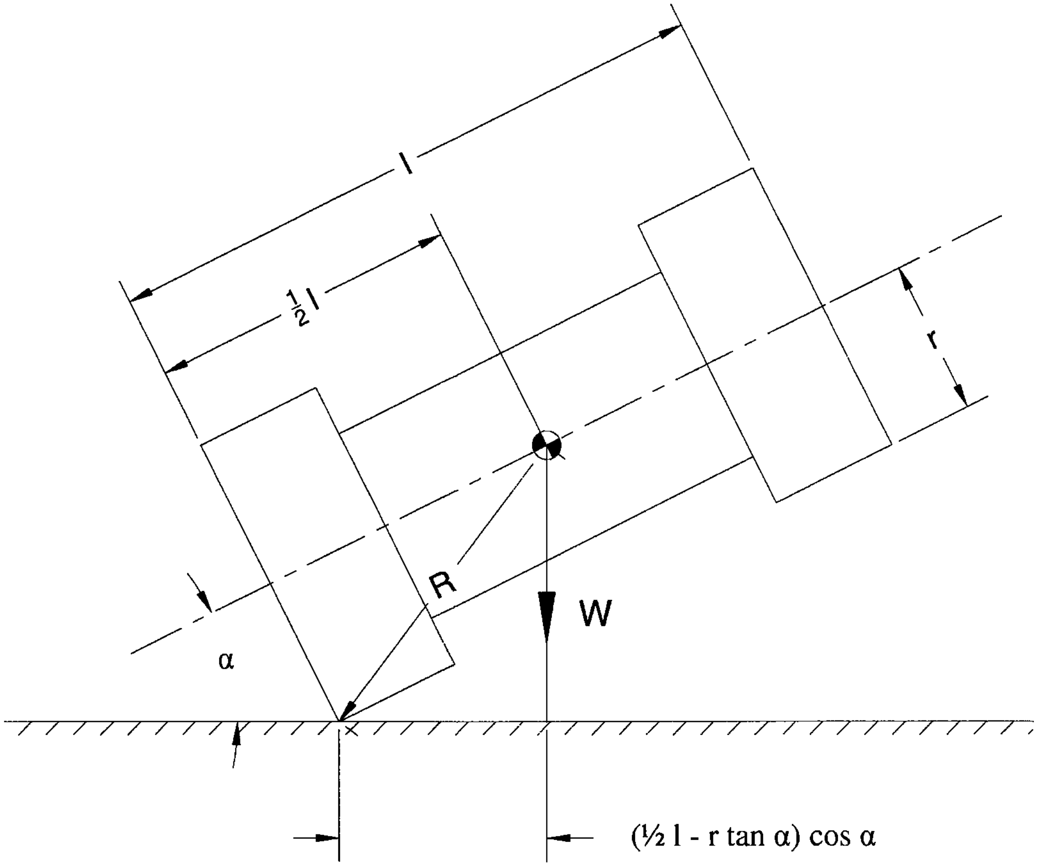


Figure 2-34 – Oblique Drop Orientation and Dimensions