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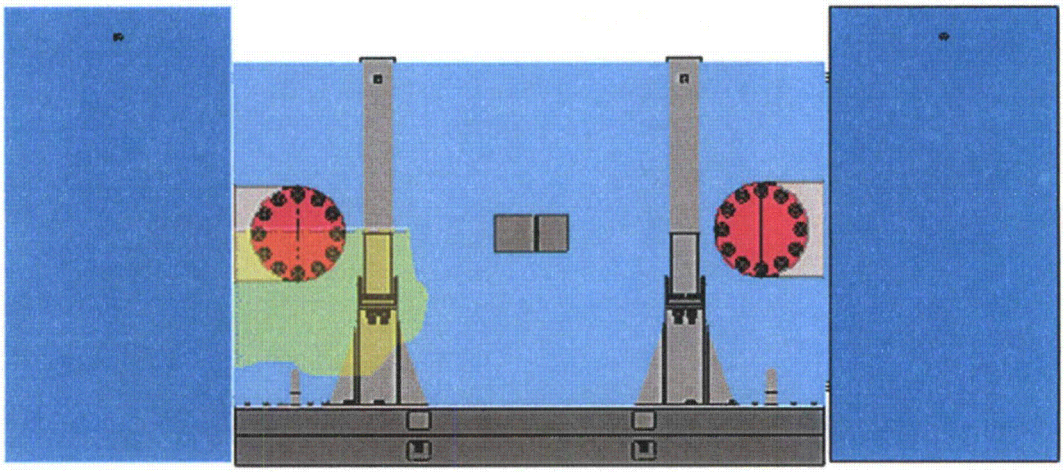
Non-Proprietary

NUHOMS®-MP197
MULTI-PURPOSE
CASK



TRANSPORT
PACKAGING

SAFETY ANALYSIS REPORT
NUH09.0101
Volume 3 of 4

Chapter A.2
MP197HB Structural Evaluation

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Chapter A.2
MP197HB Structural Evaluation

NOTE: References in this Chapter are shown as [1], [2], etc. and refer to the reference list in Section A.2.12.

A.2.1 Structural Design

This chapter, including its appendices, contains the structural evaluation of the NUHOMS®-MP197HB packaging. This evaluation consists of numerical analyses and impact limiter testing which demonstrate that the NUHOMS®-MP197HB packaging satisfies applicable 10CFR71 [1] requirements for a Type B(U) packaging.

A.2.1.1 Discussion

The structural integrity of the packaging under normal conditions of transport (NCT) and hypothetical accident conditions (HAC) specified in 10CFR71 is shown to meet the design criteria described in Section A.2.1.2. The NUHOMS®-MP197HB transport package consists of three major structural components: the cask body, one of several transportable dry shielded canisters (DSCs) or a radioactive waste container (RWC), and the impact limiters (front and rear). Each DSC consists of a shell assembly and a basket assembly. These components are described in Chapter A.1 and are shown on drawings provided in Appendix A.1.4.10.

The cask body and a DSC or RWC, together with the two impact limiters, form the packaging designed to meet all of the applicable 10CFR71 requirements for a Type B(U) packaging.

The cask body wall thickness (excluding the shield shell and neutron shield) enables the packaging to withstand the HAC puncture event. The shell is designed to be both strong and ductile. The front and rear impact limiters absorb the kinetic energy from the 1 ft NCT and 30 ft HAC free drops.

Numerical analyses have been performed for the NCT and HAC, as well as for the lifting and tie-down loads. In general, numerical analyses have been performed for the regulatory events. These analyses of the NUHOMS®-MP197HB packaging are summarized in the main body of this section and are described in detail in the following appendices:

Appendix A.2.13.1	NUHOMS®-MP197HB Cask Body Structural Analysis
Appendix A.2.13.2	NUHOMS®-MP197HB Cask Lid Bolt/Ram Access Closure Plate Bolt Analyses
Appendix A.2.13.3	NUHOMS®-MP197HB Cask Lead Slump and Containment Boundary Buckling Analysis
Appendix A.2.13.4	NUHOMS®-MP197HB Structural Analysis of the Shield Shell
Appendix A.2.13.5	NUHOMS®-MP197HB Cask Lifting and Tie-Down Devices Structural Evaluation

Appendix A.2.13.6 NUHOMS®-MP197HB Cask Containment Boundary Fatigue Evaluation

Appendix A.2.13.7 NUHOMS®-MP197HB DSC (Shell Assembly) Structural Evaluation

Appendix A.2.13.8 NUHOMS®-MP197HB DSC (Basket) Structural Evaluation

Appendix A.2.13.9 NUHOMS®-MP197HB Dynamic Load Factor Determination

Appendix A.2.13.10 NUHOMS®-MP197HB Transport Package Thermal Expansion Evaluation

Appendix A.2.13.11 NUHOMS®-MP197HB Evaluation of Fuel Assembly under Accident Impact Loads

Appendix A.2.13.12 NUHOMS®-MP197HB Package Impact Analysis using LS-DYNA

Appendix A.2.13.13 NUHOMS®-MP197HB ASME Code Alternatives

Appendix A.2.13.14 MP197HB Lid Closure Evaluation Due to Delayed Impact

A.2.1.1.1 Transportation Package (Cask)

Drawing MP197HB-71-1001 shows the overall transport configuration of the NUHOMS®-MP197HB packaging. Drawings MP197HB-71-1002 and 1003 show the parts list and the general arrangement, respectively, of the NUHOMS®-MP197HB packaging. Drawing MP197HB-71-1004 shows the cask body assembly. Drawings MP197HB-71-1005 and -1006 show the cask body and lid assembly and details. Drawing MP197HB-71-1007 presents the regulatory plate. Drawings MP197HB-71-1008 and -1009 provide the assembly and details of the impact limiter. The optional external fin and internal sleeve are shown on drawings MP197HB-71-1011 and -1014. ASME Code compliance and alternatives are provided in Section A.2.1.4 and Appendix A.2.13.13.

The shell or cask body cylinder assembly is an open ended (at the top) cylindrical unit with an integral closed bottom end. This assembly consists of concentric inner and outer shells, both SA-203 Gr E, welded to a massive closure flange (SA-350 LF3) at the lid end and a flat steel plate (SA-350 LF3) at the bottom end. The closure lid material is SA-350 LF3 or SA-203 Gr E. The annulus between the shells is filled with lead in order to meet specified shielding requirements. Molten lead is poured into the annulus using a carefully controlled procedure.

The front and rear double shoulder trunnions are cylindrical, SA-182 F316N ferritic stainless steel forgings. The rear pair of trunnions is designed for horizontal lifting of the cask and also supports the rear of the cask during rotation of the cask. A set of single shoulder front trunnions is also included in the design. These trunnions are also constructed of SA-182 F316N ferritic stainless steel forgings. The double shoulder front trunnions have a minimum factor of safety of three against yield stress or five against ultimate stress; whichever is most restrictive. The single shoulder set of front trunnions is used for lifting when single failure proof lifting system is required. That is, the single shoulder front trunnions have a minimum factor of safety of six against yield stress or ten against ultimate stress, whichever is most restrictive. Only one set of trunnions will be used depending on site and transfer operation requirements. Both the front and rear trunnions are bolted to the cask body through a flange connection, using 12-1¼ in. diameter

bolts made of SA-540 Gr B23 Cl.1 steel. The front trunnions are designed to meet the requirements of ANSI N14.6 [2]. The trunnions are shown in Drawing MP-197HB -71-1005.

The shield shell around the neutron shield consists of a cylindrical shell with end caps at each end. The end caps are welded to the outer surface of the cask body outer shell. The shield shell and end caps provide a sealed enclosure for the resin-filled aluminum boxes, and retain the resin in the proper location with respect to the fuel assemblies transported in the cask cavity. The shell and end caps are made of SA-516 Gr 70 alloy steel.

A.2.1.1.2 Impact Limiters

The NUHOMS®-MP197HB packaging includes an impact limiter at each end of the cask body. The limiters are identical, consisting of a stainless steel shell that contains balsa and redwood blocks. These blocks provide the energy absorbing capabilities of the limiters. The inside diameter of the limiter is determined by the outside diameter of the cask body. The length and outside diameter of the limiters are sized to limit the cask impact loads resulting from the 1 foot NCT and 30 foot HAC drop events so that the containment vessel (and the non-containment structures) meets the design criteria.

The impact limiter stainless steel cylinders, gussets, and end plates, are designed to position and confine the balsa and redwood blocks to minimize the impact forces and to prevent excessive deformation of the limiters. The stainless steel shell is also designed to support and isolate the wood blocks from ambient moisture and pressure during normal operation.

The impact limiter and attachments are designed to withstand the impact loads and to prevent separation of the limiters from the cask during an impact. The design of the impact limiters and attachments are specified in Appendix A.2.13.12.

A.2.1.1.3 Dry Shielded Canister Assemblies

The MP197HB will accommodate several different dry shielded canisters (DSCs) each containing a unique payload. The DSCs consist of an outer shell assembly that contains a basket which, in turn, supports the spent fuel assemblies. A detailed description of each DSC is provided in Chapter A.1, Appendices A.1.4.1 through A.1.4.9.

The details of each shell are shown on drawings provided in Appendix A.1.4.10. The shell assembly is a welded stainless steel pressure vessel that provides containment of radioactive material, maintains inert atmosphere inside the shell (the DSC is backfilled with helium before being seal welded closed) and provides biological shielding in the axial direction.

The details of the NUHOMS® Baskets are shown in drawings also contained in Appendix A.1.4.10. The basket (except for the 24PT4) is a welded assembly of stainless steel fuel compartments and is designed to accommodate various numbers of BWR fuel assemblies, with or without fuel channels, or PWR fuel assemblies, with or without control components. The basket structure consists of an assembly of stainless steel tubes (fuel compartments) separated by poison plates and surrounded by support rails, depending on the specific design. For the 24PT4 basket guidesleeves are provided by circular spacer disc plates. Axial support for the basket

assembly is provided by four support rods. The support rods extend over the full length of the cavity with allowance provided for thermal growth of the support rods in the axial direction.

The basket structure is open at each end. Therefore, longitudinal fuel assembly loads are applied directly to the DSC end plates and not to the fuel basket structure. The fuel assemblies are laterally supported in the fuel compartments, and the basket is laterally supported by the support rails and the DSC shell.

A.2.1.1.4 Radioactive Waste *Canister*

A radioactive waste *canister* (RWC) is also included as an authorized payload of the MP197HB cask. As described in Chapter A.1, *Appendix* A.1.*4.9A*, the RWC is bounded by the DSCs in terms of weight and decay heat. Also, the RWC does not provide containment for its contents. Therefore, the analyses provided in this Chapter for the DSCs are considered bounding for the RWC and no analyses for the RWC are necessary.

A.2.1.2 Design Criteria

The packaging consists of the following major components:

- Cask Body
- Impact Limiters
- Payload (DSC or RWC)

The structural design criteria for these components are described below.

A.2.1.2.1 Basic Design Criteria

Cask Containment Vessel

The containment vessel consists of the inner shell including the flange inside of the lid inner O-ring, the bottom, ram access closure plate, and the lid. The lid and ram access closure plate bolts and seals are also part of the containment vessel as are the drain and vent port plug bolts and seals. The containment vessel is designed to the maximum practical extent as an ASME Class I component in accordance with the rules of the ASME Boiler and Pressure Vessel Code, Section III, Subsection NB [3]. The Subsection NB rules for materials, design, fabrication and examination are applied to all of the above components to the maximum practical extent. In addition, the design meets the requirements of Regulatory Guides 7.6 [5] and 7.8 [6]. Alternatives to the ASME Code are discussed in Section A.2.1.4 and Appendix A.2.13.13 of this Chapter.

The acceptability of the containment vessel under the applied loads is based on the following criteria:

- Title 10, Chapter 1, Code of Federal Regulations, Part 71
- Regulatory Guide 7.6 Design Criteria
- ASME Code Design Stress Intensities
- Preclusion of Fatigue Failure
- Preclusion of Brittle Fracture

The stresses due to each load are categorized as to the type of stress induced, such as membrane or bending, and the classification of stress, such as primary or secondary. Stress limits for containment vessel components, other than bolts, for NCT (ASME Level A) and HAC (ASME Level D) are given in Table A.2-1.

The primary membrane stress and primary membrane plus bending stress are limited to S_m (S_m is the code allowable stress intensity) and 1.5 S_m, respectively, at any location in the cask for NCT (ASME Level A).

The HAC events are evaluated as short duration, Level D conditions. The stress criteria are taken from Section III, Appendix F of ASME Code [3]. For elastic quasi-static analysis, the primary membrane stress intensity (P_m) is limited to the smaller of the 2.4 S_m or 0.7 S_u, and membrane plus bending stress intensities ($P_m + P_b$) are limited to the smaller of the 3.6 S_m or S_u. For the elastic-plastic analysis, the primary membrane stress intensity (P_m) is limited to 0.7 S_u, and membrane plus bending stress intensities ($P_m + P_b$) are limited to 0.9 S_u.

The allowable stress limits for the containment bolts are listed in Table A.2-2.

The allowable stress intensity value, S_m, as defined by the Code, is taken at the maximum temperature calculated for each service load condition.

Cask Non-Containment Structure

Certain components such as the outer shell, the shield shell and the trunnions are not part of the cask containment vessel but do have structural functions. These components, referred to as non-containment structures, are required to withstand the containment environmental loads, and in some cases share the loads with the containment vessel. The outer shell stress limits are the same as those given in Table A.2-1 for the containment structure. The neutron shield shell is designed, fabricated and inspected in accordance with the ASME Code Subsection NF [3], to the maximum practical extent. Structural and structural attachment welds are examined by the *PT or MT* method, in accordance with Section V, Article 6 of the ASME Code [8]. The *PT or MT* examination acceptance standards are in accordance with Section III, Subsection NF, Paragraph NF-5350 *or NF-5340* [3].

Seal welds are examined visually, or by *PT or MT* method, in accordance with Section V of the ASME Code [8]. Electrodes, wire, and fluxes used for fabrication comply with the applicable requirements of the ASME Code, Section II, Part C [9].

The welding procedures, welders and weld operators are qualified in accordance with Section IX of the ASME Code [10].

The radial neutron shield, including the *carbon* steel enclosure, has not been designed to withstand all of the HAC loads. The shielding may degrade during the fire or due to the 40 inch drop onto the puncture bar. Therefore a bounding shielding analysis, assuming that up to 75% of the exterior neutron shielding is removed, has been performed. This analysis shows that the accident dose rates are not exceeded. These accident shielding analyses are described in Chapter A.5.

Dry Shielded Canister (DSC)

The NUHOMS® MP197HB is designed to carry several different DSCs. Some of these are currently licensed under 10CFR72 for storage of spent nuclear fuel. A table of DSCs with the licensing information is provided below.

DSC Design	Applicable Storage License CoC	ASME B&PV Code Year
NUHOMS® 32PTH	1030	1998 w/ 2000 Addenda
NUHOMS® 32PTH1	1004	1998 w/ 2000 Addenda
NUHOMS® 37PTH	Note (1)	2004 w/2006 Addenda
NUHOMS® 69BTH	Note (1)	2004 w/2006 Addenda
NUHOMS® 24PT4	1029	1992 thru1994 Addenda
NUHOMS® 24PTH	1004	1998 w/ 2000 Addenda
NUHOMS® 32PT	1004	1998 w/ 2000 Addenda
NUHOMS® 61BT	1004	1998 w/ 1999 Addenda
NUHOMS® 61BTH	1004	1998 w/ 2000 Addenda
NUHOMS® 61BTH *with failed fuel, (61BTHF)*	Note (1)	2004 w/2006 Addenda
NUHOMS® 24PTH *with failed fuel, (24PTHF)*	Note (1)	2004 w/2006 Addenda

Note: (1) These DSCs are currently not a part of CoC 1004 but will be added at a later date via amendment.

DSC Shell Assembly

The components of each DSC including the shell assembly, the top outer/inner cover plates, the inner bottom cover plate, the siphon vent block, and the siphon/vent port cover plate are designed, fabricated and inspected in accordance with the ASME Code Subsection NB to the maximum practical extent (Code alternatives are given in Section A.2.1.4 and Appendix A.2.13.13 below). Note that the applicable Code year varies depending on the storage license of the specific DSC. The basis for the allowable stresses is Article NB-3200 for NCT (Level A) loads, and Appendix F for HAC (Level D) loads. Stress limits for NCT (Level A) and HAC (Level D) are given in Table A.2-1. When evaluating the results from the non-linear elastic-plastic analysis for the accident conditions, the general primary membrane stress intensity, P_m, shall not exceed 0.7 S_u and the maximum stress intensity at any location ($P_m + P_b$) shall not exceed 0.9 S_u.

DSC Basket

The baskets for all of the DSCs are designed, fabricated and inspected in accordance with the ASME Code Subsection NG to the maximum practical extent with the applicable Code year again depending on the storage license of the applicable DSC. (Code alternatives are given in Section A.2.1.4 and Appendix A.2.13.13 below).

The basket is designed to meet the heat transfer, nuclear criticality, and the structural requirements. The basket structure must provide sufficient rigidity to maintain a subcritical configuration under all applied loads. The 304 stainless steel members in DSC baskets are the primary structural components. The neutron poison plates are the primary heat conductors, and provide the necessary criticality control.

The stress analyses of the basket for normal and accident conditions do not take credit for the aluminum and poison plates except for through-thickness-compression. Therefore, the materials are not required to be code materials. The quality assurance requirements of NQA-1 are imposed in lieu of NCA-3800. The basket is not code stamped. Therefore the requirements of NCA are not imposed. Fabrication and inspection surveillance is performed by the design organization in lieu of an authorized nuclear inspector.

The stress limits for the basket are summarized in Table A.2-3. The basis for the allowable stresses for the 304 stainless steel fuel compartments and rails is Section III, Division I, Subsection NG of the ASME Code [3]. The primary membrane stress and primary membrane plus bending stress are limited to S_m (S_m is the code allowable stress intensity) and 1.5 S_m, respectively, at any location in the basket for normal (Design and Level A) load conditions.

The HAC events are evaluated as short duration, Level D conditions. The stress criteria are taken from Section III, Appendix F of the ASME Code for the applicable year as discussed above. For elastic quasi-static analysis, the primary membrane stress intensity (P_m) is limited to the smaller of 2.4 S_m or 0.7 S_u, and membrane plus bending stress intensities ($P_m + P_b$) are limited to smaller of 3.6 S_m or S_u. When evaluating the results from the non-linear elastic-plastic analysis for the accident conditions, the general primary membrane stress intensity, P_m shall not exceed 0.7 S_u and the maximum stress intensity at any location ($P_m + P_b$) shall not exceed 0.9 S_u.

The fuel compartment response to compressive loads is also evaluated to ensure that buckling will not occur. Basket assembly allowable buckling loads are evaluated based on non-linear, large displacement quasi-static analysis models using ANSYS and LS-DYNA.

The basket hold down ring is set between the top of the basket assembly and inside surface of the lid assembly in some of the BWR fuel DSCs. The hold down ring is used to prevent the basket assembly from sliding freely in the axial direction during the NCT or HAC. The basket hold down ring is designed, fabricated, and inspected in accordance with the applicable year of ASME Code Subsection NF to the maximum practical extent.

Impact Limiters

The NUHOMS®-MP197HB packaging is provided with an impact limiter at each end of the cask body. The limiters are identical. The impact limiter stainless steel cylinders, gussets, and end plates, are designed to position and confine the balsa and redwood blocks so that the impact energy is properly absorbed. The stainless steel shell is also designed to support and protect the wood blocks under normal environmental conditions (moisture, pressure, temperature, etc.).

The impact limiter and attachments are designed to withstand the applied loads and to prevent separation of the limiters from the cask during an impact. The design of the impact limiters and attachments are specified in Appendix A.2.13.12.

Trunnions

NUHOMS®-MP197HB cask includes removable front and rear trunnions, as shown in drawing MP197HB-71-1005, which are used for on-site lifting and transfer operations. The trunnions are removed prior to transportation and replaced with non-protruding plugs to provide the largest possible stopping distance and thus minimize the package impact loads resulting from the HAC drop events.

The evaluation and design criteria for the lifting/tie-down trunnions are based on the requirements of 10CFR71.45. The details of the evaluation are presented in Section A.2.5. Two sets of front trunnions are designed. One set of trunnion has double shoulders and is used for lifting. The double shoulder front trunnions have a minimum factor of safety of three against yield stress or five against ultimate stress; whichever is most restrictive. The other set of trunnions has a single shoulder and is also used for lifting. The single shoulder front trunnions have a minimum factor of safety of six against yield or ten against ultimate; whichever is most restrictive. Only one set of trunnions will be used depending on-site and transfer operation requirements. The design and fabrication of the lifting trunnions are in accordance with the requirements of ANSI N14.6 [2].

Tie Down Devices

NUHOMS®-MP197HB cask includes a bearing block, located at the mid-length, on the bottom of the cask, designed to react all longitudinal loads encountered during transportation. As shown in drawing MP197HB-71-1001, the package is supported by saddles and tie-down straps. The saddles and tie-down straps are designed to support the vertical, lateral, and rotational loads encountered during transport, while the bearing block resists the cask longitudinal transportation loads. The details of the tie-down evaluation are presented in Section A.2.5.

A.2.1.3 Weights and Centers of Gravity

The maximum weight of the NUHOMS®-MP197HB package is 303,600 lb (approximately 152 ton). The weights of the major individual subassemblies are listed in following table. The center of gravity of the cask is located on the axial centerline between 103.5 inches and 105.75 inches from the base of the cask, depending on the DSC. Note that the DSC weight is a bounding weight encompassing all of the DSCs included in this application.

Cask Bounding Weights

Component	**Nominal Weight (lb. x 1000)**
Cask Empty Weight w/o Lid or Impact Limiters and Attachments	157.5
Cask Lid	6.0
Outer Sleeve with Fins	3.1
Impact Limiters w/Attachment bolts and Thermal Shield	25.0
Maximum Loaded DSC	112.0
Total Package Weight (Loaded)	**303.6 (~152 ton)**

A.2.1.4 Identification of Codes and Standards for Package Design

The cask containment boundary and the shell, top outer/inner plates, inner bottom cover plate, siphon vent block, and siphon/vent port cover plate of the DSC are designed, fabricated and inspected in accordance with the ASME Code Subsection NB to the maximum practical extent. The basket is designed, fabricated and inspected in accordance with ASME Code Subsection NG to the maximum practical extent. Other cask components (such as the shield shell and neutron shielding) and DSC components (such as outer bottom cover, top and bottom shield plugs) are not governed by the ASME Code. The ASME code alternatives for cask, canister, and basket are specified in Appendix A.2.13.13.

A.2.2 Materials

A.2.2.1 Material Properties and Specifications

A.2.2.1.1 Cask Material Properties

This section provides the mechanical properties of materials used in the structural evaluation of the NUHOMS®-MP197HB cask. Table A.2-4 lists the materials selected, the applicable components, and the minimum yield, ultimate, and design stress values specified by the ASME Code, Section II, Part D [9]. *Mechanical properties of lead used for gamma shielding are listed in Table A.2-5.*

A.2.2.1.2 DSC Material Properties

The material properties of the stainless steel used in the DSCs are taken from the ASME Code. However, the various DSC designs have been designed and fabricated to several different ASME code year editions. The specific DSCs and applicable ASME code year are given in Section A.2.1.2. The material properties are listed with specific references in Appendices A.2.13.7 and A.2.13.8.

A.2.2.1.3 Impact Limiter Material Properties

Mechanical properties of the energy absorbing wood used in the impact limiters are specified in Appendix A.2.13.12.

A.2.2.2 Chemical, Galvanic, or Other Reactions

The materials of the NUHOMS®-MP197HB cask have been reviewed to determine whether chemical, galvanic or other reactions among the materials, contents and environment might occur during any phase of loading, unloading, handling or transport.

- The materials from which NUHOMS®-MP197HB transportation packaging is fabricated will not experience significant chemical, galvanic, or other reactions in air, helium, or water environments. The exterior of the cask is carbon steel that with the exception of the trunnion bearing surfaces and surfaces contact to the impact limiters is painted using an epoxy, acrylic urethane, or equivalent enamel coating. The paint is selected to be

compatible with the pool water and easy to decontaminate. The interior of the cask and the sealing surfaces are overlayed with stainless steel.

- During wet loading, the DSC and the cask are submerged in BWR deionized pool water or PWR borated water. The discussion that follows will demonstrate that no significant corrosion or hydrogen generation will occur in this environment for the wetted materials.

- During transportation, the exterior of the cask and impact limiters is exposed to a variety of environmental conditions. Exterior surfaces of the cask as noted above are painted. The impact limiters are stainless steel. Therefore, the cask exterior is protected from chemical, galvanic or other reactions during transportation.

- During transportation, the interior of the DSC and the space between the DSC and the cask is filled with helium. The DSC is vacuum-dried; the space between the cask and the DSC is vacuum-dried if loaded wet. The inert environment precludes general or galvanic corrosion of the interior surfaces.

- Various materials are sealed under air at the fabricator, and remain sealed during all normal operations:

  a) Radial neutron shielding materials and the aluminum resin boxes are sealed between steel shells

  b) Lead shielding is sealed between steel shells

  c) Wood is sealed inside the stainless steel impact limiter shell

The free volume in these spaces is small. Consequently the amount of oxygen or moisture is insufficient to cause significant corrosion or galvanic reactions between these materials. The neutron shielding material is inert after it has cured and does not affect the aluminum boxes.

Dissimilar materials in contact in the NUHOMS®-MP197HB, and the material environments are summarized in the following table.

Component	Dissimilar Materials in Contact	Wet Loading Environment	Transport Environment
Basket	stainless steel/aluminum stainless steel/neutron absorber	pool water	vacuum dried, helium backfill
DSC	stainless steel/nickel-plated carbon steel top shield plug	pool water	vacuum dried, helium backfill
DSC	stainless steel/bare carbon steel bottom shield plug	air, sealed at fabricator	air, sealed at fabricator
Cask (interior)	stainless steel/lubricant (slide rails)	pool water	vacuum dried, helium backfill
Cask	lead/carbon steel aluminum/borated resin aluminum/carbon steel	air, sealed at fabricator	air, sealed at fabricator
Cask	alloy steel bolts/stainless steel	air, lubricant	air, lubricant
Cask	fluorocarbon seals/stainless steel	air, helium	air, helium, ambient weather
Cask	Stainless steel/brass (trunnion bolt plug)	pool water	not applicable
Cask	Stainless steel/lead (security wire and seal)	not applicable	ambient weather
Cask	carbon steel/polypropylene (trunnion plug)	not applicable	air
Cask	carbon steel/transport saddle(1)	not applicable	ambient weather
Impact limiter (IL)	304 stainless steel/nylon (fusible plug) 304 stainless steel/fluorocarbon (fusible plug seal) 304 stainless steel/alloy steel (lift ring bolt)	not applicable	ambient weather
Cask & IL	stainless steel/aluminum (thermal shield)	not applicable	air
IL	wood/ wood glue/304 stainless steel	not applicable	air, sealed at fabricator

Notes:

1. The transport saddle is not part of this SAR. Points of contact between cask and saddle may be stainless steel, painted carbon steel, or elastomer sheet.

The NUHOMS®-MP197HB cask and NUHOMS®- DSC materials are shown in the specific Parts Lists on the drawings provided in Chapter A.1, Appendix A.1.4.10.

The materials exposed to pool water during wet loading include the painted cask exterior, the stainless steel overlayed interior, stainless steel helical thread inserts in nickel-alloy steel, aluminum spacers, the stainless steel canister, stainless steel, aluminum, and aluminum-based neutron absorbers in the basket, and nickel-plated carbon steel shield plug.

Potential sources of chemical or reactions are galvanic interaction between stainless steel (300 series) and aluminum or between stainless steel and nickel-alloy steel, or non-galvanic corrosion of the cask and materials in water.

Aluminum and Stainless Steel

Both aluminum and stainless steel develop passive surface oxide layers that preclude any significant corrosion, galvanic or otherwise, except in aggressive or high-chloride environments. No damage to the aluminum or stainless steel will occur due to the low chloride content in spent fuel pool water, and the short duration of immersion. Stainless steels are widely used for long-term in immersion as wet racks in both borated and non-borated spent fuel pools, and aluminum is widely used in the production of borax and boric acid.

Aluminum-Based Neutron Absorbers

Three neutron absorbers may be used: borated aluminum, aluminum/boron carbide metal matrix composites (MMC) and Boral, an aluminum / boron carbide cermet with aluminum clad faces.

Borated aluminum and MMCs have been tested and shown to behave similarly to aluminum 1100 during simulated short term spent fuel pool immersion. While formation of blisters in Boral during vacuum drying and heating has been reported, this has not been associated with displacement of the boron carbide, and therefore has no effect on the criticality safety function [11].

Nickel Plated Carbon Steel

The carbon steel top shield plug of the DSC is plated with nickel. This coating minimizes corrosion of the shield plug and also minimizes contact between the carbon steel and the stainless steel DSC shell. The shield plug is immersed for only a very short period of time, after the fuel is loaded, and immediately before lifting the cask and canister out of the pool.

Low-alloy (3.5% Ni) Steel

Low alloy steel in threaded holes may be exposed to pool water during loading. Corrosion rates of 1% nickel steel are slower than those for plain carbon steel, and comparable to those for copper-bearing weathering steels [12].

The difference in potential between the low alloy steel and the stainless steel helical inserts is insufficient for galvanic corrosion without the presence of chlorides to interrupt the passive surface of the stainless steel.

Therefore, no damage to the alloy steel or stainless steel inserts will occur due to the low chloride content in spent fuel pool water, and the short duration of immersion.

Cask Exterior

The exterior of the cask is made from stainless steel or painted carbon steel and will not cause significant chemical, galvanic or other reactions in air or water environments.

Potential galvanic couples are:

- The brass trunnion bolt seal caps and the stainless trunnions during wet loading. The bolt covers are not important to safety components.
- The thermal shield and impact limiter shell. The aluminum is not directly exposed to the weather, road salt, etc., because it is covered by the impact limiter. The thermal shield is not an important to safety component.
- The low alloy steel bolts and stainless steel. The lid, test, and ram access cover bolts are not directly exposed to the weather, road salt, etc, because they are covered by the impact limiters. The impact limiter hoist ring replacement bolts and the trunnion plug bolts will be exposed.

In all these cases, minor sacrificial galvanic corrosion of these anodic (non-stainless) components will have no adverse affect on an important to safety function.

Lubricants and Cleaning Agents

A lubricant may be used to coat the threads and shoulders of the bolts and the slide rails and the contact areas of the trunnions during lifting operations. Lubricants are generally selected from the list of materials approved for contact with the pool water at the facility where wet loading occurs. Cask and DSC components are cleaned to remove all temporary markings, expendable materials, etc., during fabrication, using approved procedures. After loading, exterior surfaces of the cask will be decontaminated using procedures and decontamination agents approved at the loading facility. The cleaning agents and lubricants have no significant effect on the cask materials.

Hydrogen Generation

The NUHOMS® DSCs are wet-loaded, either in the MP-197HB transport cask, or in a transfer cask. In the latter case, the sealed DSC may, at a later date, be dry-loaded into the MP-197HB directly from the horizontal storage module or other compatible overpack. In either event, there is no mechanism for galvanic corrosion in the annulus between the DSC and the MP-197HB, because both the inner shell of the MP-197HB is coated and the outer shell of the DSC is stainless steel, and because the DSC is sealed before the lid is placed on the MP-197HB. Therefore, the following discussion applies entirely to the potential for the generation of hydrogen inside the DSC during wet loading.

Hydrogen gas will be generated in the DSC due to reaction between the water and aluminum, and due to radiolysis of the water. The resulting concentration of hydrogen depends on the surface condition of the aluminum, the free volume in the canister (how much water has been drained), and the water chemistry. The lower flammability limit for a hydrogen / air mixture is 4%. Loading operations require that the hydrogen in the space immediately below the shield plug is monitored continuously before and during welding. If the hydrogen concentration exceeds 2.4%, welding operations are suspended and the DSC purged with an inert gas.

Effect of Chemical and Galvanic Reactions

There are no significant reactions that could reduce the overall integrity of the cask or its contents during transportation. The cask and fuel cladding thermal properties are provided in Chapter A.3. The emissivity of the fuel compartment is 0.3, which is typical for non-polished stainless steel surfaces. If the stainless steel is oxidized, this value would increase, improving heat transfer. The fuel rod emissivity value used is 0.8, which is a typical value for oxidized Zircaloy. Therefore, the passivation reactions would not reduce the thermal properties of the component cask materials or the fuel cladding.

There are no reactions that would cause binding of the mechanical surfaces or the fuel to basket compartment boxes due to galvanic or chemical reactions.

There is no significant degradation of any important-to-safety components caused directly by the effects of the reactions or by the effects of the reactions combined with the effects of exposure of the materials to neutron or gamma radiation, high temperatures, or other possible conditions.

A.2.2.3 Effects of Radiation on Materials

Gamma radiation has no significant effect on metals. The effect of fast neutron irradiation of metals is a function of the integrated fast neutron flux. Studies on fast neutron damage in aluminum, stainless steel, and low alloy steels rarely evaluate damage below 10^{17} n/cm^2 because it is not significant. Extrapolation of the data available down to the 10^{14} range confirms that there will be virtually no neutron damage to any of the cask or DSC metallic components.

The neutron absorbers consist of aluminum with boron added in the inert form of boron carbide, aluminum diboride, or titanium diboride. The durability of these materials in the radiation environment is similar to that of aluminum.

Radiation levels and temperature on the cask exterior are not high enough to damage the paint. This is confirmed by dry cask experience. Paint is subject to routine maintenance and touch-up.

Seals

To evaluate irradiation damage to the seals, note that the energy absorption of polymers and tissue is similar. Therefore, the gamma radiation energy absorbed by the seals may be approximated as the rad equivalent of the surface dose in rem. The absorbed neutron energy may be estimated as half the neutron dose rate to account for the tissue quality factor. From Chapter A.5, the maximum dose rate at the surface of the MP-197HB is approximately 59 mrem/hour gamma, and 151 neutron. This is less than 0.1 rad/hr absorbed dose rate in polymers. If we increase that by a factor of 100 to account for the fact that the seals are somewhat below the surface, at the end of one year of continuous exposure, this would result in absorbed energy in the seals of about 1×10^5 rad, well below the threshold of polymer damage, generally about than 10^6 rad.

Neutron Shielding

The radial neutron shield material is a proprietary resin (VYAL B). It has been developed and tested for applications such as the MP197HB packaging. The neutron and gamma doses expected for this application are below those that could degrade the effectiveness of the material.

A.2.3 Fabrication and Examination

A.2.3.1 Fabrication

Fabrication of the MP197HB and the DSCs is conducted per the requirements of the ASME Code to the maximum extent possible. See Sections A.2.1.2 and A.2.1.4 above for additional information.

A.2.3.2 Examination

Examination of the MP197HB and the DSCs during and after fabrication is conducted per the requirements of the ASME Code to the maximum extent possible. See Sections A.2.1.2 and A.2.1.4 above for additional information.

A.2.4 General Requirements for All Packages

The NUHOMS®-MP197HB transport package is designed to comply with the general standards for all packages specified by 10CFR71.43.

A.2.4.1 Minimum Package Size

The overall package dimensions of approximately 271 inches long and 126 inches in diameter exceed the minimum dimension requirement of 10 cm (4 inches).

A.2.4.2 Tamper-Indicating Feature

The primary access path into the package is through the closure lid. During transport the front (top) impact limiter entirely covers and prevents access to the cask closure lid. The vent port, test port, drain port and ram access closure plate are smaller access paths and are all covered by the impact limiters during transport. A security wire seal is installed in the front impact limiter above an attachment bolt prior to each shipment. The presence of this seal demonstrates that unauthorized entry into the package has not occurred.

A.2.4.3 Positive Closure

Positive fastening of all access openings through the containment vessel is accomplished by bolted closures which preclude unintentional opening. In addition, the presence of the impact limiters and security seal described in Section A.2.4.2 provide further protection against unintentional opening.

A.2.5 Lifting and Tie-down Standards for All Packages

A.2.5.1 Lifting Devices

The NUHOMS®-MP197HB cask includes removable front and rear trunnions, as shown on drawing MP197HB-71-1005, which are used for on-site lifting and transfer operations. The detailed structural evaluations of the trunnions are contained in Appendix A.2.13.5. This section provides a summary of the structural analysis of the NUHOMS®-MP197HB cask trunnions.

10CFR71.45(a) requires that a minimum factor of safety of three against yield is required for all lifting attachments which are structural parts of the package. In addition, the package must be designed such that failure of any lifting device under excessive load would not impair the ability of the package to meet the other requirements of 10CFR71. Two sets of trunnions will be provided for the NUHOMS®-MP197HB transport package lifting. One set of trunnions has double shoulders (non single failure proof). The other set of trunnions has a single shoulder (single failure proof). Only one set of trunnions will be used depending on the site and transfer operation requirements.

Appendix A.2.13.1 provides the global stresses in the cask wall due to the lifting loads on the trunnions. The maximum global stress intensities in the containment vessel and outer shell are presented in Table A.2.13.1-7. The local stress intensities in the cask wall due to the 3G (double shoulder trunnion) and 6G (single shoulder trunnion) lifting load are presented below. The maximum 3G local stress intensity is 20.6 ksi (Table A.2.13.5-5). The maximum stress intensity due to the 6G lifting load is 26.0 ksi (Table A.2.13.5-7). These stresses are less than the yield stress of the outer shell material (35.4 ksi, SA-203 Gr. E at 300°F). Therefore the requirements of 10CFR71.45(a) are met. The stress analyses of the front trunnion and trunnion flange bolts are also provided in the following sections.

Stress at Trunnion/Cask Outer Shell Intersection

The local stresses induced in the outer shell cylinder by the trunnions are calculated using "Bijlaard's" method. The neutron shield and thin outer shell are not considered to strengthen either the trunnions or outer shell. The trunnion is approximated by an equivalent attachment so that the curves of the Reference WRC 107 [13] can be used to obtain the necessary coefficients. These resulting coefficients are inserted into blanks in the column entitled "Read Curves For," in a standard computation form. The stresses are calculated by performing the indicated multiplication in the column entitled "Compute Absolute Values of Stress and Enter Result". The detailed calculation is shown in Table A.2.13.5-5 and Table A.2.13.5-7 of Appendix A.2.13.5.

Trunnion Bolt Stresses

The trunnion flange is attached to the outer shell by twelve 1.25-7UNC bolts constructed from SA-540 Gr. B23 Cl. 1 material. The bolted flange is tightly fitted into the trunnion attachment block, which is welded to the cask outer shell. This trunnion block recess provides a bearing area between the outside perimeter of the trunnion flange and the block. The radial clearance between the bolt shank and trunnion flange bolt holes is large enough so that shear loads are carried by

the trunnion flange-to-block recess interface and not the bolts. The bolts develop only the tensile load due to trunnion moment and thermal loads. Stresses are summarized in the following table.

Summary of Lifting Stresses – Double Shoulder Trunnions (ksi)

	Calculated (3 g)	Allowable (S_y)	Margin	Calculated (5 g)	Allowable (S_u)	Margin
Stress intensity in section A-A	25.1	28.5	0.13	41.9	77.0	0.84
Stress intensity in section B-B	24.2		0.18	40.3		0.91
Stress intensity in section C-C	25.1		0.13	41.8		0.84
Bolt tensile stress	76.4	140.3	0.84	111.8	165.0	0.48
Stress intensity in trunnion flange	8.0	28.5	2.56	13.3	77.0	4.77
Weld bending stress	5.5	35.4	5.44	9.2	70.0	6.62
Outer cask shell stress	20.6	35.4	0.72	34.3	70.0	1.04

Note: See Figure A.2.13.5-2 of Appendix A.2.13.5 for locations of Sections A-A, B-B, and C-C

Summary of Lifting Stresses – Single Shoulder Trunnions (ksi)

	Calculated (6 g)	Allowable (S_y)	Margin	Calculated (10 g)	Allowable (S_u)	Margin
Stress intensity in section A-A	25.4	28.5	0.12	42.3	77.0	0.82
Bolt tensile stress	78.0	140.3	0.8	118.0	165.0	0.40
Stress intensity in trunnion flange	8.2	28.5	2.48	13.7	77.0	4.62
Weld bending stress	6.9	35.4	4.13	11.5	70.0	5.09
Outer cask shell stress	26.0	35.4	0.36	43.3	70.0	0.62

Note: See Figure A.2.13.5-5 of Appendix A.2.13.5 for locations of Sections A-A, B-B, and C-C

Trunnion Stress Results

Based on the above calculations, the design meets the requirements of 10CFR71, including the requirement that failure of the trunnion due to excessive load would not impair the packaging. Since the minimum margin of safety occurs at the trunnion shoulder instead at the junction of the trunnion and cask outer shell (0.13 vs. 0.72 for double shoulder trunnion and 0.12 vs. 0.36 for single shoulder trunnions), an excessive load would damage the trunnions, but the cask would maintain its structural integrity.

A.2.5.2 Tie-Down Devices

10CFR71.45 (b) (1) requires that a system of tie–down devices that is a structural part of the package 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 horizontal component along the direction in which the vehicle travels of 10 times the weight of the package with its contents.

The NUHOMS®-MP197HB package is secured during transport to the transportation skid. A shear key extending from the transport skid into a pocket in the cask is designed to transfer the longitudinal cask transport loads to the skid. The vertical and transverse cask transport loads are reacted by saddles and tie-down straps. Detailed tie-down analyses are described in Appendix

A.2.13.5. The results of the analysis are provided in the table below. The bending stress in the pad plate remains well below the allowable value. The shear load is transmitted from the bearing block to the cask structural shell through the pad plate.

Based on the above calculations, the minimum margin of safety occurs in the base metal junction between the pad plate and the cask outer shell. Therefore, under excessive load, the weld between the shear key pad plate and the cask structural shell would fail in shear, leaving the cask body intact without impairing the ability of the package to meet the other requirements of 10CFR71.

Summary of Longitudinal Stresses – Shear Key Assembly (ksi)

Stress Type and Location		**Calculated (10 g)**	**Allowable (S_y or $0.6\times S_y$)**	**Margin**
Bearing block	Bearing stress	31.2	84.6	1.71
	Bending stress	10.7	84.6	6.91
	Shear stress	18.1	50.8	1.81
	Maximum stress intensity	37.8	84.6	1.24
	Bending stress in the weld with pad plate	13.0	84.6	5.51
Weld between pad plate and cask shell	Shear stress in base metal	15.0	21.2	0.41

A.2.6 Normal Conditions of Transport

Overview

This section describes the response of the NUHOMS®-MP197HB package to the loading conditions specified by 10CFR71.71. The design criteria established for the NUHOMS®-MP197HB for the normal conditions of transport (NCT) are described in Section A.2.1.2. These criteria are selected to ensure that the package performance standards specified by 10CFR71.43 and 71.51 are satisfied. Under NCT there will be no loss or dispersal of radioactive contents, no significant increase in external radiation levels, and no substantial reduction in the effectiveness of the packaging.

Detailed structural analyses of various NUHOMS®-MP197HB packaging components subjected to individual loads are provided in the Appendices to this chapter. The limiting results from these analyses are used in this section to quantify package performance in response to the NCT load combinations, specified in 10CFR71.71 and Regulatory Guide 7.8. Table A.2-6 provides an overview of the performance evaluations reported in each load combination subsection. Each subsection provides the limiting structural analysis result for the affected cask component(s) in comparison to the established design criteria. This comparison permits the minimum margin of safety for a given component subjected to a given loading condition to be readily identified. In all cases, the acceptability of the NUHOMS®-MP197HB packaging design with respect to established criteria, and consequently with respect to 10CFR71 performance standards is demonstrated.

The structural analysis of the cask body is presented in Appendix A.2.13.1 and covers a wide range of individual loading conditions. The stress results from the various individual loads must be combined in order to represent the stress condition in the cask body under the specified condition evaluated in this section. An explanation of the reporting format used for the results, and the stress combination technique used in applying the results from Appendix A.2.13.1 is provided here.

Reporting Method for Cask Body Stresses

Appendix A.2.13.1 provides the detailed description of the structural analyses of the NUHOMS®-MP197HB cask body. That appendix describes the detailed ANSYS [7] model used to analyze various applied loads. Table A.2-7 identifies the individual loads analyzed which are applicable to NCT. Some of these individual loads are axisymmetric (e.g., pressure) and others are asymmetric (e.g., gravity). Due to the nonlinearities associated with contact elements, it is not possible to run the separate individual load cases and then combine the results by superposition. Rather, it is necessary to run each of the individual load cases or combined load cases independently and post-process the results separately. Table A.2-8 identifies the combined load cases for the normal condition of transport. A total of 26 separate loading conditions (individual and combined load cases) are evaluated. Refer to Section A.2.13.1.10 of Appendix A.2.13.1 for the method of obtaining the stress results from the ANSYS runs and Section A.2.13.1.7 for detailed descriptions of how the loads were combined and reported.

A. Individual load conditions: cases 1-12, see Table A.2-7. The stress results are presented in Table A.2.13.1-1 to A.2.13.1-17. Some of the stress results from these runs are used for fatigue analysis.

B. Load combinations for NCT: cases 13-26, see Table A.2-8. The stress results are presented in Table A.2.13.1-18 to A.2.13.1-31.

For the increased external pressure load combination, it is assumed that the NUHOMS®-MP197HB cask cavity is at 0 psia. Since the specified load combination condition is 20 psia, the net differential pressure acting on the cask body is 20 psi. However, for conservatism, a 25 psi external pressure is used for the load combinations.

A.2.6.1 Heat

Chapter A.3 describes the thermal analyses performed for the NUHOMS®-MP197HB package subjected to hot environment conditions. These thermal analysis results are used to support various aspects of the structural evaluations as described in the following subsections.

A.2.6.1.1 Summary of Temperatures and Pressures

Allowable stresses for packaging components are a function of the component temperatures. They are based on calculated maximum temperatures or conservatively selected higher temperatures. Table A.3.1-8 and Table A.3.1-9 of Chapter A.3 summarizes significant temperatures calculated for the NUHOMS®-MP197HB subjected to hot environment conditions. These temperatures are used to establish the allowable stress values for every NCT evaluated in this Safety Analysis Report.

The thermal analysis presented in Chapter A.3 also provides the average cavity gas temperature under hot environment conditions. This value is used to determine the Maximum Normal Operating Pressure (MNOP). The resulting calculated cask MNOP is 12.7 psig. For the purpose of the structural analysis of containment a value of 30 psig is conservatively assumed. Because of the thick walled construction of the NUHOMS®-MP197HB containment vessel, this pressure loading provides a minimal contribution to calculated stress intensities. This pressure loading is analyzed using ANSYS as described in Appendix A.2.13.1. The results using the 3D ANSYS model are reported in Tables A.2.13.1-2 of Appendix A.2.13.1.

A.2.6.1.2 Differential Thermal Expansion

The thermal expansion evaluations of the MP197HB cask cavity and DSCs in both the radial and the axial directions are described in Appendix A.2.13.10. Based on the results of these analyses, there is adequate clearance between the various components of the DSC and cask to allow free thermal expansion. Consequently, no significant stress will develop in the NUHOMS®-MP197HB transport cask due to thermal expansion. The following table summarizes the thermal expansion calculation results from the above analyses.

Thermal Expansion of MP197HB Cask Cavity vs. DSCs

DSC	Sleeve	Spacer	Hot Diametrical Gap	Hot Axial Gap
			in	in
69BTH	No	Yes	0.64	0.74
37PTH-S			0.66	0.77
37PTH-M				0.77
32PTH			0.66	0.76
32PTH, Type 1			0.66	0.76
32PTH1, Type 1 (32PTH1-L)		No	0.66	0.51
32PTH1, Type 1 (32PTH1-S)		Yes		0.76
32PTH1, Type 2 (32PTH1-L)		No	0.66	0.52
32PTH1, Type 2 (32PTH1-S)		Yes		0.77
61BTH, Type 1	Yes	Yes	0.78	0.79
61BTH, Type 2			0.78	0.79
61BT			0.77	0.83
32PT S-125			0.83	0.76
32PT L-125				0.75
24PTH			0.83	0.62
24PT4			0.83	0.51

A.2.6.1.3 Stress Calculations

The thermal analysis of the NUHOMS®-MP197HB Packaging, described in Chapter A.3, is performed using a 3D ANSYS model. The temperature distribution from this analysis is used to perform an ANSYS structural thermal stress analysis of containment vessel with details given in Appendix A.2.13.1.

Containment vessel stresses for the hot environment NCT are obtained from a combined load case (Load Case 13) as indicated in Table A.2-8. For this condition it is assumed that the cask is in its NCT configuration, mounted horizontally on the transport skid, and supported by the saddles and tie down straps. The combined loads included in the run are as follows:

- bolt preload
- gravity (1G down)
- 30 psig internal pressure
- thermal hot

A.2.6.1.4 Comparison with Allowable Stresses

The NUHOMS®-MP197HB cask stress results for the Load Case 13 are reported in Table A.2.13.1-18 of Appendix A.2.13.1. As shown in the table, all the calculated stress values are well below the code allowables.

A.2.6.2 Cold

The Regulatory Guide 7.8 [6] cold environment load combination requires all cask components to be in thermal equilibrium at -40°F. As with the hot environment, it is assumed that the cask is in its NCT configuration, mounted horizontally on the transport skid, and supported by the saddles and tie down straps. The combined loads included in this analysis are as follows:

- bolt preload
- gravity (1G Down)
- 25 psig external pressure
- -40°F thermal Uniform Temperature

The cold load case is evaluated in Appendix A.2.13.1. The stress results for this load case (Load Case 14) are reported in Table A.2.13.1-19 of Appendix A.2.13.1. As shown in the table, all the calculated stress values are well below the code allowables.

A.2.6.3 Reduced External Pressure

Containment vessel stresses for the 3.5 psia ambient NCT pressure are obtained from a combined load case (Load Case 16) as indicated in Table A.2-8. The conservatively assumed MNOP of 12.7 psig results in a net pressure loading of 23.9 psi (12.7 + 14.7 – 3.5) (cask stresses are conservatively calculated based on 30 psi pressure). For this condition it is assumed that the cask is in its normal transport configuration, mounted horizontally on the transport skid, and supported by the saddles and tie down straps. The combined loads included in the run are as follows:

- bolt preload
- gravity (1G down)
- 30 psig internal pressure
- thermal hot

The stress results for this load case (Load Case 16) are reported on Table 2.13.1-21 of Appendix A.2 .13.1. As shown in the table, all the calculated stress values are well below the code allowables.

A.2.6.4 Increased External Pressure

Containment vessel stresses for the NCT, 20 psia ambient are obtained from a combined load case (Load Case 15) as indicated in Table A.2-8. This load combination is similar to the cold environment load combination with the exception of the pressure loading. The conservatively assumed minimum cask cavity pressure of 0 psia results in a net external pressure loading of 20 psi (25 psi is conservatively used). For this condition, the cask is in the horizontal orientation mounted on the transport skid, and supported by the saddles and tie down straps. The combined loads included in the run are as follows:

- bolt preload
- gravity (1G down)
- 25 psig external pressure
- -20°F thermal cold

The stress results for this load case are provided in Appendix A.2.13.1, Table A.2.13.1-20. As shown in the table, all the calculated stress values are well below the code allowables.

A.2.6.5 Shock and Vibration

Shock

The transport rail shock loads used to evaluate the NUHOMS®-MP197HB cask are based on NUREG 766510 [15] which specifies a maximum inertia loading of 4.7G in each of the three x-y-z coordinate directions:

- Vertical 4.7G
- Longitudinal 4.7G
- Lateral 4.7G

The resultant transverse load is $(4.7^2 + 4.7^2)^{1/2} = 6.65$ G

The stresses due to the transport rail shock load case are obtained from combined load cases (Load Cases 19 and 20) as indicated in Table A.2-8. Table A.2.13.1-24 lists the combined stresses under hot thermal conditions where the load combination is performed for the maximum temperature thermal stresses. Lid bolt pre-load, internal pressure, and the thermal effects are included.

In addition, Table A.2.12.1-25 lists the combined stresses under –20°F thermal conditions where the load combination is performed for the –20°F thermal stresses (bounding values of –20°F and –40°F thermal stresses are used for the load combinations). Lid bolt pre-load and external pressure are also included.

As shown in these tables, all the calculated stress values are well below the code allowables.

The transport truck shock loading used to evaluate the NUHOMS®-MP197HB cask are based on truck bed accelerations in ANSI N14.23 [14] which are:

- Vertical 3.5G
- Longitudinal 2.3G
- Lateral 1.6G

The resultant transverse load is $(3.5^2 + 1.6^2)^{1/2} = 3.85$ G

The truck shock loadings are less than the rail car shock loadings; therefore, the rail car shock loadings are used for structural analysis of the cask body.

Vibration

The input loading conditions used to evaluate the NUHOMS®-MP197HB cask for transport rail vibration are obtained from NUREG 766510 [15]. The peak inertia values used are:

- Vertical 0.37G
- Longitudinal 0.19G
- Lateral 0.19G

The resultant transverse load is $(0.37^2 + 0.19^2)^{1/2} = 0.416$ G

The stresses due to the transport rail vibration load cases are obtained from combined load cases (Load Cases 17 and 18) as indicated in Table A.2-8. Table A.2.13.1-22 lists the combined stresses under hot thermal conditions where the load combination is performed for the maximum temperature thermal stresses. Lid bolt pre-load, internal pressure and the thermal effects are included. In addition, Table A.2.13.1-23 lists the combined stresses under –20°F thermal conditions where the load combination is performed for the –20°F thermal stresses (bounding values of –20°F and –40°F thermal stresses are used for the load combinations). Lid bolt pre-load and external pressure are also included.

The input truck transport vibration loading conditions used to evaluate the NUHOMS®-MP197HB cask for are also obtained from truck bed accelerations given in ANSI N14.23 [14]. The peak inertia values used are:

- Vertical 0.60G
- Longitudinal 0.30G
- Lateral 0.30G

The resultant transverse load is $(0.6^2 + 0.3^2)^{1/2} = 0.67$ G

Since vibration accelerations are higher on a truck than on a rail car, the truck vibration loads are considered bounding. The maximum stress intensity generated by truck vibration is computed by extrapolating from the maximum stress intensity obtained in the railcar vibration load case. The truck vibration load is roughly 150% of the railcar vibration load. The maximum stress intensity in the NUHOMS®-MP197HB cask due to railcar vibration is less than 1.0 ksi (Table A.2.13.1-12) at the containment boundary and 1.68 ksi at outer shell (the outer shell is not a containment boundary). Therefore the maximum stress intensity in the NUHOMS®-MP197HB cask due to truck vibration would be roughly 1.5 ksi and 2.52 ksi at outer shell component.

The fatigue analysis of the cask containment boundary is contained in Appendix A.2.13.6 and summarized in Section A.2.6.13 of this Chapter.

A.2.6.6 Water Spray

All exterior surfaces of the NUHOMS®-MP197HB cask body are metal and therefore not affected by soaking. Additionally, the outer shells of the impact limiters completely enclose the wood crushable medium. Therefore, no structural degradation will result from water absorption. The water spray condition is therefore of no consequence to the NUHOMS®-MP197HB packaging.

A.2.6.7 Free Drop

A.2.6.7.1 Transportation Cask

Two drop orientations are considered credible for the NCT one foot free drop. The structural response of the NUHOMS®-MP197HB cask body is evaluated for a one foot end drop of the package on the bottom end, one foot end drop of the package on the lid end, and a one foot side drop. The impact limiters are installed for these evaluations. The assessment of cask body stresses follows the same logic as that established in the previous sections. For the three drop cases, the evaluations are performed for both the high temperature environment and the -20°F minimum transport temperature. These analyses are detailed in Appendix A.2.13.1 for the cask containment and structural components and A.2.13.4 for the shield shell that encloses the neutron shield. The impact loads used in these analyses are developed in Appendix A.2.13.12, the cask drop analysis.

The load combinations performed to evaluate these drop events are indicated in Table A.2-8. In all cases, bolt pre-load effects and fabrication stress are included. For the hot environment condition, thermal stress load, 30 psig internal pressure, and impact load cases are combined. For the cold environment evaluation, -20°F thermal stress (bounding values of –20°F and –40°F thermal stresses are used for the load combinations), 25 psi external pressure, and impact load cases are combined.

Table A.2.13.1-28 lists the combined stress intensities for the bottom end drop under hot environment conditions. Table A.2.13.1-29 lists the combined stress for the bottom end drop under cold environment conditions.

Table A.2.13.1-26 lists the combined stress intensities for the lid end drop under hot environment conditions. Table A.2.13.1-27 lists the combined stress for the lid end drop under cold environment conditions.

Table A.2.13.1-30 lists the combined stress intensities for the side drop under hot environment conditions. Table A.2.13.1-31 lists the combined stress for the side drop under cold environment conditions.

Appendix A.2.13.4 presents the structural analysis of the shield shell of the MP197HB Transport package. The shield shell consists of a cylindrical shell section and closure plates at each end

which connect the shell to the cask body. The shell is evaluated for NCT drops including an internal pressure of 25 psig with the shell temperature at 300 °F. The analysis is done using ANSYS for both side and end drop events. The resulting stresses are compared to the allowable stress limits defined in Chapter A.2 to assure that the design criteria are met. The results of the analysis are presented in Table A.2.13.4-2 and these results demonstrate that the shield shell and associated weld stresses remain below allowable limits during the NCT free drops.

As shown in these tables, all the calculated stress values are well below the code allowables for the NCT free drop loading conditions.

A.2.6.7.2 DSC Assembly

The DSC evaluation for the NCT free drops is contained in Section A.2.6.15.2 below.

A.2.6.8 Corner Drop

This test does not apply to the NUHOMS®-MP197HB Package since the package weight is in excess of 100 kg (220 lb).

A.2.6.9 Compression

This test does not apply to the NUHOMS®-MP197HB Package since the package weight is in excess of 5,000 kg (11,000 lb).

A.2.6.10 Penetration

Due to lack of sensitive external protuberances, the one meter (40 in.) drop of a 13 pound steel cylinder of 1 1/4 in. diameter with a hemispherical head is of negligible consequence to the NUHOMS®-MP197HB package.

A.2.6.11 Fabrication Stresses

The NUHOMS®-MP197HB cask is subjected to stresses during the lead pouring process and subsequent cool down. However, the cask stresses due to the molten lead pouring process and subsequent freezing to room temperature are small. The differential contraction induced stresses during the –40°F normal condition are negligible. Further, the fabrication stresses remaining in the cask components at the time the cask will be used for transportation will be insignificant.

A.2.6.12 Lid Bolt and Ram Access Cover Plate Bolts

The lid bolts are analyzed for the following loading conditions: operating pre-load, gasket seating load, internal pressure, temperature changes, impact loads, and puncture loads. The analysis is based on NUREG/CR 6007 [16].

The bolt preload is calculated to withstand the worst case load combination and to maintain a clamping (compressive) force on the closure joint. Based upon the load combination results (see

Appendix A.2.13.2, Section A.2.13.2.3); it is shown that a positive (compressive) load is maintained on the clamped joint for all NCT load combinations.

A summary of the calculated stresses is listed in the Table A.2.13.2-7 of Appendix A.2.13.2.

The lid bolt fatigue analysis is also presented in Section A.2.13.2.6 of Appendix A.2.13.2. The results are summarized in Table A.2.13.2-8 of Appendix A.2.13.2. As shown from the table, the total damage factor is less than 1, the MP197HB cask lid bolts will not fail due to fatigue at 250 round trip shipments.

The ram access cover plate bolts are also evaluated (Section A.2.13.2.9) using the same methodology as described above. The results show the bolt loads are bounded by the preload and that the bolt stresses remain below allowables

A.2.6.13 Fatigue Analysis of the Containment Boundary

The purpose of the fatigue analysis is to show that the containment vessel stresses are within acceptable limits under normal transport conditions. This is done by determining the fatigue damage factor for each normal transport event at locations on the containment vessel with the highest stresses. The cumulative fatigue damage or usage factor for all of the events is conservatively determined by adding the fatigue usage factors for the individual events, assuming these maximum stress intensities occur at the same location.

The fatigue analysis is based on the procedure described in Regulatory Guide 7.6 [5] and ASME Code Section III [3]. When determining the stress cycles, consideration is given to the superposition of individual loads which can occur together and produce a total stress intensity range greater than the stress intensity range of individual loads. Also, the maximum stress intensities for all individual loads are conservatively combined simultaneously. The fatigue evaluation is based on 1000 shipments for the cask and a limit of 600 shipments for the lid. The following sequence of events was assumed for the fatigue evaluation.

1. Operating bolt preload
2. Test pressure
3. Road shock/vibration
4. Pressure and temperature fluctuations
5. 1 foot normal condition drop

Details of the calculation are described in Appendix A.2.13.6.

The results of the fatigue evaluation show that the total damage factor for the cask containment is 0.854 after 1000 shipments and 0.889 for the lid after 600 shipments. Both values are less than 1.0, demonstrating that the fatigue effects on the NUHOMS®-MP197HB containment are acceptable.

A separate fatigue analysis of the lid bolts is presented in Appendix A.2.13.2.

A.2.6.14 Summary of Normal Condition Cask Body Structural Analysis

The following table lists the highest stress ratio in each cask component and also identifies the load combination tables where these stress intensities are given in Appendix A.2.13.1. The stress limits based on the Section A.2.1.2 structural design criteria are also listed in the table.

Comparison of the Maximum Stress Intensities with Allowables

Component	Calculated Stress Intensity (ksi)	Allowable Stress Intensity (ksi)	Stress Ratio	Stress Result Table
Outer Shell	28.2	$P_l + P_b = 34.7$	81.4%	A.2.13.1-31
Inner Shell	14.5	$P_m = 23.1$	62.8%	A.2.13.1-30
Lid	21.6	$P_l + P_b = 34.7$	62.3%	A.2.13.1-29
Top Flange	27.6	$P_l + P_b = 32.6$	84.7%	A.2.13.1-30
Bottom Flange	37.9	$P + Q = 65.3$	58.1%	A.2.13.1-30
Bottom Plate	29.2	$P + Q = 65.3$	44.7%	A.2.13.1-24
RAM Closure Plate	20.4	$P + Q = 69.3$	29.4%	A.2.13.1-27

The stress values in the RAM closure plate shown in the above table were calculated for the case when plate is made of carbon steel. If stainless steel is used to fabricate RAM closure plate then the increase in primary stresses would be insignificant due to the small, below 2%, difference in Young's modulus and the primary stress will remain well below the stress limit of the SA-240 Type 304 stainless. The thermal stresses also would remain unchanged due to diametric clearance of 0.06" between RAM closure plate OD and Bottom forging ID, and 0.06" clearance of bolt holes.

From the analysis results presented in the above table, it can be shown that the NCT loads will not result in any structural damage to the cask and that the containment function of the cask will be maintained.

A.2.6.15 Structural Evaluation of the Basket/Canister Shell under Normal Condition Loads

A.2.6.15.1 Basket Stress Analysis

The loading conditions considered in the evaluation of the fuel basket consist of inertial loads resulting from normal inertial loading (1foot drop) and thermal loads. The inertial loads of significance for the basket analysis are those transverse to the cask and basket longitudinal axes, so that the loading from the fuel assemblies is applied normal to the basket plates and transferred to the cask wall by the basket.

The structural adequacy of the basket plates in the NUHOMS® basket assembly under a NCT free drop is analyzed in Appendix A.2.13.8. The baseline g loads and drop orientations used for the structural analysis of the basket are described in Appendix A.2.13.12. The baseline g loads are multiplied by the dynamic load factor calculated in Appendix A.2.13.9. The maximum g loads used for the basket structural evaluations are summarized in Table A.2.13.8-1 of Appendix A.2.13.8. The stress analysis of the basket due to inertial and thermal loads is also described in

detail in Appendix A.2.13.8. Based on the results of analyses shown in Appendix A.2.13.8, all the basket designs meet the ASME Code Subsection NG requirements [3]. Therefore, the basket is structurally adequate and it will properly support and position the fuel assemblies under normal loading conditions.

A.2.6.15.2 DSC Shell Stress Analysis

The MP197HB DSC shell assemblies each consist of a cylindrical shell, top outer/inner cover plates, bottom inner/outer cover plates and bottom and top shield plugs. Each DSC shell assembly functions to support a basket assembly and confine associated fuel assemblies that are contained within the DSC shell assembly. The confinement vessel for each of the MP197HB DSCs consists of a shell which is a welded, stainless steel cylinder with a stainless steel bottom closure assembly, and a stainless steel top closure assembly. Additional details, geometry, and shell and plate thicknesses are provided in Appendix A.1.4.10.

Multiple DSC shell assembly designs are evaluated in Appendix A.2.13.7. Each design is categorized into one of four groups based on similarity of geometry, plate thicknesses and compartment payload. For each group, the bounding payload weight (basket plus fuel assembly) is used for the analyses.

Finite element analyses are performed in order to quantify stresses in the DSCs generated by transport loads. The applied loads considered are top end, bottom end, and side drops combined with internal and external pressures and temperature distributions (thermal expansion stresses). Several three-dimensional finite element models are used to evaluate stresses for the normal and accident loads: 180° 3D models are used for side drop analyses; 2D axisymmetric models are used for end drop and thermal expansion analyses.

The loading conditions considered in the evaluation of the DSC shell consist of inertial loads resulting from normal condition inertial loading (1foot drop), internal /external pressures and thermal loads. The inertial loads of significance for the DSC shell analysis are those transverse to the cask and DSC shell longitudinal axes, so that the loadings from the fuel assemblies and basket are transferred to the cask wall by the DSC shell.

The baseline g loads and drop orientations used for structural analysis of the DSCs are described in Appendix A.2.13.12. The baseline g loads are multiplied by the dynamic load factor calculated in Appendix A.2.13.9. The maximum g loads used for the DSC shell assembly structural evaluations are summarized in Section A.2.13.7.3 of Appendix A.2.13.7. The stress analysis of the DSC shell assembly due to inertial and thermal loads is also described in detail in Appendix A.2.13.7. Based on the results of analyses shown in Appendix A.2.13.7, all the DSC shell assembly designs meet the ASME Code Subsection NB requirements [3].

A.2.7 Hypothetical Accident Conditions

Overview

This section describes the response of the NUHOMS®-MP197HB package to the hypothetical accident condition loads specified by 10CFR71.73. The design criteria established for the NUHOMS®-MP197HB packaging for the HAC are described in Section A.2.1.2. These criteria are selected to ensure that the packaging performance standards specified by 10CFR71.51 are satisfied.

The presentation of the HAC analyses and results is accomplished in the same manner as that used for the NCT analysis. Table A.2-9 provides an overview of the performance evaluations presented in this section. The detailed analyses of the various packaging components under different loading conditions are presented in the Appendices to this Chapter. The limiting results for the specified HAC load are taken from the Appendices and summarized here along with comparisons with the established design criteria. In all cases, the acceptability of the NUHOMS®-MP197HB packaging design with respect to HAC loads is demonstrated.

An analytical evaluation of the impact limiters is presented in Appendix A.2.13.12. The analytical results are used to determine the baseline g loads used in the cask, canister and basket structural evaluations.

Reporting Method for Containment Vessel Stresses

Appendix A.2.13.1 provides the detailed description of the structural analyses of the NUHOMS®-MP197HB cask body. Table A.2-9 provides a matrix of the loads that were analyzed to determine the cask body stresses for the hypothetical accident conditions. The combined load cases for the accident conditions of transport were performed in load cases 27 - 42, as shown in Table A.2-9. The stress results are presented in Table A.2.13.1-32 to A.2.13.1-47 of Appendix A.2.13.1. Refer to Section A.2.13.1.10 of Appendix A.2.13.1 for the method of obtaining the stress results from the ANSYS runs.

A.2.7.1 Free Drop

The response of the NUHOMS®-MP197HB Packaging is evaluated for a free drop from a height of 30 feet onto an unyielding surface at various orientations. The inertial loading applied to the NUHOMS®-MP197HB components is determined in the dynamic analysis presented in Appendix A.2.13.12.

The stresses in the cask body are reported for the following drop orientations:

- End drop onto bottom end
- End drop onto lid end
- Side drop
- C. G. over corner drop on bottom end
- C. G. over corner drop on lid end
- 10° slap down impact on lid end

- 10° slap down impact on bottom end
- 20° slap down impact on lid end
- 20° slap down impact on bottom end

The response of the DSCs to the HAC drops is discussed in Section A.2.7.8. This includes both DSC shells and baskets.

Appendix A.2.13.4 presents the structural analysis of the shield shell of the MP197HB Transport package. The shield shell consists of a cylindrical shell section and closure plates at each end which connect the shell to the cask body. The shell is evaluated for HAC drops including an internal pressure of 25 psig with the shell temperature at 300 °F. The analysis is done using ANSYS for both side and end drop events. The resulting stresses are compared to the allowable stress limits defined in Chapter A.2 to assure that the design criteria are met. The results of the analysis are presented in Table A.2.13.4-2 and these results demonstrate that the shield shell and associated weld stresses remain below allowable limits during the HAC free drops.

A.2.7.1.1 End Drop

The dynamic impact analysis of the NUHOMS®-MP197HB packaging shows that the maximum expected inertia loading from the 30 foot end drop is 55 g as described in Section A.2.13.12 of Appendix A.2.13.12. Because of the symmetry of the cask and impact limiters, these values are applicable for both the bottom end drop and lid end drop.

The load combinations performed to evaluate these drop events are indicated in Table A.2-9. Tables A.2.13.1-32 through A.2.13.1-35 of Appendix A.2.13.1 list the combined stress intensities for the bottom end drop and lid end drop load combinations. Based on the results shown in these tables, all the stresses are below the Code allowables

A.2.7.1.2 Side Drop

The dynamic analysis of the 30 foot side drop provided a baseline inertial loading of 55 g as described in Section A.2.13.12 of Appendix A.2.13.1. The load combinations performed to evaluate these drop events are indicated in Table A.2-9. Tables A.2.13.1-36 and A.2.13.1-37 of Appendix A.2.13.1 list the combined stress intensities for the side drop load combinations. Based on the results shown in these tables, all the stresses are below the code allowables.

A.2.7.1.3 Corner Drop

The response of the NUHOMS®-MP197HB package to the 30 foot corner drops was analyzed for impact on the bottom and lid ends. The analyses were performed using the ANSYS model described in Appendix A.2.13.1. The C.G. over corner drop occurs at a drop angle of approximately 65°. That is, the longitudinal axis of the containment vessel is at an angle of 65° from the impact surface. The dynamic analysis in Appendix A.2.13.12 calculated the baseline g load of 37g for the cask 30 ft CG over corner drop case. As described in Appendix A.2.13.1, Section A.2.13.1.2, a conservative g load of 45g is used for cask structural evaluations.

Tables A.2.13.1-38 through A.2.13.1-41 of Appendix A.2.13.1 list the combined stress intensities for the CG over corner drop on bottom end drop and CG over corner drop on lid end load combinations. Based on the results shown in these tables, all the stresses are below the code allowables

A.2.7.1.4 Oblique Drop

The limiting oblique drop (slap down) for the containment vessel occurs at a drop angle of 10°. Based on the dynamic impact analysis described in Appendix A.2.13.12, this drop orientation is limiting because it results in the highest rigid body deceleration and highest rotational deceleration. The 10° slap down impact has a maximum rigid body deceleration of 32g and rotational deceleration of 166 rad/sec^2 as specified in Appendix A.2.13.12. The stress analysis of the cask body was conservatively performed using the ANSYS model with rigid body deceleration g load of 45g and a rotational deceleration of 551 rad/sec^2.

The 20° slap down load case has slightly lower rigid body deceleration and rotational deceleration as specified in Appendix A.2.13.12. The cask body stress evaluation is also performed for this slap down drop case. The stresses resulting from 10° slap down drop load case is bounding.

Tables A.2.13.1-42 through A.2.13.1-45 of Appendix A.2.13.1 list the combined stress intensities for the 10° slap down drop on bottom end drop and 10° slap down drop on lid end load combinations. Based on the results shown in these tables, all the stresses are below the code allowables.

A.2.7.1.5 Summary of Results

Based on the stress results list in the Tables A.2.13.1-32 through A.2.13.1-47, all the stresses are within the code allowables.

Stress results summarized in Table A.2.13.1-32 through Table A.2.13.1-47 are based on elastic-plastic analysis methodology and evaluated in accordance with the ASME Code, Appendix F [3] Plastic Analysis criteria (Paragraph F-1341.2). Based on the results shown in these tables, cask component stresses for most of the load cases remain in the elastic range except for the following three load cases: side drop, CG over corner drop on lid ends, and slap down.

By reviewing these results, two bounding load cases (side drop with 25 psig external pressure-Table A.2.13.1-37 and slap down drop on lid end with 25 psig external pressure–Table A.2.13.1-45) are analyzed using elastic analysis methodology and the resulting stresses evaluated in accordance with the ASME Code, Appendix F [3] Elastic Analysis criteria (Paragraph F-1331.1).

The stresses resulting from the analyses of the two load cases above are compared with the Code allowable stress limits for elastic analysis and are summarized in Table A.2.13.1-52 (for the side drop with 25 psig external pressure load case) and Table A.2.13.1-53 (for the slap down drop on lid end with 25 psig external pressure load case). These tables show that all the calculated stresses in the containment boundary meet the ASME Code elastic analysis allowable stress limits. For the slap down drop on lid end with 25 psig external pressure case, the stresses in the

outer shell slightly exceed the Code elastic allowables. However, as shown in Figure A.2.13.1-2, the outer shell is not a part of the cask containment boundary. Moreover, the outer shell has been shown to meet the ASME Code allowable stress limits for plastic analysis, as shown in Table A.2.13.1-45.

A.2.7.1.6 Lid and Ram Access Cover Plate Bolts

The lid bolts are analyzed for the following loadings: operating pre-load, gasket seating load, internal pressure, temperature changes, impact loads, and puncture loads. The analysis is based on NUREG/CR 6007 [16].

The bolt preload is calculated to withstand the worst case load combination and to maintain a clamping (compressive) force on the closure joint. Based upon the load combination results (see Appendix A.2.13.2, Section A.2.13.2.9) it is shown that a positive (compressive) load is maintained on the clamped joint for all load combinations except for the accident condition impact plus pressure load. A more detailed finite element analysis is performed in Section A.2.13.2 7 of Appendix A.2.13.2. It is concluded that there is no decompression of the seal during the accident condition impact plus pressure loading condition. Since the seal exists all along the circumference of the cask lid seal, the internal contents will not leak during the worst case loading condition.

A summary of the calculated stresses is listed in the Table A.2.13.2-7 of Appendix A.2.13.2. *The lid bolt evaluation due to delayed impact is presented in Appendix A.2.13.14.*

The ram access cover plate bolts are also evaluated (Section A.2.13.2.9) using the same methodology as described above. The results show the bolt loads are bounded by the preload and that the bolt stresses remain below allowables.

A.2.7.1.7 Impact Limiter Attachments

The impact limiters must remain attached to the cask body before, during, and after each HAC drop. The limiting loading condition for the impact limiter attachments is the secondary impact (slap-down) associated with the 10° slap down 30 foot drop. This loading condition applies the greatest separating moment between the impact limiter and cask body interface. Although this loading condition is not limiting with respect to any other cask component, an evaluation of the attachments is performed to demonstrate that the effected impact limiter remains in place to insulate the cask during the subsequent hypothetical thermal accident.

The analysis and results are provided in detail in Section A.2.13.12.11 of Appendix A.2.13.12.

The analysis concludes that the impact limiter attachment design is sufficiently strong to ensure that the impact limiters remain attached to the cask body during and following all HAC loads.

A.2.7.1.8 Cask Lead Slump and Containment Buckling Analyses

In the event of a drop of the NUHOMS®-MP197HB package, permanent deformation of the lead gamma shield may result for certain impact orientations. An analysis is performed to evaluate the inner cylindrical shell stability and lead slump when subject to the end drop impact loads.

A nonlinear finite element analysis is performed in order to evaluate the buckling capacity of the inner shell of the NUHOMS®-MP197HB cask. A 2-dimensional axisymmetric ANSYS [7] finite element model is constructed for this purpose. The results of the finite element analysis provide both stresses and displacements generated during the end drop event. The allowable buckling load is 215g and the maximum lead slump is 0.32 inches. The detailed analysis is provided in Appendix A.2.13.3.

A.2.7.2 Crush

This test does not apply to the NUHOMS®-MP197HB Package since the package weight is in excess of 5,000 kg (11,000 lb).

A.2.7.3 Puncture

An evaluation of the puncture drop as specified by 10CFR71.73(c)(3) is presented below. This is considered to be the worst case scenario of the package dropped from a distance of 40 in. onto a vertical puncture bar. The specified puncture bar is a 6 in. diameter solid, vertical, cylindrical, mild steel bar. The impact limiters will protect the ends of the cask body during this event. Consequently, the most severe damage to the cask body, resulting from the puncture drop, will occur on the outer cylindrical shell midway between the impact limiters. For this load condition it is conservatively assumed that the cask outer shell surface impacts the puncture bar directly.

Required Thickness

The required thickness t_{req} to preclude puncture is calculated using the Nelms equation for lead backed shells [4], which is given by:

$$t_{req} = \left[\frac{W}{S_u}\right]^{0.71}$$

Where W is the weight of the package (conservatively taken equal to 310,000 lb) *and the material property of S_u is taken at 352 °F*:

$$t_{req} = \left[\frac{310{,}000}{70{,}000}\right]^{0.71} = 2.88\,\text{in}.$$

The thickness of the outer shell is 2.75 in, and the thickness of the neutron shield shell is equal to 0.375 in. The total steel thickness is therefore equal to 2.75 + 0.375 = 3.125 in, which is greater than the required thickness computed above. Therefore, the outer shell combined with the neutron shield shell will preclude penetration of the bar during the postulated puncture event.

A.2.7.4 Thermal

A.2.7.4.1 Summary of Pressures and Temperatures

The analysis of the thermal accident is presented in Chapter A.3. The maximum internal pressure during the thermal accident is calculated in Section A.3.4.3. The calculated pressure is 14.4 psig. However, the structural analysis is performed conservatively assuming a 120 psig internal pressure for the accident pressure stress calculations.

An ANSYS transient thermal analysis of the cask for the 30 minute thermal accident is reported in Chapter A.3. The initial condition is steady state, at an ambient temperature of 100°F and maximum decay heat. The initial steady state condition is followed by a 0.5 hour severe thermal transient which is then followed by a cool down period. The temperatures from the thermal analysis are reported in Chapter A.3.

The temperature through the cross section of the cask, at the time of the maximum thermal gradient, is used for input to the cask model for thermal stress analysis.

A.2.7.4.2 Differential Thermal Expansion

The DSC temperature does not change appreciably while the cask temperature rises during the fire accident. The gap between the outside diameter of the DSC/inside diameter of the cask and DSC length/cask cavity length will increase slightly based on thermal expansion evaluation results from NCT thermal loading conditions; therefore, there is adequate clearance between the various components of the DSC and cask to allow free thermal expansion.

A.2.7.4.3 Stress Calculations

The load combination performed to evaluate the fire accident event is indicated in Table A.2-9. Table A.2.13.1-47 of Appendix A.2.13.1 lists the combined stress intensities for the fire accident condition.

A.2.7.4.4 Comparison with Allowable Stresses

Table A.2.13.1-47 provides a comparison of the calculated stress with the specified allowable stresses. All stresses are below allowables.

A.2.7.5 Immersion–Fissile Material

The criticality evaluation presented in Chapter A.6 considers the effect of water in-leakage. Thus, the requirements of 10CFR71.73(c)(5) are met. The cask body stresses for this immersion condition (1.3 psi external pressure) is bounded by the immersion condition for all packages (water pressure of 290 psi) described in Section A.2.7.7 below.

A.2.7.6 Immersion–All Packages

The immersion loading condition results in an external pressure applied to the cask body corresponding to a 50 foot head of water (21.7 psig). Assuming a 0 psia cask cavity pressure, the resulting maximum external pressure loading is 36.4 psi (21.7 + 14.7). The cask body stresses for this immersion condition (36.4 psi external pressure) is enveloped by the deep water immersion condition (water pressure of 290 psi) described in Section A.2.7.7 below.

A.2.7.7 Deep Water Immersion Test

10CFR 71.61 requires that the package be subjected to an external water pressure of 290 psig for a period of not less than one hour without collapse, buckling, or inleakage of water. The load combination performed to evaluate this event is included in Table A.2-9.

Table A.2.13.1-46 of Appendix A.2.13.1 lists the combined stress intensities for this accident event.

A.2.7.8 Summary of Damage

A.2.7.8.1 Summary of Accident Condition Cask Body Structural Analysis

The following table lists the highest stress ratio in the cask components and also identifies the load combination tables from Appendix A.2.13.1 where these stresses are shown. Also listed in the tables are the stress limits based on the Section A.2.1.2 structural design criteria.

Comparison of the Maximum Stress Intensities with the Allowables (Elastic-Plastic Analysis)

Component	Maximum Stress Intensity (ksi)	Allowable Stress Intensity (ksi)	Stress Ratio	Stress Result Table
Outer Shell	40.5	$P_m = 49.0$	82.6%	A.2.13.1-43
Inner Shell	41.6	$P_m = 49.0$	84.9%	A.2.13.1-44
Lid	32.9	$P_l + P_b = 63.0$	52.2%	A.2.13.1-45
Top Flange	38.8	$P_m = 49.0$	79.2%	A.2.13.1-44
Bottom Flange	35.9	$P_m = 49.0$	73.4%	A.2.13.1-43
Bottom Plate	30.5	$P_l = 63.0$	48.4%	A.2.13.1-38
RAM Closure Plate	17.6	$P_m = 63.0$	28.0%	A.2.13.1-43

The stress values in the RAM closure plate shown in the above table were calculated for the case when plate is made of carbon steel. If stainless steel is used to fabricate RAM closure plate then the increase in primary stresses would be insignificant due to the small, below 2%, difference in Young's modulus and the primary stress will remain well below the stress limit of the SA-240 Type 304 stainless.

From the analysis results presented in the above table, it can be shown that the accident loads will not result in any structural damage to the cask.

A.2.7.8.1.1 Basket Stress Analysis

The structural adequacy of the basket plates in the NUHOMS® DSC fuel basket under HAC free end and side drop load cases are performed in Appendix A.2.13.8. Based on the results of analyses shown in Appendix A.2.13.8, all the basket designs meet the ASME Code Subsection NG and Appendix F requirements [3]. The basket is structurally adequate and will properly support and position the fuel assemblies under accident loading conditions.

A.2.7.8.1.2 DSC Shell Stress Analysis

The g loads and drop orientations used for the structural analysis of the *DSC Shell* are described in Appendix A.2.13.7. Based on the results of analyses shown in Appendix A.2.13.7, all the DSC shell assembly designs meet the ASME Code Subsection NB and Appendix F requirements [3].

A.2.8 Accident Conditions for Air Transport of Plutonium

This section does not apply to the NUHOMS®-MP197HB Packaging because the package will not be transported by air.

A.2.9 Accident Conditions for Fissile Material Packages for Air Transport

This section does not apply to the NUHOMS®-MP197HB Packaging because the package will not be transported by air.

A.2.10 Special Form

This section does not apply to the NUHOMS®-MP197HB Packaging because the payloads are not considered to be special form.

A.2.11 Fuel Rods

As discussed in Chapter A.4, containment of the radioactive material is provided by the cask containment boundary. Analyses of the cask boundary for 10CFR71 NCT and HAC requirements demonstrate that the cask remains leak tight.

The structural adequacy of the fuel rod in the NUHOMS® DSC fuel basket under HAC free end and side drop load cases are performed in Appendix A.2.13.11. Based on the results of analyses shown in Appendix A.2.13.11, the integrity of the fuel rod will not be breached during the normal and hypothetical accident loads.

A.2.12 References

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15. USNRC, "Shock and Vibration Environments for Large Shipping Containers on Rail Cars and Trucks," NUREG 766510, June, 1977.
16. USNRC, "Stress Analysis of Closure Bolts for Shipping Casks," NUREG/CR-6007 Lawrence Livermore National Laboratory, 1992.
17. *Tietz, T. E., "Determination of the Mechanical Properties of a High Purity Lead and a 0.058 % Copper-Lead Alloy," WADC Technical Report 57-695, ASTIA Document No. 151165, Stanford Research Institute, Menlo Park, CA, April 1958.*
18. *H.J. Rack, G.A. Knorovsky, "An Assessment of Stress-Strain Data Suitable for Finite-Element Elastic-Plastic Analysis of Shipping Containers," Sandia Laboratories, NUREG/CR-0481, SAND77-1872 R-7, 1978.*
19. *R.A. Robinson, et. al., " A survey of Strain-Rate Effects for some common Structural Materials used in Radioactive Material Packaging and Transportation Systems", Report BMI-1954, August 1976, Battelle Columbus Laboratories.*

Table A.2-1
Containment Vessel and DSC Shell Stress Limits

CLASSIFICATION	STRESS INTENSITY LIMIT
Normal (Level A) Conditions[1]	
P_m	S_m
P_l	1.5 S_m
(P_m or P_l) + P_b	1.5 S_m
Shear Stress	0.6 S_m
Bearing Stress	S_y
(P_m or P_l) + P_b + Q	3 S_m
(P_m or P_l) + P_b + Q + F	S_a
Hypothetical Accident (Level D)[2][3]	
P_m	Smaller of 2.4 S_m or 0.7 S_u
P_l	Smaller of 3.6 S_m or S_u
(P_m or P_l) + P_b	Smaller of 3.6 S_m or S_u
Shear Stress	0.42 S_u

Notes:

1. Classification and stress limits are as defined in ASME Code, Section III, Subsection NB [3]. Limit analysis specified in Section NB-3228.1, Simplified elastic-plastic analysis specified in Section NB-3228.5, and Shakedown analysis specified in NB-3228.4 also can be used for structural evaluation of the canister.
2. Classification and stress limits are as defined in ASME Code, Section III, Appendix F [3].
3. When evaluating the results from the nonlinear elastic-plastic analysis for the accident conditions, the general primary membrane stress intensity, P_m, shall not exceed greater of 0.7 S_u or S_y + 1/3 (S_u - S_y) and the maximum primary stress intensity at any location (P_L or P_L + P_b) shall not exceed 0.9 S_u. These limits are in accordance with Appendix F of Section III of the Code.

Table A.2-2
Containment Bolt Stress Limits

CLASSIFICATION[2]	STRESS INTENSITY LIMIT[1][5]
Normal (Level A) Conditions	
Average Tensile Stress	2/3 S_y
Maximum Combined Stress	0.9 S_y
Bearing Stress	S_y
Hypothetical Accident (Level D)[3]	
Average Tensile Stress	Smaller of S_y or 0.7 S_u
Average Shear Stress	Smaller of 0.42 S_u or 0.6 S_y
Maximum Combined Stress	S_u
Combined Shear & Tension	$R_t^2 + R_s^2 < 1$[4]

Notes:

1. The stress analysis of the lid bolt is performed in accordance with NUREG/CR-6007 [16] described in Appendix B.2.13.2. The stress limits for the lid bolt are listed separately in Tables A.2.13.2-3 and 4.
2. Classification and stress limits are as defined in ASME B&PV Code, Section III, Subsection NB [3].
3. Stress limits are in accordance with ASME B&PV Code, Section III, Appendix F [3].
4. R_t : Ratio of average tensile stress to allowable average tensile stress.
   R_s : Ratio of average shear stress to allowable average shear stress.
5. All stresses include the effect of tensile and torsional loads due to bolt preloading.

Table A.2-3
DSC Basket Stress Limits

CLASSIFICATION	STRESS INTENSITY LIMIT
Normal (Level A) Conditions [1]	
P_m	S_m
P_l	1.5 S_m
$(P_m + P_l) + P_b$	1.5 S_m
$(P_m + P_l) + P_b + Q$	3 S_m
$(P_m + P_l) + P_b + Q + F$	S_a
Shear Stress	0.6 S_m
Hypothetical Accident (Level D) [2][3]	
P_m	Smaller of 2.4 S_m or 0.7 S_u
P_l	Smaller of 3.6 S_m or S_u
$(P_m + P_l) + P_b$	Smaller of 3.6 S_m or S_u
Shear Stress	0.42 S_u

Notes:

1. Classification and stress limits are as defined in ASME Code, Section III, Subsection NG [3]. Limit analysis specified in Section NG-3228.2, Simplified elastic-plastic analysis specified in Section NG-3228.3, and Shakedown analysis specified in NG-3228.1 also can be used for structural evaluation of the basket.
2. Classification and stress limits are as defined in ASME Code, Section III, Appendix F [3].
3. When evaluating the results from the nonlinear elastic-plastic analysis for the accident conditions, the general primary membrane stress intensity, P_m, shall not exceed greater of 0.7 S_u or $S_y + 1/3 (S_u - S_y)$ and the maximum primary stress intensity at any location (P_L or $P_L + P_b$) shall not exceed 0.9 S_u. These limits are in accordance with Appendix F of Section III of the Code.

Table A.2-4
Cask Material Properties

Material	Class	Temp. (°F)	S_y (ksi)	S_u [2] (ksi)	S_m (ksi)	E (10^{-6} psi)	$\alpha x10^{-6}$ (in/in/°F)
SA-540, Gr. B23, Cl 1 and Gr. B24, Cl 1[1] (Bolt)	Sect III Class 1	70	150.0	165.0	50.0	27.8	6.4
		200	144.0	165.0	47.8	27.1	6.7
		300	140.3	165.0	46.2	26.7	6.9
		400	137.9	165.0	44.8	26.2	7.1
		500	136.0	165.0	43.4	25.7	7.3
		600	133.4	165.0	41.4	25.1	7.4
		700	129.0	158.6	---	24.6	7.6
SA-240, Type 304	Sect III Class 1	70	30.0	75.0	20.0	28.3	8.5
		200	25.0	71.0	20.0	27.5	8.9
		300	22.4	66.2	20.0	27.0	9.2
		400	20.7	64.0	18.6	26.4	9.5
		500	19.4	63.4	17.5	25.9	9.7
		600	18.4	63.4	16.6	25.3	9.8
		700	17.6	63.4	15.8	24.8	10.0
SA-182, Type F304 >5"	Sect III Class 1	70	30.0	70.0	20.0	28.3	8.5
		200	25.0	66.3	20.0	27.5	8.9
		300	22.4	61.8	20.0	27.0	9.2
		400	20.7	59.7	18.6	26.4	9.5
		500	19.4	59.2	17.5	25.9	9.7
		600	18.4	59.2	16.6	25.3	9.8
		700	17.6	59.2	15.8	24.8	10.0
SA-182, Type F304 ≤5"	Sect III Class 1	70	30.0	75.0	20.0	28.3	8.5
		200	25.0	71.0	20.0	27.5	8.9
		300	22.4	66.2	20.0	27.0	9.2
		400	20.7	64.0	18.6	26.4	9.5
		500	19.4	63.4	17.5	25.9	9.7
		600	18.4	63.4	16.6	25.3	9.8
		700	17.6	63.4	15.8	24.8	10.0
SA-182, Type F304N	Sect III Class 1	70	35.0	80.	23.3	28.3	8.5
		200	28.6	80	23.3	27.6	8.9
		300	25.0	76.1	22.5	27.0	9.2
		400	22.6	73.2	20.3	26.5	9.5
		500	21.0	71.2	18.9	25.8	9.7
		600	19.9	69.7	17.9	25.3	9.8
		700	19.1	68.6	17.2	24.8	10.0

[1] SA-540 Gr. B24 Cl 1 bolt material is specified for the 1/3 scale benchmark analyses.
[2] *Lid bolt will be fabricated with minimum S_u of 175 ksi.*

Table A.2-4
Cask Material Properties (concluded)

Material	Class	Temp. (°F)	S_y (ksi)	S_u (ksi)	S_m (ksi)	E (10^{-6}) psi	$\alpha x10^{-6}$ (in/in/°F)
SA-203 Gr. E Carbon	Sect III Class 1	70	40.0		23.3	27.8	6.4
		200	36.6	70.0	23.3	27.1	6.7
		300	35.4	70.0	23.3	26.7	6.9
		400	34.2	70.0	22.9	26.2	7.1
		500	32.5	70.0	21.6	25.7	7.3
		600	30.0	70.0		25.1	7.4
		700	27.0	66.5		24.6	7.6
SA-350-LF3, Carbon Forgings	Sect III Class 1	70				27.8	6.4
		200	34.3	70.0	22.9	27.1	6.7
		300	33.2	70.0	22.1	26.7	6.9
		400	32.0	70.0	21.4	26.2	7.1
		500	30.4	70.0	20.3	25.7	7.3
		600	28.2	70.0	18.8	25.1	7.4
		700	25.3	66.5	16.9	24.6	7.6
SA-516-70, Carbon Plate	Sect III Class 1	70			23.3	27.8	6.4
		200	34.8	70.0	23.2	27.1	6.7
		300	33.6	70.0	22.4	26.7	6.9
		400	32.5	70.0	21.6	26.2	7.1
		500	31.0	70.0	20.6	25.7	7.3
		600	29.1	70.0	19.4	25.1	7.4
		700	27.2	70.0	18.1	24.6	7.6
SA-182, Type F6NM	Sect III Class 1	70				29.2	5.9
		200	86.5	115.0	38.3	28.4	6.2
		300	84.6	115.0	38.3	27.9	6.3
		400	82.8	113.7	37.9	27.3	6.4
		500	80.8	109.5	36.5	26.8	6.5
		600	78.5	105.1	35.0	26.2	6.5
		700	75.7	100.3	33.4	25.5	6.6
SA-182 Type F316N	Sect III Class 1	70	35.0	80.0	23.3	28.3	8.5
		200	31.0	80.0	23.3	27.5	8.9
		300	28.5	77.0	23.3	27.0	9.2
		400	26.4	75.1	23.3	26.4	9.5
		500	24.7	74.4	23.3	25.9	9.7
		600	23.4	74.3	21.0	25.3	9.8
		700	22.3	74.3	20.0	24.8	10.0

Table A.2-5
Mechanical Lead Properties

Static Mechanical Lead Properties

Temp. (°F)	Static Stress Properties (ksi) *[17]*			E *[18]* (10^6 psi)	Coef. of Thermal Exp *[18]* (10^{-6} in/in/°F)
	Yield (S_Y)		Ultimate (S_U)		
	Tension	Compression	Tension		
-99	-	-	-	2.50	15.28
70	-	-	-	2.34	16.07
100	0.584	0.490	1.570	2.30	16.21
175	0.509	0.428	1.162	2.20	16.58
250	0.498	0.391	0.844	2.09	16.95
325	0.311	0.320	0.642	1.96	17.54
440	-	-	-	1.74	18.50
620	-	-	-	1.36	20.39

Dynamic Stress-Strain Lead Properties

Strain (in/in)	Stress (ksi) *[19]*				
	At 100 °F	At 230 °F	At 300 °F	At 350 °F	At 500 °F
0.00048	1.14	1.06	1.00	0.97	0.86
0.03	2.2	2.0	1.7	1.5	1.1
0.1	3.3	2.8	2.38	2.1	1.26
0.3	4.9	3.2	2.72	2.4	1.44
0.5	5.6	3.6	3.06	2.7	1.62

Table A.2-6
NUHOMS®-MP197 Package Performance Evaluation Overview (NCT)

Loading Condition	SAR Section	Scope of Evaluation
Heat 71.71(c)(1)	A.2.6.1.1	Summary of temperature and pressure
	A.2.6.1.2	Different thermal expansion
	A.2.6.1.3	Stress calculation
	A.2.6.1.4	Comparison with allowable stresses
Cold 71.71(c)(2)	A.2.6.2	Cask body stresses due to cold environment load combinations
Reduced External Pressure 71.71(c)(3)	A.2.6.3	Cask body stresses due to 30 psig internal pressure load combinations
Increase External Pressure 71.71(c)(4)	A.2.6.4	Cask body stresses due to 25 psig external pressure load combinations
Shock Loads 71.71(c)(5)	A.2.6.5	Cask body stresses due to rail/truck shock loads
		Cask body stresses due to rail/truck shock loads
Vibration Loads 71.71(c)(5)	A.2.6.5	Cask body stresses due to rail/truck vibration loads
		Cask body stresses due to rail/truck vibration loads
Water Spray 71.71(c)(6)	A.2.6.6	Negligible for NUHOMS®-MP197HB cask
Free Drop 71.71(c)(7)	A.2.6.7	Cask body stresses due to 1 foot bottom end drop
		Cask body stresses due to 1 foot lid end drop
		Cask body stresses due to 1 foot side drop
Corner Drop 71.71(c)(8)	A.2.6.8	Not applicable
Compression 71.71(c)(9)	A.2.6.9	Not applicable
Penetration 71.71(c)(10)	A.2.6.10	Not applicable
Fabrication Stress	A.2.6.11	Discuss the cask stresses during the lead pouring process and subsequent cool down
Lid Bolt Analysis	A.2.6.12	Bolt stresses due to preload, pressure loads, temperature, impact and puncture loads
Fatigue Analysis of Containment Vessel	A.2.6.13	Fatigue evaluation of containment vessel due to pressure, temperature, shock/vibration, and 1 foot drop loads
Summary of NCT Cask Analysis	A.2.6.14	Lists the highest stress intensity ratio in the containment vessel and gamma shield and compares results with the allowables
Basket/canister Evaluation	A.2.6.15	Structural analysis of the basket/canister due to 1 foot end drop and 1 foot side drop loads

Table A.2-7
NCT Structural Analyses - List of Individual Loads

NCT Structural Analyses–List of Individual Loads						
Case No.	**Individual Loads**	**Temperature** (°F)[1]	**Inertia Load** Vertical	**Inertia Load** Longitudinal	**Pressure Load** (psig)	**Stress Result Table No.**
1	Bolt Preload	350	0	0	0	A.2.13.1-1
2	Internal Pressure	350	0	0	30	A.2.13.1-2
3	External Pressure	350	0	0	25	A.2.13.1-3
4	Hot Environment (100 °F Ambient Temp)	Distribution	0	0	0	A.2.13.1-4
5A	Cold Environment (-20 °F Ambient. Temp)	Distribution	0	0	0	A.2.13.1-5
5B	Cold Environment (-40 °F Ambient Temp)	Distribution	0	0	0	A.2.13.1-6
6	3 g Lifting	350	0	3 g	0	A.2.13.1-7
7A	Rail Car Shock Loads Scenario A	350	4.7 g	0	0	A.2.13.1-8
7B	Rail Car Shock Loads Scenario B	350	0	-4.7 g	0	A.2.13.1-9
7C	Rail Car Shock Loads Scenario C	350	-4.7 g	0	0	A.2.13.1-10
7D	Rail Car Shock Loads Scenario D	350	0	4.7 g	0	A.2.13.1-11
8A	Rail Car Vibration Loads Scenario A	350	0.42 g	0.19 g	0	A.2.13.1-12
8B	Rail Car Vibration Loads Scenario B	350	0.42 g	-0.19 g	0	A.2.13.1-13
9	1 ft. End Drop on Lid End	350	0	-25 g	0	A.2.13.1-14
10	1 ft. End Drop on Bottom End	350	0	25 g	0	A.2.13.1-15
11	1 ft. Side Drop	350	25 g	0	0	A.2.13.1-16
12	1 g Gravity Loading	350	1 g	0	0	A.2.13.1-17

Notes:

1. Material properties based temperature of 350 °F bound temperature of structural components for thermal hot and thermal cold conditions

Table A.2-8
Summary NCT Load Combinations

Load Case[1]	Load Combination	NCT–Individual Loads Participating in Load Combination											
		1	2	3	4[2]	5A[3]	5B[4]	7[5]	8[6]	9	10	11	12
13	Hot Environment	X	X		X								X
14	Cold Environment	X		X			X						X
15	Increased Ext. Pressure	X		X		X							X
16	Minimum Ext. Pressure	X	X		X								X
17	Rail Car Vibration	X	X		X				X				
18		X		X		X			X				
19	Rail Car Shock	X	X		X			X					
20		X		X		X		X					
21	One Foot End Drop on Lid End	X	X							X			
22		X		X						X			
23	One Foot End Drop on Bottom End	X	X								X		
24		X		X							X		
25	One Foot Side Drop	X	X									X	
26		X		X								X	

1. Load Case numbers 13 to 26 combine the results of individual load cases 1 to 12, shown in the previous table.
2. The envelope of all the individual thermal hot environment cases with ambient temperature 100 °F is used in the load combination.
3. The envelope of the individual thermal cold environment cases with ambient temperature -20 °F is used in the load combination.
4. The envelope of the individual thermal cold environment cases with ambient temperature -40 °F is used in the load combination.
5. The envelope of the individual rail car shock cases 7A, 7B, 7C, 7D as specified in previous table is used in the load combination.
6. The envelope of the individual rail car vibration cases 8A and 8B as specified in previous table is used in the load combination.

Table A.2-9
Summary of HAC Load Combinations

HAC–List of Load Cases					
Load Combination No.	**Load**	**Internal Pressure** (psig)	**External Pressure** (psig)	**Temp. Hot** (°F)	**Stress Result Table No.**
27	30 Ft. End Drop on Bottom End	30		X	Table A.2.13.1-32
28			25	X	Table A.2.13.1-33
29	30 Ft. End Drop on Lid End	30		X	Table A.2.13.1-34
30			25	X	Table A.2.13.1-35
31	30 Ft. Side Drop	30		X	Table A.2.13.1-36
32			25	X	Table A.2.13.1-37
33	30 Ft. CG Over Corner Drop on Bottom End	30		X	Table A.2.13.1-38
34			25	X	Table A.2.13.1-39
35	30 Ft. CG Over Corner Drop on Lid End	30		X	Table A.2.13.1-40
36			25	X	Table A.2.13.1-41
37	30 Ft. Slap-Down Drop on Bottom End(1)	30		X	Table A.2.13.1-42
38			25	X	Table A.2.13.1-43
39	30 Ft. Slap-Down Drop on Lid End(1)	30		X	Table A.2.13.1-44
40			25	X	Table A.2.13.1-45
41	Immersion + Weight		290	X	Table A.2.13.1-46
42	Fire Accident + Weight	120		620	Table A.2.13.1-47

Note: 1. For the slap down case, two drop angles were analyzed (10° and 20°).

A.2.13 Appendices

The detailed structural analyses of the NUHOMS®-MP197HB packaging are included in the following appendices:

Appendix A.2.13.1	NUHOMS®-MP197HB Cask Body Structural Evaluation
Appendix A.2.13.2	NUHOMS®-MP197HB Cask Lid Bolt/Ram Access Closure Plate Bolt Analyses
Appendix A.2.13.3	NUHOMS®-MP197HB Cask Lead Slump and Containment Boundary Buckling Analysis
Appendix A.2.13.4	NUHOMS®-MP197HB Structural Analysis of the Shield Shell
Appendix A.2.13.5	NUHOMS®-MP197HB Cask Lifting and Tie-Down Devices Structural Evaluation
Appendix A.2.13.6	NUHOMS®-MP197HB Cask Containment Boundary Fatigue Evaluation
Appendix A.2.13.7	NUHOMS®-MP197HB DSC (Shell Assembly) Structural Evaluation
Appendix A.2.13.8	NUHOMS®-MP197HB DSC (Basket) Structural Evaluation
Appendix A.2.13.9	NUHOMS®-MP197HB Dynamic Load Factor Determination
Appendix A.2.13.10	NUHOMS®-MP197HB Transport Package Thermal Expansion Evaluation
Appendix A.2.13.11	NUHOMS®-MP197HB Evaluation of Fuel Assembly under Accident Impact Loads
Appendix A.2.13.12	NUHOMS®-MP197HB Package Impact Analysis using LS-DYNA
Appendix A.2.13.13	NUHOMS®-MP197HB ASME Code Alternatives
Appendix A.2.13.14	*MP197HB Lid Closure Evaluation Due to Delayed Impact*

Appendix A.2.13.1
MP197HB Cask Body Structural Analysis

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Appendix A.2.13.1
MP197HB Cask Body Structural Analysis

NOTE: References in this Appendix are shown as [1], [2], etc. and refer to the reference list in Section A.2.13.1.12.

A.2.13.1.1 Introduction

This appendix documents the structural evaluation of the NUHOMS®-MP197HB cask body structure for the loading conditions specified in 10CFR71.71 and 10CFR71.73 [1], and the load combinations outlined in Regulatory Guide 7.8 [3]. Maximum stresses for the various load combinations are evaluated against the design criteria of the ASME Code [4]. The structural evaluation is performed in accordance with the guidance provided in the Standard Review Plan for Transportation Packages for Spent Nuclear Fuel, NUREG-1617 [5].

The specific methods, models and assumptions used to analyze the response of the cask body structure to the various individual loading conditions are described in the following sections. The stresses and deformations due to the applied loads are determined using the ANSYS® computer program [7].

Loading conditions for Normal Conditions of Transport (NCT) are specified in Section A.2.13.1.4. Design criteria and stress results for NCT events are described in Section A.2.13.1.7. Loading conditions for Hypothetical Accident Conditions (HAC) are also specified in Section A.2.13.1.4. Design criteria and stress results for HAC events are described in Section A.2.13.1.8.

The detailed evaluations of the lid bolts are presented in Appendix A.2.13.2. Stress evaluations for the lifting and tie-down devices, including the stresses at the trunnion/cask body interface, are described in Appendix A.2.13.5.

A.2.13.1.2 Description of the MP197HB Cask

A. Dimensions

The cask body structure is the primary containment boundary of the packaging. Key dimensions of the cask body are shown in Figure A.2.13.1-1. The shell, or cask body cylinder assembly, is an open ended (at the top) cylindrical unit with an integral closed bottom end. This assembly consists of a concentric inner shell (SA-203 Grade E) and an outer shell (SA-203 Grade E) welded to a massive closure flange (SA-350 Grade LF3) at the lid end and a flat steel plate (SA-350 Grade LF3) at the bottom end.

The annulus between the shells is filled with lead shielding (ASTM-B29). The lead is poured into the annulus in a molten state using a carefully controlled procedure. The lid is bolted to the cylindrical shell by 48-1½ inch diameter high strength bolts and sealed with two O-rings.

A detailed description of the containment vessel is provided in Chapter A.1. Appendix A.1.4.10 of Chapter A.1 contains reference drawings of the NUHOMS®-MP197HB cask which are the source of dimensions and other information used to develop analysis models.

B. ANSYS Models–Description

Four 3D ANSYS finite element models were constructed to represent the MP197HB cask body in the analyses. Due to symmetry considerations, all four models consist of 180° representations of the cask with symmetry boundary conditions. Figure A.2.13.1-2 shows the basic structural components of the MP197HB cask used in the development of the finite element models. The main features of each of the four models are summarized below.

Model MOD20	**Model MOD20S**	**Model MOD20SP**	**Model MOD20TI**
Used in HAC Evaluations	Used in NCT Evaluations	Used in NCT Evaluations	Used in NCT Evaluations
All HAC cases	Side drop cases End drop cases 3 g lifting case	Bolt preload case	Rail car shock cases Rail car vibration cases 1g gravity case
Includes main structural components	Includes main structural components	Includes main structural components	Added saddles, straps, impact limiter steel blocks, neutron shield shell components
Nonlinear spring model of bolts in tensile and shear directions	Nonlinear spring model of bolts in tensile and shear directions	LINK8 model with imposed preload in tensile direction Nonlinear spring model in shear direction	Nonlinear spring model of bolts in tensile and shear directions
Linear elastic material properties for steel components for elastic analysis. Bilinear kinematic hardening model for steel components, with 5% tangent modulus for elastic-plastic analysis	Linear elastic material properties for steel components for elastic analysis.	Linear elastic material properties for steel components for elastic analysis.	Linear elastic material properties for steel components for elastic analysis.
Multi-linear kinematic hardening model for lead component	Bilinear kinematic hardening model for lead component, with 1% tangent modulus	Bilinear kinematic hardening model for lead component, with 1% tangent modulus	Bilinear kinematic hardening model for lead component, with 1% tangent modulus

All four models use ANSYS structural solid elements SOLID45 for modeling the cask structural components. The interfaces between the steel and lead gamma shielding, between lid and the top flange, and between RAM closure plate and bottom plate are modeled with surface to surface contact elements CONTA173 and TARGE170.

The analyses for NCT cases are based on linear elastic material properties for the steel components. The analyses for HAC cases are based on elastic material properties for the elastic analyses and elastic-plastic material properties for the non-linear (elastic-plastic) analyses. For the elastic-plastic analyses, a bilinear kinematic hardening material law is used, assuming a tangent modulus of 5% of the material elastic modulus. Lead material *properties from Table A.2-5 in Chapter A.2 are used.*

The finite element model (MOD20) used for the HAC accident drop analyses is shown on Figures A.2.13.1-3 and A.2.13.1-4.

A separate model, (MOD20TI), is developed to analyze the cask for shock, vibration and gravity loadings while in the transport configuration. In the transport configuration, the cask is oriented horizontally and secured to the transport skid at the bearing block in the longitudinal direction, supported at two saddles and held by tie down straps.

The load path from the saddles or straps of the transport skid to the outer shell component of the cask consists of a set of steel blocks (the impact limiter attachment blocks, shown as part 11 on drawings MP197HB-71-1002 in Appendix A.1.4.10), these blocks are welded to the cask body. The MOD20TI model also includes the basic components of the neutron shield assembly (the neutron shield shell, and the neutron shield end caps), as well as a simplified representation of the two saddles and straps. The interface between the skid saddles and straps, and the cask is modeled by surface contact elements CONTA173.

The MOD20TI finite element model is shown in Figures A.2.13.1-5 and A.2.13.1-6.

C. Payload and Cask Component Weight Data Used in the Analysis

The payload of the MP197HB package may consist of any of the DSCs types listed in the following table, along with their respective loaded weights:

	DSC Type	**Weight**
	NUHOMS® 32PTH DSC	110 kips
	NUHOMS® 32PTH1 DSC	**112 kips**
	NUHOMS® 37PTH DSC	110 kips
	NUHOMS® 69BTH DSC	105 kips
	NUHOMS® 24PT4 DSC	90 kips
	NUHOMS® 24PTH DSC	99 kips
	NUHOMS® 32PT DSC	107 kips
	NUHOMS® 61BT DSC/ NUHOMS® 61BTH DSC	110 kips
	RWC	Less than 110 kips
	Bounding payload used for cask structural evaluation	**118.5 kips**

The structural evaluations of the package use a bounding DSC payload weight of 118.5 kips. This bounding weight envelops the weight of the expected payloads for the MP197HB cask (112,000 lbs as specified in Chapter A.2, Section A.2.1.3).

Loads applied to the cask model use a total weight of the front impact limiter of 16,000 lb and a total weight of the rear impact limiter of 16,000 lb. These weight values bound the calculated weights of the front and rear impact limiters (12,500 lb as specified in Chapter A.2, Section A.2.1.3).

The neutron shield shell assembly located outside of the structural cask shell is not explicitly included in the stress analysis model (the stress analysis of the neutron shield shell structural evaluation is performed separately, as described in Appendix A.2.13.4). However, because of its large mass, it has a significant contribution to the structural response of the cask. Therefore, the mass of the neutron shield assembly was distributed over the interface area of cask body.

D. Baseline g Loads Used for the Drop Analysis

The baseline g loads used for the cask drop analyses are established in Appendix A.2.13.12 and are listed in the following table.

Drop Orientation		**g Loads *Including -40 °F Effect*** *(App. A.2.13.12)*	**g Loads used in cask body stress calculation**
30 feet end drop		*52* g	55
30 feet side drop		55 g	55
30 feet CG over corner drop		*39* g	45
30 feet slap down (10°)	1st impact	*23* g	Translation =45 g Rotational α = 551 rad/sec^2 to bound both 1st and 2nd impacts
		α =*122* rad/sec^2	
	2nd impact	*31*	
		α =*170* rad/sec^2	
30 feet slap down (20°)	1st impact	*18*	Translation =45 g Rotational α = 507 rad/sec^2 to bound both 1st and 2nd impacts
		α = *72* rad/sec^2	
	2nd impact	28	
		α = *160.9* rad/sec^2	
1 foot end drop		18	25
1 foot side drop		*13*	25

E. Method of Load Application to the Cask Body

The weight of the payload, the impact limiters, and the reaction loads at the interfaces of the cask with the impact limiters are modeled as radially applied pressures. Co-sinusoidal distribution functions are used to represent the circumferential distribution of these loads.

The magnitude and the distribution of the loads applied to the model are such as to ensure a conservative estimation of the resulting stresses. The following sections describe the details of the modeling of the pressure distribution for the HAC or NCT events.

In general, loads resulting from component weights are applied as pressures in the form of cosine functions in the circumferential direction, within a ±75° angle sector, and are generally assumed uniform in the axial direction. A ramped pressure distribution profile was used to represent the DSC loading in the corner drop case.

Loads due to reaction forces are modeled as applied pressures on the interface surfaces between the cask body and impact limiters in the form of cosine × cosh functions in the circumferential direction, within a ±90° angle sector.

Pressure loads acting in the axial direction are in general uniform, except for pressure due to the corner drop. For the corner drop, pressures acting in axial direction are modeled as varying linearly in the direction transverse to the impact plane, with the maximum pressure at the bottom location and the minimum pressure (zero magnitude) at the top location.

The following provides a detailed description of the methods of load application to the cask body used in the analysis:

1. Application of Payload Weight and Impact Limiter Weight to the Cask Body

Inertia loads due to the weight of the DSC payload and the weight of the impact limiters, are applied as radial pressures with a cosine shaped circumferential distribution.

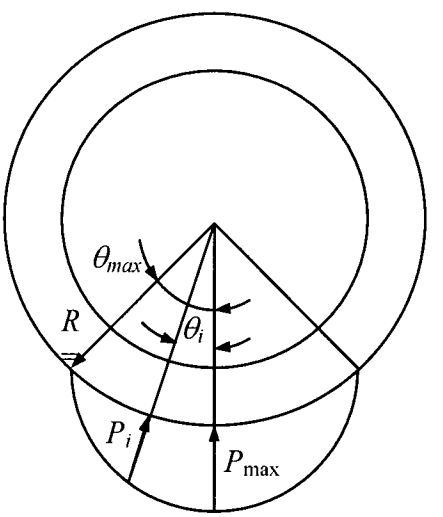
The circumferential cosine distribution of pressure over a half angle, θ_{max}, is calculated as follows:

$$P_i = P_{\max} \cos(\pi\theta_i / 2\theta_{max})$$

where:

P_i = Pressure load at angle θ_i.
$P_{\max}$ = Peak pressure load, at the base of the interface (θ_i=0).
θ_i = Circumferential angle corresponding to location of interest.

The circumferential distribution of the pressure is illustrated in the following sketch:



The peak pressure load, $P_{\max}$, can be determined by setting the integral of the vertical pressure components, Q_i, equal to the net force in the transverse direction, F_t, defined as follows:

$$F_t = (\textit{Transverse Component of G-load}) \times (\textit{Imposed Weight Load}) = G_t \times W$$

Thus,

$$G_t \times W = F_t = \int_{-\theta_{\max}}^{\theta_{\max}} Q_i L R d\theta_i = \int_{-\theta_{\max}}^{\theta_{\max}} P_i \cos(\theta_i) L R d\theta_i = \int_{-\theta_{\max}}^{\theta_{\max}} P_{\max} \cos\left(\frac{\pi\theta_i}{2\theta_{\max}}\right) \cos(\theta_i) L R d\theta_i$$

$$= \frac{P_{\max} LR}{2} \int_{-\theta_{\max}}^{\theta_{\max}} \left[\cos\left(\frac{\pi\theta_i}{2\theta_{\max}} + \theta_i \right) + \cos\left(\frac{\pi\theta_i}{2\theta_{\max}} - \theta_i \right) \right] d\theta_i$$

$$= P_{\max} LR \left[\frac{\sin\left(\frac{\pi}{2} + \theta_{\max} \right)}{\left(\frac{\pi}{2\theta_{\max}} \right) + 1} + \frac{\sin\left(\frac{\pi}{2} - \theta_{\max} \right)}{\left(\frac{\pi}{2\theta_{\max}} \right) - 1} \right]$$

In the above formulas:

θ_i = Position angle of circumferential distribution
$\pm\theta_{max}$ = Circumferential span of pressure load
F_t = Net force in the transverse direction
L = Axial span of pressure load
R = Radius of pressure load surface
G_t = Acceleration in the transverse direction of cask
W = Payload or impact limiter weight

Therefore, the pressure at any circumferential location is given by:

$$P_i = \frac{G_t \times W}{L \times R} \left[\frac{\sin\left(\frac{\pi}{2} + \theta_{\max} \right)}{\left(\frac{\pi}{2\theta_{\max}} \right) + 1} + \frac{\sin\left(\frac{\pi}{2} - \theta_{\max} \right)}{\left(\frac{\pi}{2\theta_{\max}} \right) - 1} \right]^{-1} \cos\left(\frac{\pi\theta_i}{2\theta_{\max}} \right)$$

For example, the applied pressure due to payload for the 55g Side Drop case, distributed over a ±75° circumferential sector, with an axial length of 199.25 inch and inner shell radius of 35.25 inches can be calculated as follows:

$$P_i = \frac{55 \times 118500}{199.25 \times 35.25} \times \frac{1}{\frac{\sin(90+75)}{(\frac{180}{2 \times 75}) + 1} + \frac{\sin(90-75)}{(\frac{180}{2 \times 75}) - 1}} \times \cos(\frac{180 \times 0}{2 \times 75}) = 657\, psi$$

The pressure value calculated above corresponds to the peak pressure load, P_{max}, (calculated at 0°). Magnitudes of peak pressure P_{max} for the various drop conditions are summarized in Table A.2.13.1-50 (for the Bottom End impact) and Table A.2.13.1-51 (for Top Lid End impact) and used in the ANSYS evaluations.

2. Application of Impact Limiter Reaction Forces to the Cask Body

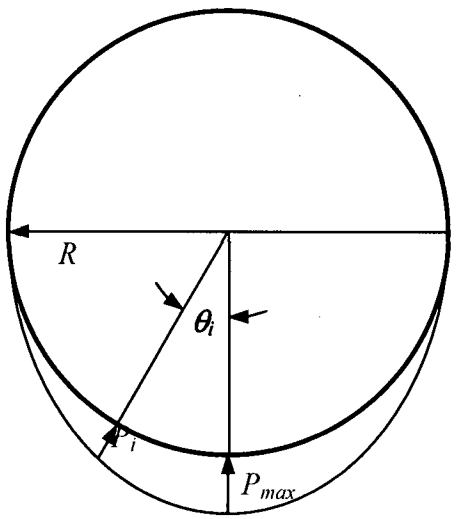
Inertia loads due to impact limiter reaction forces are applied as radial pressures, with a cosine x hyperbolic cosine shaped circumferential distribution. The circumferential pressure distribution over an angle of 90° is calculated as follows:

$$P_i = P_{\max} \cos(\theta_i) \times \cosh(\theta_i)$$

Where:

P_i = Pressure load at angle θ_i.
$P_{\max}$ = Peak reaction pressure load, at base point of impact.
θ_i = Position angle of circumferential distribution.

The circumferential distribution of pressure is illustrated in the following sketch:



The peak pressure load, $P_{\max}$, is determined by setting the integral of the vertical pressure components, Q_i, equal to the total transverse impact load, F_t, defined as follows:

$$F_t = \text{(Transverse Component of G-load)} \times \text{(Imposed Weight Load)} = G_t \times W$$

Thus,

$$F_t = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} Q_i LR d\theta_i = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} P_i \cos(\theta_i) LR d\theta_i = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} P_{\max} \cos(\theta)\cosh(\theta) \times \cos(\theta) LR d\theta$$

$$= P_{\max} LR \left[\frac{1}{2}\sinh(\theta) + \frac{1}{10}\left(\sinh(\theta)\cos(2\theta) + 2\cosh(\theta)\sin(2\theta)\right) \right] \Bigg|_{-\frac{\pi}{2}}^{\frac{\pi}{2}}$$

$$P_{\max} = \frac{F_t}{L \times R}(0.543)$$

Therefore, the pressure at any circumferential location is given by:

$$p_i = \frac{G_t \times W \times 0.543}{L \times R} \cos(\theta_i) \times \cosh(\theta_i)$$

In the above formulas:
θ_i = Position angle of circumferential distribution
$\pm\theta_{max}$ = Circumferential span of pressure load
F_t = Net force in the transverse direction
L = Axial span of pressure load
R = Radius of pressure load surface
G_t = Acceleration in the transverse direction of cask
W = Imposed weight load

An example of radial reaction pressure calculation is provided below for the 30 ft Bottom End Corner Drop with a 10° impact angle.

The transverse G-load for 10° impact angle is 45G × cosine (10°) = 44.316G (see Table A.2.13.1-48). The outer radius of the cask is 42.25 inches. The total weight applied is W = (weight of cask) + (payload) + (weight of front impact limiter) = 294,934 lb.

Therefore, for a total axial length of the rear impact limiter of 27.5 inch and a uniform distribution of the load in the axial direction, the peak pressure at the cask–rear impact limiter interface can be calculated as follows:

The peak pressure, P_{max}, (at circumferential angle of 0°) is:

$$P_{max} = \frac{44.316 \times 294934 \times 0.543}{27.5 \times 42.25}$$

$$P_{max} = 6108 \text{ psi}$$

The total transverse reaction load induced by this pressure is $R_{ER} + R_{IR} = G_t \times W = 44.316 \times 294934 = 13{,}070{,}295$ lb (total transverse reaction force).

For the case of a step function form of the pressure load distribution in the axial direction with a load split ratio of 65/275, 23.64% of the load is distributed to the outer 6.5 inch section of the bottom end impact limiter, and 76.36% of the load is distributed to the 27.5-6.5 = 21 inch inner section of the bottom end impact limiter.

Thus, $R_{ER} = \frac{65}{275} \times G_t \times W = \frac{65}{275} \times 44.316 \times 294934 = 3{,}089{,}342$ lb, and

$R_{IR} = \frac{210}{275} \times (R_{ER} + R_{IR}) = \frac{210}{275} \times 13{,}070{,}295 = 9{,}980{,}952$ lb.

With these modifications, the peak pressures at the outer and inner parts of bottom end impact limiter can be calculated as:

$$P_{max}(R_{ER}) = \frac{R_{ER} \times 0.543}{L \times R} = \frac{3089342 \times 0.543}{6.5 \times 42.25} = 6108\ psi$$

$$P_{max}(R_{IR}) = \frac{R_{IR} \times 0.543}{L \times R} = \frac{9980952 \times 0.543}{21.0 \times 42.25} = 6108\ psi$$

The peak reaction pressure values P_{max} for all corner drop/slap down cases are provided in Table A.2.13.1-48 for Bottom End (Rear End) impact and Table A.2.13.1-49 for Lid End (Front End) impact.

A.2.13.1.3 Boundary Conditions

Four separate sets of boundary conditions are required for the various loading cases analyzed. These sets of boundary conditions are used to prevent rigid body motion and are assigned based on the specific loading configuration. In each of the boundary condition sets, displacement constraints are fixed, such that no displacement is permitted in the prescribed direction. All 3D boundary condition sets have the symmetry plane fixed in the hoop direction. Figure A.2.13.1-7 and Figure A.2.13.1-8 list two sets of the boundary conditions as described in the following table.

Listing of Applied Boundary Conditions	
Boundary Condition Description	Figure
Side Drop, End & Corner Drop on Top Lid End Loading	Figure A.2.13.1-7
End Drop & Corner Drop on Bottom End Loading	Figure A.2.13.1-8

A.2.13.1.4 Load Cases and Load Combinations

The load cases and load combinations used in the analysis are in accordance with Reg. Guide 7.8 [3]. The analyzed load cases and load combinations represent the limiting mechanical and thermal loading conditions and serve as the structural design bases for the MP197HB packaging for transport conditions.

A. Normal Conditions of Transport Cases

The individual loads cases and associated loading conditions used for the NCT evaluations of the cask are presented in the table below.

NCT Structural Analyses–List of Individual Loads						
Case No.	**Individual Loads**	**Temperature** (°F)[1]	**Inertia Load** Vertical	**Inertia Load** Longitudinal	**Pressure Load** (psig)	**Stress Result Table No.**
1	Bolt Preload	350	0	0	0	A.2.13.1-1
2	Internal Pressure	350	0	0	30	A.2.13.1-2
3	External Pressure	350	0	0	25	A.2.13.1-3
4	Hot Environment (100 °F Ambient Temp)	Distribution	0	0	0	A.2.13.1-4
5A	Cold Environment (-20 °F Ambient. Temp)	Distribution	0	0	0	A.2.13.1-5
5B	Cold Environment (-40 °F Ambient Temp)	Distribution	0	0	0	A.2.13.1-6
6	3 g Lifting	350	0	3 g	0	A.2.13.1-7
7A	Rail Car Shock Loads Scenario A	350	4.7 g	0	0	A.2.13.1-8
7B	Rail Car Shock Loads Scenario B	350	0	-4.7 g	0	A.2.13.1-9
7C	Rail Car Shock Loads Scenario C	350	-4.7 g	0	0	A.2.13.1-10
7D	Rail Car Shock Loads Scenario D	350	0	4.7 g	0	A.2.13.1-11
8A	Rail Car Vibration Loads Scenario A	350	0.42 g	0.19 g	0	A.2.13.1-12
8B	Rail Car Vibration Loads Scenario B	350	0.42 g	-0.19 g	0	A.2.13.1-13
9	1 ft. End Drop on Lid End	350	0	-25 g	0	A.2.13.1-14
10	1 ft. End Drop on Bottom End	350	0	25 g	0	A.2.13.1-15
11	1 ft. Side Drop	350	25 g	0	0	A.2.13.1-16
12	1 g Gravity Loading	350	1 g	0	0	A.2.13.1-17

Notes:

1. Material properties based temperature of 350 °F bound temperature of structural components for thermal hot and thermal cold conditions

The above table identifies the individual load cases analyzed using the ANSYS models. Stress results for all the individual load cases identified in the table above are documented in Table A.2.13.1-1 through Table A.2.13.1-17.

Loads 7A, 7B, 7C, 7D represent four different bounding scenarios for the rail shock loads. Scenarios 7A and 7B address configurations whereby the applied shock load is resisted by the transport skid saddles. Scenarios 7C and 7D address shock load configurations that are resisted by the transport skid straps.

In load cases 7A and 7C, the axial component of the structural inertia load is directed toward the top end lid) of the cask, while in load cases 7B and 7D the axial component of structural inertia load is directed toward the bottom end of the cask.

Similarly, load cases 8A and 8B represent bounding vibration load scenarios. In load case 8A, the axial component of the inertia load is directed toward the top end of the cask (lid end), while in case 8B the axial component of inertia load is directed toward the bottom end of the cask.

The thermal analysis includes thirteen thermal load distributions for hot environment conditions (with ambient temperature of 100 °F), two limiting cases for cold environment conditions with ambient temperature -20 °F, and two limiting cases for cold environment conditions with ambient temperature -40 °F. All these cases represent enveloping temperature distributions that encompass the range of ambient conditions and heat loads for the various DSCs that are payloads of the MP197HB package..

The thermal stresses are determined using the temperature distributions obtained from the thermal heat transfer analysis of the various DSCs with their corresponding heat loads and ambient conditions. The bounding thermal stress results for each environmental case (100°F, -20°F, and -40°F) are summarized in Tables A.2.13.1-4 (100°F), Table A.2.13.1-5 (-20°F), and Table A.2.13.1-6 (-40°F) for subsequent use in the load combinations.

The table below shows the load combinations used for the NCT evaluations. The combinations of the results from the individual load cases (Load Cases 1 to 12) are performed and correspond to Load Cases 13 to 26 in the table below.

Load Case[1]	Load Combination	NCT–Individual Loads Used in Load Combination											
		1	2	3	4[2]	5A[3]	5B[4]	7[5]	8[6]	9	10	11	12
13	Hot Environment	X	X		X								X
14	Cold Environment	X		X			X						X
15	Increased Ext. Pressure	X		X		X							X
16	Minimum Ext. Pressure	X	X		X								X
17	Rail Car Vibration	X	X		X				X				
18		X		X		X	X		X				
19	Rail Car Shock	X	X		X			X					
20		X		X		X	X	X					
21	One Foot End Drop on Lid End	X	X		X					X			
22		X		X		X	X			X			
23	One Foot End Drop on Bottom End	X	X		X						X		
24		X		X		X	X				X		
25	One Foot Side Drop	X	X		X							X	
26		X		X		X	X					X	

1. Load Case numbers 13 to 26 combine the results of individual load cases 1 to 12, shown in the previous table.
2. The envelope of all the individual thermal hot environment cases with ambient temperature 100 °F is used in the load combination.
3. The envelope of the individual thermal cold environment cases with ambient temperature -20 °F is used in the load combination.
4. The envelope of the individual thermal cold environment cases with ambient temperature -40 °F is used in the load combination.
5. The envelope of the individual rail car shock cases 7A, 7B, 7C, 7D as specified in previous table is used in the load combination.
6. The envelope of the individual rail car vibration cases 8A and 8B as specified in previous table is used in the load combination.

B. Hypothetical Accident Conditions Cases

The individual load cases and associated loading conditions used for the HAC evaluations of the cask are presented in the table below. Pictorial illustrations of the applied loads for the various evaluated accident conditions are presented in Figure A.2.13.1-9 through Figure A.2.13.1-17.

HAC–List of Load Cases								
Load Case	Load Combination	Internal Pressure (psig)	External Pressure (psig)	Temp. Hot[1] (°F)	Front Impact Limiter Loads[2] Radial	Front Impact Limiter Loads[2] Axial	Rear Impact Limiter Loads[2] Radial	Rear Impact Limiter Loads[2] Axial
27	30 ft. End Drop on Bottom End	30		X		P_L		R_I, R_E
28			25	X		P_L		R_I, R_E
29	30 ft. End Drop on Lid End	30		X		R_I, R_E		P_L
30			25	X		R_I, R_E		P_L
31	30 ft. Side Drop	30		X	R_F		R_R	
32			25	X	R_F		R_R	
33	30 ft. CG Over Corner Drop on Bottom End	30		X	P_{LR}	P_{LA}	R_{IR}, R_{ER}	R_{IA}, R_{EA}
34			25	X	P_{LR}	P_{LA}	R_{IR}, R_{ER}	R_{IA}, R_{EA}
35	30 ft. CG Over Corner Drop on Lid End	30		X	R_{IR}, R_{ER}	R_{IA}, R_{EA}	P_{LR}	P_{LA}
36			25	X	R_{IR}, R_{ER}	R_{IA}, R_{EA}	P_{LR}	P_{LA}
37	30 ft. Slap-Down Drop on Bottom End[3]	30		X	P_{LR}	P_{LA}	R_{IR}, R_{ER}	
38			25	X	P_{LR}	P_{LA}	R_{IR}, R_{ER}	
39	30 ft. Slap-Down Drop on Lid End[3]	30		X	R_{IR}, R_{ER}	R_{IA}, R_{EA}	P_{LR}	P_{LA}
40			25	X	R_{IR}, R_{ER}	R_{IA}, R_{EA}	P_{LR}	P_{LA}
41	Immersion + Weight		290	X	R_F		R_R	
42	Fire Accident + Weight	120		620	R_F		R_R	

Notes:

1. Material properties based on temperature of 350 °F bound temperature of thermal hot and thermal cold conditions; temperature 620 °F envelops the fire accident thermal conditions.
2. Magnitudes of these loads are provided in Table A.2.13.1-48 and Table A.2.13.1-49, information about their geometrical profile is provided in Figure A.2.13.1-9 through Figure A.2.13.1-15.
   P_L, P_{LA}, Pressure Loads Due to Limiter Weight – Axial Components
   P_{LR}, Pressure Loads Due to Limiter Weight – Radial Components
   R_I, R_E, R_{IA}, R_{EA} Reaction Pressure Loads at Interface of Impact Limiter and cask body –Axial Components
   R_R, R_F, R_{IR}, R_{ER} Reaction Pressure at Interface of Impact Limiter and cask body –Radial Components.
3. Two slap-down drop orientations (10° and 20°) are analyzed.

A.2.13.1.5 NCT Loads Structural Evaluations

1. Application of Payload Weight to the Cask Body

Payload (weight of DSC) is applied to the cask model based on the bounding DSC weight of 118.5 kips.

1a. One-Foot Side Drop and 1G Gravity

For the one-foot side drop and 1g gravity load evaluations , the payload weight is applied as a pressure load, distributed uniformly in the axial direction and as a cosine shaped function over a ±75° angle sector in the circumferential direction. The maximum pressure is at the Inner Shell bottom (at the model symmetry line). The DSC weight distribution for these load cases is shown in Figure A.2.13.1-11 (pressure P_s).

1b. One-Foot End Drop and 3G Lifting

For the one-foot end drop and the 3g lifting load evaluations, the payload weight is applied as a pressure load distributed uniformly over the area of DSC in contact with the Lid (for the top end drop) or the Bottom Plate (for the bottom end drop). The way the DSC weight is applied in the top end drop and bottom end drop evaluations is illustrated in Figure A.2.13.1-9 (for the top end drop) and Figure A.2.13.1-10 (for the bottom end drop). The DSC weight pressure for these loads is denoted by P_I.

1c. Rail Car Shock and Vibration

For the rail car shock and vibration loads evaluations, the payload weight has an axial and a radial components. The axial load component is applied as a pressure distributed uniformly over the area of the DSC contact with the top Lid (load case 7, scenarios A and C) or the Bottom Plate (load case 7, scenarios B and D). The radial load is applied as a pressure load distributed uniformly in the axial direction and as a cosine function in the circumferential direction, over a $\pm 75^{\circ}$ angle sector.

2. Application of Impact Limiter Weight to the Cask Body

2a. One-Foot Side Drop

In the one-foot side drop, it is assumed that 1 ft. impact is mitigated evenly by both front and rear limiters and the impact limiters weight does not contribute to cask response.

2b. One-Foot End Drop

For the one-foot bottom end drop evaluations, the full weight of the front limiter is imposed as a uniform axial pressure load acting on the effective area of contact of the front impact limiter with the cask body.

For the one-foot top end drop evaluations, the full weight of the rear impact limiter is imposed as a uniform axial pressure load acting on the effective area of the contact of the rear impact limiter with cask body.

The pressure load due to impact limiter weight for top and bottom end drop cases are illustrated in Figure A.2.13.1-9 and Figure A.2.13.1-10 for the top and bottom end drops, respectively. The pressure for these loads is denoted P_L.

2c. Rail Car Shock & Vibration

For the rail car shock and vibration loads evaluations, the impact limiter weight is applied as axial and radial pressure loads.

For the case when the load is directly towards the bottom end, the axial component of the weight of the front impact limiter is applied as a positive (pushing) pressure load distributed uniformly over the contact area of the limiter with the cask lid and top flange. The radial component, acting on the outer surface of the top flange and outer shell is applied as a pressure load distributed

uniformly in the axial direction and as a cosine shaped function over a ±75° sector in the circumferential direction.

A negative (pulling) pressure is applied to account for the weight of the rear impact limiter distributed uniformly over the area of contact of the bottom flange ring and rear impact limiter.

For the case when the load is directly toward the lid end, the axial component of the weight of the rear impact limiter is applied as a positive pressure distributed uniformly across the area of contact of the rear impact limiter with the bottom plate and bottom flange. The radial component, acting on outer surface of the bottom flange and outer shell is applied as a pressure load distributed uniformly in the axial direction and as a cosine shaped function over a ±75° sector in the circumferential direction.

A negative (pulling) pressure is applied to account for the weight of the front impact limiter distributed uniformly over the area of contact of the top flange ring and the front impact limiter.

3. Application of Reaction Forces from Impact Load to the Cask Body

For the side drop and end drop evaluations, the impact limiters are not explicitly modeled. The crush loads or the reaction forces at the interface between impact limiters and cask body are represented as pressure loads.

3a. Side Drop

In the side drop evaluations, the radial reaction forces are imposed as a pressure load distributed uniformly in the axial direction and as a cosine shaped function in the circumferential direction over a ±75° sector. The maximum pressure is at cask bottom (at the model symmetry line). The reaction pressure loads are illustrated in Figure A.2.13.1-11. The R_R is the reaction load of rear impact limiter; R_F is the reaction load of front limiter.

3b. End Drop

In the end drop evaluations, the axial reaction force is imposed as a pressure load distributed in the form of two-level step function. Due to the significantly dissimilar axial stiffness, the reaction force is represented by a two level step function (lower in the central area within the lid or bottom plate perimeter) and higher in the outer part of the top flange or bottom flange rings.

These loads are shown in Figure A.2.13.1-9 (for the top end drop) and Figure A.2.13.1-10 (for the bottom end drop) as loads R_I and R_E. The ratio of total reaction forces for R_E and R_I can be estimated by the following relations:

For the bottom end drop case, the following relation is employed to calculate R_{EA} and R_{IA}:

$$\frac{R_{EA}}{R_{IA}} = \frac{\text{Cask Body Weight + Front Impact Limiter Weight - Bottom Plate Weight - RAM Weight}}{\text{Payload Weight + Bottom Plate Weight + RAM Weight}}$$

$$R_{EA} + R_{IA} = \text{Cask Body Weight} + \text{Payload Weight} + \text{Front Impact Limiter Weight}$$

For the top end drop case, the following ratio R_E/R_I is employed to calculate R_{EA} and R_{IA}:

$$\frac{R_{EA}}{R_{IA}} = \frac{\text{Cask Body Weight} + \text{Rear Impact Limiter Weight} - \text{Lid Weight}}{\text{Payload Weight} + \text{Lid Weight}}$$

$$R_{EA} + R_{IA} = \text{Cask Body Weight} + \text{Payload Weight} + \text{Rear Impact Limiter Weight}$$

A.2.13.1.6 HAC Loads Structural Evaluations

1. Application of Payload to the Cask Body

Payload (weight of DSC) is applied to the cask model based on the bounding DSC weight of 118.5 kips.

1a. Side Drop Evaluation

For the side drop evaluations the payload weight is applied as a pressure load distributed uniformly in the axial direction and as a cosine shaped function over a ±75° angle sector in the circumferential direction. The maximum of pressure is at the inner shell bottom (at the model symmetry line). The DSC weight distribution for the side drop case is shown in Figure A.2.13.1-11 (pressure P_s).

1b. End Drop Evaluation

For the end drop evaluation the payload weight is applied as a pressure load distributed uniformly over the area of DSC contact with the lid (for the top end drop) or the bottom plate (for the bottom end drop). The way the DSC weight is applied for the top end drop and the bottom end drop is illustrated in Figure A.2.13.1-9 (top end drop) and Figure A.2.13.1-10 (for the bottom end drop). The DSC weight pressure for these loads is denoted by P_I.

1c. Corner Drop/Slap Down Evaluations

In the corner drop calculations the payload (DSC weight) is applied as an axial load and a radial load.

The axial load component is applied as a pressure load distributed uniformly over the area of the DSC in contact with the lid (for top end drop) or the bottom plate (for the bottom end drop). The radial load component is applied as a pressure rising linearly towards the striking corner in the axial direction and as a cosine shaped function over a ±75° angle sector in the circumferential direction. The maximum pressure P_{max} is at the cask bottom (at the model symmetry line), at the striking corner.

The DSC pressures for corner drops are illustrated in Figure A.2.13.1-12 (for CG Over Corner Drop on the Lid End), Figure A.2.13.1-13 (for CG Over Corner Drop on the Bottom End),

Figure A.2.13.1-14 (for Slap Down on the Lid End), and Figure A.2.13.1-15 (for Slap Down on the Bottom End). The payload axial pressure is denoted P_{IA}. The radial pressure is denoted P_{IR}.

2. Application of Impact Limiter Weight to the Cask Body

Loads applied to the cask model are based on a front impact limiter weight of 16,000 lb and a rear impact limiter weight of 16,000 lb. These weights bound the actual weight of the impact limiters.

2a. Side Drop

In the side drop accident it is assumed that the impact is mitigated evenly by both the front and rear impact limiters and the impact limiters weight does not contribute to cask response.

2b. End Drop

For the bottom end drop evaluations the full weight of the front limiter is applied as a uniform axial pressure load acting on the effective area of contact of the front impact limiter with the cask body.

For the top end drop evaluations, the full weight of the rear impact limiter is applied as a uniform axial pressure load acting on the effective area of contact of the rear impact limiter with the cask body.

The pressure load due to impact limiter weight for the top end drop and the bottom end drop cases are illustrated in Figure A.2.13.1-9 (top end drop) and Figure A.2.13.1-10 (bottom end drop). The pressure for these loads is denoted P_L

2c. Corner Drop/Slap Down

For the corner drops scenarios, axial and radial pressure loads simulate the effect of impact limiter weight.

For the corner drops on the bottom end, the axial component is applied as a pressure load distributed uniformly across the area of contact of the impact limiter with the lid and top flange. The radial component acting on outer surface of the top flange and outer shell is applied as a pressure load distributed uniformly in the axial direction, and as a cosine shaped function over a $\pm 75^{\circ}$ angle sector in the circumferential direction.

For the corner drops on the lid end, the axial component is applied as a pressure load distributed uniformly across the area of contact of the rear impact limiter with the bottom plate and bottom flange. The radial component acting on the outer surface of the bottom flange and outer shell is applied as a pressure load distributed uniformly in an axial direction and as a cosine shaped function over a $\pm 75^{\circ}$ angle sector in the circumferential direction.

The pressure load due to impact limiter weight for the corner drops is illustrated in Figure A.2.13.1-12 (CG Over Corner Drop on Lid End), Figure A.2.13.1-13 (CG Over Corner Drop on Bottom End), Figure A.2.13.1-14 (Slap Down on Lid End), and Figure A.2.13.1-15 (Slap Down on Bottom End). The radial pressure component for these loads is denoted P_{LR}. The axial pressure component for these loads is denoted P_{LA}.

3. Application of Reaction Forces from Impact Load to the Cask Body

The crush loads at the interface between the impact limiters and the cask body are represented as the pressure loads.

3a. Side Drop

For the side drop evaluations the radial reaction forces are applied as a pressure load distributed uniformly in the axial direction and as the cosine shaped function over a $\pm 75^{\circ}$ angle sector in the circumferential direction. The maximum pressure is at the cask bottom (at the model symmetry line). The reaction pressure loads are illustrated in Figure A.2.13.1-11. The R_R is the reaction load of the rear impact limiter; R_F is the reaction load of the front limiter. Values of reaction forces R_F and R_R are tabulated in Table A.2.13.1-48 (rear impact limiter) and Table A.2.13.1-49 (front impact limiter).

3b. End Drop Calculations

For the end drop evaluations the axial reaction force is applied as a pressure load distributed in the form of two-level step function. Due to the significantly dissimilar axial stiffness, the reaction force is lower in the central part of crush area (area within lid or bottom plate perimeter) and higher in the outer part (top flange or bottom flange rings).

These pressure loads are shown in Figure A.2.13.1-9 (top end drop) and Figure A.2.13.1-10 (bottom end drop) as loads R_{IA} and R_{EA}. It is assumed that the ratio of total reaction forces for R_{EA} and R_{IA} can be estimated by the following relations:

For the end drop on bottom end cases, the following relation is employed to calculate the R_E and R_I:

$$\frac{R_{EA}}{R_{IA}} = \frac{\text{Cask Body Weight} + \text{Front Impact Limiter Weight} - \text{Bottom Plate Weight} - \text{RAM Weight}}{\text{Payload Weight} + \text{Bottom Plate Weight} + \text{RAM Weight}}$$

$$R_{EA} + R_{IA} = \text{Cask Body Weight} + \text{Payload Weight} + \text{Front Impact Limiter Weight}$$

For the top end drop case the following ratio for R_E/R_I is employed to calculate R_E and R_I:

$$\frac{R_{EA}}{R_{IA}} = \frac{\text{Cask Body Weight} + \text{Rear Impact Limiter Weight} - \text{Lid Weight}}{\text{Payload Weight} + \text{Lid Weight}}$$

$$R_{EA} + R_{IA} = \text{Cask Body Weight} + \text{Payload Weight} + \text{Rear Impact Limiter Weight}$$

Values of total reaction forces R_{IA} and R_{EA} for all end drop evaluations are presented in Table A.2.13.1-48 (rear impact limiter) and Table A.2.13.1-49 (front impact limiter).

3c. Corner Drop/Slap Down

The axial reaction force is modeled consistently with the end drop model, but it is assumed to be distributed linearly in the transverse direction, with maximum pressure at the bottom, at the impacted corner.

The axial reaction pressure loads for corner drops are shown in Figure A.2.13.1-12 (for CG Over Corner Drop on Lid End), Figure A.2.13.1-13 (for CG Over Corner Drop on Bottom End), Figure A.2.13.1-14 (for Slap Down on Lid End), and Figure A.2.13.1-15 (for Slap Down on Bottom End). The axial reaction loads are denoted as loads R_{IA} and R_{EA}.

It is assumed that the ratio of total reaction forces for R_{IA} and R_{EA} can be estimated by the following relations:

For the scenario of the corner bottom end drop, the following relation is employed to estimate ratio of R_{IA} and R_{EA}:

$$\frac{R_{EA}}{R_{IA}} = \frac{\text{Cask Body Weight} + \text{Front Impact Limiter Weight} - \text{Bottom Plate Weight} - \text{RAM Weight}}{\text{Payload Weight} + \text{Bottom Plate Weight} + \text{RAM Weight}}$$

For the scenario of the corner top end drop the following relation is employed to estimate ratio of R_{IA} and R_{EA}:

$$\frac{R_{EA}}{R_{IA}} = \frac{\text{Cask Body Weight} + \text{Rear Impact Limiter Weight} - \text{Lid Weight}}{\text{Payload Weight} + \text{Lid Weight}}$$

The radial reaction pressure loads for corner drops are shown Figure A.2.13.1-12 (for CG Over Corner top end drop), Figure A.2.13.1-13 (CG Over Corner bottom end drop), Figure A.2.13.1-14 (Slap Down on lid end), and Figure A.2.13.1-15 (Slap Down on bottom end). The radial reaction loads are denoted as loads R_{ER} and R_{IR}.

Reaction pressure load magnitudes used in calculations are summarized in Table A.2.13.1-48 and Table A.2.13.1-49.

A.2.13.1.7 NCT Stress Evaluation

The stresses resulting from the NCT evaluations of the MP197HB transport cask design are assessed against the stress limits for Service Level A of the ASME Code, Section III, Subsection NB. The Code imposes limits on:

1. General primary membrane stress (PM),
2. Local primary membrane stress (PL),
3. Primary membrane plus bending stress (PM/PL+PB),
4. Primary membrane plus bending and secondary membrane plus bending stress (PM+PB+Q), referred as P+Q in the following stress reporting tables.

The ASME code limits are S_m–for general primary membrane stress; $1.5S_m$ – for local primary membrane stress; $1.5S_m$ – for primary membrane plus bending stress; $3.0S_m$ – for primary membrane plus bending stress and secondary membrane plus bending stress.

A. Stress Criteria

The stress criteria employed in stress assessments of the MP197HB are summarized below:

Allowable Stresses	Carbon Steel Plate SA 203 Grade E				Carbon Steel Forging SA350 Grade LF3			
Temperature	Properties		NCT Allowables		Properties		NCT Allowables	
350 °F	S_y	34.8 ksi	PM	23.1 ksi	S_y	32.6 ksi	PM	21.8 ksi
	S_u	70.0 ksi	PL + PB	34.7 ksi	S_u	70.0 ksi	PL + PB	32.7 ksi
	S_m	23.1 ksi	P + Q	69.3 ksi	S_m	21.75 ksi	P + Q	65.3 ksi

B. Load Combinations and Reporting of Stress Results

The individual NCT load cases analyzed are described in Section A.2.13.1.4. For purposes of reporting stress results, the cask body is divided into the following seven components shown in Figure A.2.13.1-2: outer shell, inner shell, lid, top flange, bottom flange, bottom plate, and ram closure plate. For each component, the stresses are categorized according to the rules of the ASME Code, Section III, Subsection NB for Class 1 Components (PM, PL+PB, P+Q). The highest stress intensity values obtained for each component and for the each individual load case are summarized in Table A.2.13.1-1 to Table A.2.13.1-17.

The stress intensity values for the individual load cases shown in Table A.2.13.1-1 to Table A.2.13.1-17 are combined in accordance with the various load combinations to determine the total stress for each cask component for a particular load combination. The tables in Section A.2.13.1.4 provide a matrix of the individual loads (load cases 1 to 12) and the various load combinations (load cases 13 to 26) used to determine the cask body stresses for the specified normal conditions of transport. The "x" in the table for load cases 13 to 26 indicates the individual load cases that are used in the load combinations.

The following conservative procedure is used in the calculation of the reported total (combined) stress intensity. For a given cask component, the maximum stress intensity from each individual

load case are calculated and added (per each load combination) together regardless of the location of maximum stress. This approach is conservative relative to algebraically adding the corresponding stress components for each individual load case and then determining the resulting stress intensity for the appropriate load combination. The stress intensity obtained per the above conservative procedure is, therefore, an upper bound since it represents the absolute sum rather than the algebraic sum of the stresses. The above procedure is used for all the load combination cases except for load combinations 25 and 26. For these two load combination cases, the stress components resulting from individual load cases 1 and 11 are first added algebraically within ANSYS and the resultant stress intensity is summed together with the stress intensities from the other load cases to get the total stress for the load combination.

The following table shows the NCT load combinations used and points to the tables that summarize the results for each load combination. The results for the individual load cases (Load Cases 1 to 12 in Section A.2.13.1-4) are summarized in Table A.2.13.1-1 to Table A.2.13.1-17 and the results for each load combination for NCT (Load Cases 13 to 26) are summarized in Table A.2.13.1-18 to Table A.2.13.1-31.

Load Combination Number	Load Combination Method	Load Combination Stress Result Table No.
13	1 + 2 + 4 + 12	Table A.2.13.1-18
14	1 + 3 + 5B + 12	Table A.2.13.1-19
15	1 + 3 + 5A + 12	Table A.2.13.1-20
16	1 + 2 + 4 + 12	Table A.2.13.1-21
17	1 + 2 + 4 + max(8A, 8B)	Table A.2.13.1-22
18	1 + 3 + max (5A, 5B) + max(8A, 8B)	Table A.2.13.1-23
19	1 + 2 + 4 + max(7A,7B,7C,7D)	Table A.2.13.1-24
20	1 + 3 + max (5A, 5B) + max(7A,7B,7C,7D)	Table A.2.13.1-25
21	1 + 2 + 4 + 9	Table A.2.13.1-26
22	1 + 3 + max (5A, 5B)+ 9	Table A.2.13.1-27
23	1 + 2 + 4 + 10	Table A.2.13.1-28
24	1 + 3 + max (5A, 5B) + 10	Table A.2.13.1-29
25	1 + 2 + 4 + 11	Table A.2.13.1-30
26	1 + 3 + max (5A, 5B) + 11	Table A.2.13.1-31

For example, for load combination number 13 (Table A.2.13.1-18), the stress intensity values for the outer shell in the individual load cases (1 + 2 + 4 + 12) are combined as shown in the following table:

	PM	PL + PB	P +Q
Individual Load Case #1 (Table A.2.13.1-1)	0.2 ksi	0.4 ksi	0.4 ksi
Individual Load Case #2 (Table A.2.13.1-2)	0.3 ksi	0.7 ksi	0.7 ksi
Individual Load Case #4 (Table A.2.13.1-4)	0	0	13.9 ksi
Individual Load Case #12 (Table A.2.13.1-17)	1.51 ksi	3.58 ksi	3.58 ksi
Combined Load Case #13 (Table A.2.13.1-18)	2.01 ksi	4.68 ksi	18.58 ksi

For those load cases that have alternative scenarios (rail car shock cases 7A, 7B, 7C, 7D, and rail car vibration cases 8A, 8B), the maximum stress of the given load category is used in the load combination.

C. Summary of the NCT Stress results

Table A.2.13.1-18 through Table A.2.13.1-31 summarize the stress results for all the NCT loading conditions. These tables show the general primary membrane stresses PM, local primary membrane plus bending stresses PL + PB, and primary plus secondary stresses P + Q for all the analyzed load cases meet the applicable ASME code stress criteria. The stress ratio listed in the table is the calculated stresses divided by the allowable stresses.

From the analysis results presented in these tables, it is concluded that the normal loads stress limits are met and, therefore, that the containment function of the transport cask is maintained.

A.2.13.1.8 HAC Stress Evaluation

The stresses resulting from the HAC evaluations of the MP197HB transport cask design are assessed against the stress limits for Service Level D of the ASME Code. For Level D the stress criteria based of Appendix F, Section F-1341.2 (Plastic Analysis) are used. For accident conditions (Service Level D), the ASME code criteria are intended to ensure structural integrity of pressure retaining boundary. In accordance with the Level D provisions of the Code, secondary stresses need not be evaluated. Similarly, bearing stresses need not be evaluated except for pinned or bolted joints (F-1341.6).

Thus, for accident conditions, the code imposes limits on

1. general primary membrane stress intensity (PM),
2. maximum primary stress intensity (PL, PL+PB),

The ASME code limits for plastic analysis are $0.7*S_u$–for general primary membrane stress intensity, $0.9*S_u$–for maximum primary stress intensity. Acceptance Criteria for steel components are summarized below.

A. Stress Criteria

Stress criteria employed in stress assessments are summarized below:

Allowable Stresses	**Carbon Steel Plate SA 203 Grade E**				**Carbon Steel Forging SA350 Grade LF3**			
Temperature	**Properties**		**Allowable Stress**		**Properties**		**Allowable Stress**	
350 °F	Sy	34.8 ksi	PM	49.0 ksi	Sy	32.6 ksi	PM	49.0 ksi
	Su	70.0 ksi	PL	63.0 ksi	Su	70.0 ksi	PL	63.0 ksi
	Sm	23.1 ksi	PL+PB	63.0 ksi	Sm	21.75 ksi	PL+PB	63.0 ksi
620 °F	Sy	29.4 ksi	PM	48.5 ksi	Sy	27.6 ksi	PM	48.5 ksi
	Su	69.3 ksi	PL	57.1 ksi	Su	69.3 ksi	PL	62.5 ksi
	Sm	NA	PL+PB	57.1 ksi	Sm	18.6 ksi	PL+PB	62.5 ksi

B. Load Combination and Reporting of Stress Results

This section summarizes stress results for all HAC load combinations. The following table shows the HAC load combinations used and points to the tables that summarize the results for each HAC load combination. The stress results for each load for HAC shown in the table in Section A.2.13.1.4 (Load Cases 27 to 42) are summarized in Table A.2.13.1-32 to Table A.2.13.1-47.

HAC–List of Load Cases					
Load Combination No.	**Load**	**Internal Pressure (psig)**	**External Pressure (psig)**	**Temp. Hot (°F)**	**Stress Result Table No.**
27	30 Ft. End Drop on Bottom End	30		X	Table A.2.13.1-32
28			25	X	Table A.2.13.1-33
29	30 Ft. End Drop on Lid End	30		X	Table A.2.13.1-34
30			25	X	Table A.2.13.1-35
31	30 Ft. Side Drop	30		X	Table A.2.13.1-36
32			25	X	Table A.2.13.1-37
33	30 Ft. CG Over Corner Drop on Bottom End	30		X	Table A.2.13.1-38
34			25	X	Table A.2.13.1-39
35	30 Ft. CG Over Corner Drop on Lid End	30		X	Table A.2.13.1-40
36			25	X	Table A.2.13.1-41
37	30 Ft. Slap-Down Drop on Bottom End(1)	30		X	Table A.2.13.1-42
38			25	X	Table A.2.13.1-43
39	30 Ft. Slap-Down Drop on Lid End(1)	30		X	Table A.2.13.1-44
40			25	X	Table A.2.13.1-45
41	Immersion + Weight		290	X	Table A.2.13.1-46
42	Fire Accident + Weight	120		620	Table A.2.13.1-47

Note: 1. For the slap down case, two drop angles were analyzed (10° and 20°).

For the analysis of the HAC load cases all the loads that are part of the load combination are included as input to the ANSYS analysis (drop load, pressure load, etc.), therefore the resulting stress corresponds to the load combination result.

Table A.2.13.1-32 through Table A.2.13.1-47 summarize stress results for the HAC loading conditions. For the slap down cases, the stress results from the 10° slap down are slightly higher than 20° load case. Therefore, only stress results from the 10° slap down load cases are reported (Table A.2.13.1-42 to Table A.2.13.1-45).

Stress assessments show that MP197HB design satisfies imposed ASME stress criteria for Hypothetical Accident Conditions.

From the analysis results presented in Table A.2.13.1-32 through Table A.2.13.1-47, it is concluded that the structural integrity and containment function of the MP197HB transport cask are maintained for HAC loads.

A.2.13.1.9 Elastic Analysis of MP197HB Cask Body Due to HAC Loads

Stress results summarized in Table A.2.13.1-32 through Table A.2.13.1-47 are based on elastic-plastic analysis methodology and evaluated in accordance with the ASME Code, Appendix F [4] Plastic Analysis criteria (Paragraph F-1341.2). Based on the results shown on these tables, cask

component stresses for most of the load cases remain in the elastic range except for the following three load cases: side drop, CG over corner drop on lid ends, and slap down.

By reviewing these results, two bounding load cases (side drop with 25 psig external pressure-Table A.2.13.1-37 and slap down drop on lid end with 25 psig external pressure–Table A.2.13.1-45) are analyzed using elastic analysis methodology and the resulting stresses evaluated in accordance with the ASME Code, Appendix F [4] Elastic Analysis criteria (Paragraph F-1331.1).

The stresses resulting from the analyses of the two load cases above are compared with the Code allowable stress limits for elastic analysis and are summarized in Table A.2.13.1-52 (for the side drop with 25 psig external pressure load case) and Table A.2.13.1-53 (for the slap down drop on lid end with 25 psig external pressure load case). These tables show that all the calculated stresses in the containment boundary meet the ASME Code elastic analysis allowable stress limits. For the slap down drop on lid end with 25 psig external pressure case, the stresses in the outer shell slightly exceed the Code elastic allowables. However, as shown in Figure A.2.13.1-2, the outer shell component is not a containment boundary of the cask. Moreover, the outer shell component has been shown to meet the ASME Code allowable stress limits for plastic analysis, as shown in Table A.2.13.1-45.

A.2.13.1.10 Method of Interpretation/Obtaining the Stress Results From ANSYS Model

The stress results from the ANSYS finite element model are used to compare with the code allowables. The criteria are based on ASME code, Section III, Subsection NB requirements. The code imposes limits on:

1. General primary membrane stress (PM)
2. Local primary stress (PL)
3. Primary membrane plus bending stress (PM/PL+PB)
4. Primary membrane plus bending and secondary membrane plus bending stress (P+Q)

The general primary stress PM is interpreted as an average stress across the solid section of structural component that does not include the effect of discontinuities and concentrations and is produced only by pressure and/or mechanical loads. The local membrane stress PL is the same as PM, except that it takes also an account of the effect of gross discontinuities. Primary bending stress PB is a variable part of stress across the solid section that does not include the effect of discontinuities and concentrations and is produced only by pressure and/or mechanical loads. Secondary membrane plus bending stress Q represents self-limiting stress controlled by structure gross deformation, for example, caused by differential thermal expansion of spatially constrained structure.

A. Stress Classification Paths

Per ASME code requirements, stress classification sections or lines (paths) should comprise of all sections of the steel structure that potentially can contribute to the design failure. In case of the cask design the special attention needs to be focused on cask parts that compose the containment casing of payload.

In order to obtain an adequate amount of information regarding each category of ASME code primary or secondary stresses, for all cask components stress information is collected for a comprehensive, structured set of stress classification lines (paths).

For shell and plate sections of cask structure, the ASME code stress classification paths are predefined at all section locations as the across the wall thickness paths, normal to the cylinder or plate section mid-plane. For more complicated shapes of cask components stress paths are also defined for the most, surface-node to surface-node, paths across the wall thickness in locations and orientations meaningful for anticipated stress flow routes. The path locations are described in the following table. Stress paths at cask body symmetry plane are illustrated in Figure A.2.13.1-18 (cask top end) and A.2.13.1-19 (cask bottom end).

Cask Component Finite Element Model Stress Paths

Component	Stress Paths
Outer Shell	Paths are defined using all nodal points on the inside shell surface (shell ID) to the corresponding point on the shell OD.
Inner Shell	Paths are defined using all nodal points on the inside shell surface (shell ID) to the corresponding point on the shell OD.
Lid	Paths are defined using all nodal points on the inside face of the lid (including the section of reduced thickness at the bolt area) to the corresponding point on the outside surface.
Top Flange	Paths are defined from all nodes on the inner surface to the corresponding nodes on the outer surface of cylinder of cone segments of flange.
Bottom Flange	Paths are defined from all nodes on the inner surface to the corresponding nodes on the outer surface of cylinder of cone segments of flange.
Bottom Plate	Paths are defined using all nodal points on the inside face of the plate to the corresponding points on the outside surface.
Ram Closure Plate	Paths are defined using nodal points on the inside face of the plate to the corresponding point on the outside surface.

B. Stress Linearization Method

In order to correctly report the resulting stress as classified by the ASME Code, the stresses are linearized and membrane and bending stresses are separated for comparison with the allowables.

Stress information at predefined paths and stress linearization procedure is based on the method employed in the ANSYS code. The method used in ANSYS is based on Gordon methodology [11]. Principal results data are mapped onto a path by first interpolating individually stress components (σ_x, σ_y, σ_z, σ_{xy}, σ_{xz}, σ_{zx}) to the path. Then, stress averaging through the wall path and the linearization are done independently for all six stress components.

Principal membrane stresses and membrane stress intensity are derived from membrane parts of the individual stress components. Similarly, linearized principal stresses and linearized stress intensity at the path section surface are derived from linearized individual stress components of that surface.

In case of elastic analysis methodology stress path evaluation in ANSYS brings the information about an average stress intensity across the path, as well as maximum linearized stress at classification path surface, PL+PB.

Conservatively no distinction is assumed between paths located at gross or local discontinuities and areas remote from these discontinuities and all path averaged stresses (including general primary stress intensities, PM, and local primary stress intensities, PL) are classified conservatively and reported as PM stresses and assessed against PM stress allowable.

Also, in order to simplify PM+PB stress assessment, all membrane plus bending stresses reported from ANSYS model paths are classified as primary membrane and bending stresses, PM+PB, and assessed against PM+PB stress allowables.

Following are two examples to show how this methodology is performed.

Example 1- Load Case number 40, (Table A.2.13.1-45, Outer Shell Component)

Figures A.2.13.1-18 and A.2.13.1-19 show the MP197HB 3D finite element model and the pass selections at each component for stress linearization.

Figure A.2.13.1-20 shows an example of outer shell component stress plot before stress linearization is performed. This plot shows the total stress intensity for outer shell component for load case no. 40. Based on the stress plot, the maximum stress intensity for the outer shell component for this load case is 42,280 psi. The bottom side of the Figure A.2.13.1-20 shows the stress results after performing the stress linearization based on the pass selections as shown in Figures A.2.13.1-18 and A.2.13.1-19. The linearized stress results (PM = 41.7 ksi, PL = 47.3 ksi, and PL + PB = 47.3 ksi) are shown in Table A.2.13.1-45.

Example 2- Load Combination Number 44, (Table A.2.13.1-53, Outer Shell Component)

Figures A.2.13.1-18 and A.2.13.1-19 show the MP197HB 3D finite element model and the pass selections at each component for stress linearization.

Figure A.2.13.1-21 shows an example of outer shell component stress plot before stress linearization is performed. This plot shows the total stress intensity for outer shell component for load case no. 44. Based on the stress plot, the maximum stress intensity for the outer shell component for this load case is 81,557 psi. The bottom side of the Figure A.2.13.1-21 shows the stress results after performing the stress linearization based on the pass selections as shown in Figures A.2.13.1-18 and A.2.13.1-19. The linearized stress results (PM = 54.3 ksi and PL + PB = 81.3 ksi) are shown in Table A.2.13.1-45.

A.2.13.1.11 Summary of MP197HB Cask Body Structural Evaluations

The stress results from the NCT loads are summarized in Table A.2.13.1-18 through Table A.2.13.1-31. The stress limits based on the ASME code, Subsection NB [4] structural design criteria are also included in these tables. From the analysis results presented in these tables, it is shown that the NCT loads will not result in any structural damage to the cask and the containment function of the cask will be maintained.

The stress results from the HAC loads are summarized in Table A.2.13.1-33 through Table A.2.13.1-47 for plastic analysis results and Table A.2.13.1-52 and Table A.2.13.1-53 for elastic analysis results. The stress limits based on the ASME code, Appendix F [4] structural design criteria for both plastic analysis and elastic analysis are also listed in the tables. From the analysis results presented in these tables, it is shown that the HAC loads will not result in any structural damage to the cask and the containment function of the cask will be maintained.

A.2.13.1.12 References

1. 10CFR PART 71, Packaging and Transportation of Radioactive Material.
2. Not used.
3. Regulatory Guide 7.8, "Load Combinations for the Structural Analysis of Shipping casks for Radioactive Material."
4. ASME Code Section III, Division 1, Subsection NB and Appendix F, 2004, including 2006 addenda.
5. NUREG-1617, "Standard Review Plan for Transportation Packages for Spent Nuclear Fuel," March 2000.
6. Regulatory Guide 7.9, "Standard Format and Content of Part 71 Applications for Approval of Packages for Radioactive Material."
7. ANSYS Computer Code and User's Manual, Release 10A1.
8. Not used.
9. Not Used.
10. *Not Used.*
11. Gordon, J. L., "OUTCUR: An Automated Evaluation of Two-Dimensional Finite Element Stresses" ASME Paper No. 76-WA/PVP-16, ASME Winter Annual Meeting (December 1976).

Table A.2.13.1-1
NCT Stress Results–Load Case 1–Bolt Preload

Load Case 1			NCT–Bolt Preload								
			Max Stress [ksi] Stress Ratio			Allowable Stress [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL+PB	P+Q(1)	PM	PL+PB	P+Q(1)	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	0.2 0.8%	0.4 1.1%	0.4 0.5%	23.1	34.7	69.3	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	0.4 1.6%	0.6 1.7%	0.6 0.8%	23.1	34.7	69.3	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	5.9 25.4%	12.5 36.0%	12.5 18.0%	23.1	34.7	69.3	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	3.8 17.2%	9.8 30.1%	9.8 15.0%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	0.04 0.1%	0.1 0.2%	0.1 0.1%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	1.6 7.5%	4.5 13.8%	4.5 6.9%	21.8	32.6	65.3	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	0.2 0.7%	0.4 1.0%	0.4 0.5%	23.1	34.7	69.3	34.8	70	23.1

Note 1: P+Q stands for primary plus secondary stresses

Table A.2.13.1-2
NCT Stress Results–Load Case 2–Internal Pressure 30 psig

Load Case 2			NCT–Internal Pressure Load 30 psig								
			Max Stress [ksi] Stress Ratio			Allowable Stress [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL+PB	P+Q	PM	PL+PB	P+Q	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	0.3 1.2%	0.7 1.9%	0.7 1.0%	23.1	34.7	69.3	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	0.6 2.7%	0.6 1.9%	0.6 0.9%	23.1	34.7	69.3	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	0.5 2.0%	2.7 7.7%	2.7 3.8%	23.1	34.7	69.3	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	0.5 2.4%	0.6 1.9%	0.6 1.0%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	0.4 2.0%	1.4 4.4%	1.4 2.2%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	0.3 1.4%	1.4 4.2%	1.4 2.1%	21.8	32.6	65.3	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	0.3 1.1%	1.0 2.9%	1.0 1.5%	23.1	34.7	69.3	34.8	70	23.1

Table A.2.13.1-3
NCT Stress Results–Load Case 3–External Pressure 25 psig

Load Case 3			NCT–External Pressure 25 psig								
			Max Stress [ksi] Stress Ratio			Allowable Stress [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL+PB	P+Q	PM	PL+PB	P+Q	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	0.3 1.4%	0.8 2.2%	0.8 1.1%	23.1	34.7	69.3	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	0.4 1.8%	0.6 1.8%	0.6 0.9%	23.1	34.7	69.3	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	0.2 0.8%	2.1 6.2%	2.1 3.1%	23.1	34.7	69.3	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	0.2 1.0%	0.5 1.4%	0.5 0.7%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	0.4 2.0%	1.2 3.6%	1.2 1.8%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	0.3 1.2%	1.2 3.6%	1.2 1.8%	21.8	32.6	65.3	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	0.1 0.6%	0.8 2.2%	0.8 1.1%	23.1	34.7	69.3	34.8	70	23.1

Table A.2.13.1-4
NCT Stress Results–Load Case 4–Hot Environment–Stress Envelope

Load Case 4			NCT–Hot Environment–Stress Envelope								
			Max Stress [ksi] Stress Ratio			Allowable Stress [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL+PB	P+Q[1]	PM	PL+PB	P+Q	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	0.0	0.0	13.9 20.1%	23.1	34.7	69.3	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	0.0	0.0	20.9 30.2%	23.1	34.7	69.3	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	0.0	0.0	15.5 22.3%	23.1	34.7	69.3	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	0.0	0.0	22.0 33.7%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	0.0	0.0	23.9 36.6%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	0.0	0.0	15.9 24.3%	21.8	32.6	65.3	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	0.0	0.0	13.9 20.0%	23.1	34.7	69.3	34.8	70	23.1

Note 1: General Membrane plus Bending Stress classified as the secondary stress Q

Table A.2.13.1-5
NCT Stress Results–Load Case 5A–Cold Environment -20 °F–Stress Envelope

Load Case 5A			NCT–Cold Environment -20°F–Stress Envelope								
			Max Stress [ksi] Stress Ratio			Allowable Stress [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL+PB	P+Q(1)	PM	PL+PB	P+Q	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	0.0	0.0	13.8 20.0%	23.1	34.7	69.3	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	0.0	0.0	20.7 29.9%	23.1	34.7	69.3	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	0.0	0.0	13.7 19.7%	23.1	34.7	69.3	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	0.0	0.0	20.7 31.7%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	0.0	0.0	23.8 36.5%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	0.0	0.0	16.3 24.9%	21.8	32.6	65.3	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	0.0	0.0	14.5 20.9%	23.1	34.7	69.3	34.8	70	23.1

Note 1: General Membrane plus Bending Stress classified as the secondary stress Q

Table A.2.13.1-6
NCT Stress Results–Load Case 5B–Cold Environment -40 °F–Stress Envelope

Load Case 5B			NCT–Cold Environment -40 °F								
			Max Stress [ksi] Stress Ratio			Allowable Stress [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL+PB	P+Q(1)	PM	PL+PB	P+Q	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	0.0	0.0	12.5 18.0%	23.1	34.7	69.3	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	0.0	0.0	19.5 28.1%	23.1	34.7	69.3	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	0.0	0.0	16.9 24.4%	23.1	34.7	69.3	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	0.0	0.0	22.2 34.0%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	0.0	0.0	18.4 28.2%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	0.0	0.0	10.1 15.4%	21.8	32.6	65.3	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	0.0	0.0	7.9 11.4%	23.1	34.7	69.3	34.8	70	23.1

Note 1: General Membrane plus Bending Stress classified as the secondary stress Q

Table A.2.13.1-7
NCT Stress Results–Load Case 6–3G Lifting

Load Case 6			NCT–3G Lifting								
			Max Stress [ksi] Stress Ratio			Allowable Stress [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL+PB	P+Q	PM	PL+PB	P+Q	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	2.3 10.1%	3.3 9.5%	3.3 4.8%	23.1	34.7	69.3	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	2.2 9.3%	3.2 9.3%	3.2 4.7%	23.1	34.7	69.3	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	0.1 0.5%	0.5 1.4%	0.5 0.7%	23.1	34.7	69.3	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	1.8 8.3%	2.7 8.3%	2.7 4.2%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	2.2 9.9%	4.5 13.7%	4.5 6.9%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	1.3 5.8%	4.3 13.2%	4.3 6.6%	21.8	32.6	65.3	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	0.1 0.6%	0.3 0.9%	0.3 0.5%	23.1	34.7	69.3	34.8	70	23.1

Table A.2.13.1-8
NCT Stress Results–Load Case 7A–Rail Car Shock Loads–Scenario A

Load Case 7A			NCT–Rail Car Shock Loads–Scenario A								
			Max Stress [ksi] Stress Ratio			Allowable Stress [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL+PB	P+Q	PM	PL+PB	P+Q	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	6.1 26.5%	12.6 36.4%	12.6 18.2%	23.1	34.7	69.3	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	4.4 19.0%	5.7 16.5%	5.7 8.2%	23.1	34.7	69.3	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	0.1 0.6%	0.4 1.2%	0.4 0.6%	23.1	34.7	69.3	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	2.8 13.0%	4.6 14.1%	4.6 7.1%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	1.8 8.4%	2.8 8.5%	2.8 4.2%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	1.1 5.2%	1.5 4.5%	1.5 2.2%	21.8	32.6	65.3	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	0.1 0.3%	0.1 0.4%	0.1 0.2%	23.1	34.7	69.3	34.8	70	23.1

Table A.2.13.1-9
NCT Stress Results–Load Case 7B–Rail Car Shock Loads–Scenario B

Load Case 7B			NCT–Rail Car Shock Loads–Scenario B								
			Max Stress [ksi] Stress Ratio			Allowable Stress [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL+PB	P+Q	PM	PL+PB	P+Q	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	5.3 22.9%	8.3 23.9%	8.3 11.9%	23.1	34.7	69.3	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	2.6 11.5%	3.7 10.8%	3.7 5.4%	23.1	34.7	69.3	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	2.2 9.7%	13.0 37.4%	13.0 18.7%	23.1	34.7	69.3	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	2.8 12.7%	5.5 16.9%	5.5 8.5%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	1.7 7.8%	4.0 12.3%	4.0 6.2%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	0.9 4.2%	2.0 6.1%	2.0 3.0%	21.8	32.6	65.3	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	0.03 0.1%	0.2 0.5%	0.2 0.2%	23.1	34.7	69.3	34.8	70	23.1

Table A.2.13.1-10
NCT Stress Results–Load Case 7C–Rail Car Shock Loads–Scenario C

Load Case 7C			NCT–Rail Car Shock Loads–Scenario C								
			Max Stress [ksi] Stress Ratio			Allowable Stress [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL+PB	P+Q	PM	PL+PB	P+Q	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	6.9 30.0%	12.9 37.1%	12.9 18.6%	23.1	34.7	69.3	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	3.1 13.4%	5.5 15.9%	5.5 8.0%	23.1	34.7	69.3	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	0.1 0.4%	0.3 0.9%	0.3 0.5%	23.1	34.7	69.3	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	2.4 11.2%	3.8 11.7%	3.8 5.8%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	1.3 6.1%	3.0 9.3%	3.0 4.6%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	0.5 2.3%	1.1 3.3%	1.1 1.6%	21.8	32.6	65.3	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	0.1 0.3%	0.2 0.5%	0.2 0.2%	23.1	34.7	69.3	34.8	70	23.1

Table A.2.13.1-11
NCT Stress Results–Load Case 7D–Rail Car Shock Loads–Scenario D

Load Case 7D			NCT–Rail Car Shock Loads–Scenario D								
			Max Stress [ksi] Stress Ratio			Allowable Stress [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL+PB	P+Q	PM	PL+PB	P+Q	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	5.2 22.4%	8.5 24.6%	8.5 24.6%	23.1	34.7	34.7	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	3.9 16.8%	6.1 17.6%	6.1 17.6%	23.1	34.7	34.7	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	0.2 0.7%	1.7 4.8%	1.7 4.8%	23.1	34.7	34.7	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	3.5 15.9%	5.6 17.2%	5.6 17.2%	21.8	32.6	32.6	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	3.9 17.9%	8.8 26.9%	8.8 26.9%	21.8	32.6	32.6	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	2.2 10.3%	7.4 22.7%	7.4 22.7%	21.8	32.6	32.6	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	0.3 1.4%	0.8 2.2%	0.8 2.2%	23.1	34.7	34.7	34.8	70	23.1

Table A.2.13.1-12
NCT Stress Results–Load Case 8A–Rail Car Vibration Loads–Scenario A

Load Case 8A			NCT–Rail Car Vibration Loads –Scenario A								
			Max Stress [ksi] Stress Ratio			Allowable Stress [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL+PB	P+Q	PM	PL+PB	P+Q	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	0.83 3.6%	1.68 4.9%	1.68 2.4%	23.1	34.7	69.3	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	0.24 1.0%	0.34 1.0%	0.34 0.5%	23.1	34.7	69.3	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	0.02 0.1%	0.07 0.2%	0.07 0.1%	23.1	34.7	69.3	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	0.34 1.6%	0.56 1.7%	0.56 0.9%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	0.29 1.3%	0.56 1.7%	0.56 0.9%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	0.18 0.8%	0.37 1.1%	0.37 0.6%	21.8	32.6	65.3	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	0.01 0.03%	0.02 0.06%	0.02 0.03%	23.1	34.7	69.3	34.8	70	23.1

Table A.2.13.1-13
NCT Stress Results–Load Case 8B–Rail Car Vibration Loads–Scenario B

Load Case 8B			NCT–Rail Car Vibration Loads–Scenario B								
			Max Stress [ksi] Stress Ratio			Allowable Stress [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL+PB	P+Q	PM	PL+PB	P+Q	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	0.82 3.6%	1.68 4.8%	1.68 2.4%	23.1	34.7	69.3	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	0.34 1.5%	0.49 1.4%	0.49 0.7%	23.1	34.7	69.3	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	0.09 0.4%	0.54 1.6%	0.54 0.8%	23.1	34.7	69.3	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	0.55 2.5%	0.93 2.8%	0.93 1.4%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	0.18 0.8%	0.30 0.9%	0.30 0.5%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	0.10 0.4%	0.13 0.4%	0.13 0.2%	21.8	32.6	65.3	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	0.01 0.02%	0.01 0.04%	0.01 0.02%	23.1	34.7	69.3	34.8	70	23.1

Table A.2.13.1-14
NCT Stress Results–Load Case 9–One Foot Vertical Drop on Lid End

Load Case 9			NCT–One Foot Vertical Drop on Lid End								
			Max Stress [ksi] Stress Ratio			Allowable Stress [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL+PB	P+Q	PM	PL+PB	P+Q	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	4.6 20.0%	7.3 21.0%	7.3 10.5%	23.1	34.7	69.3	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	4.6 19.8%	9.0 26.0%	9.0 13.0%	23.1	34.7	69.3	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	2.8 12.2%	10.4 30.1%	10.4 15.0%	23.1	34.7	69.3	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	8.6 39.6%	10.2 31.2%	10.2 15.6%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	2.5 11.4%	4.3 13.1%	4.3 6.6%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	1.2 5.5%	4.5 13.7%	4.5 6.9%	21.8	32.6	65.3	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	1.6 7.0%	4.8 13.8%	4.8 6.9%	23.1	34.7	69.3	34.8	70	23.1

Table A.2.13.1-15
NCT Stress Results–Load Case 10–One Foot Vertical Drop on Bottom End

Load Case 10			NCT–One Foot Vertical Drop on Bottom End								
			Max Stress [ksi] Stress Ratio			Allowable Stress [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL+PB	P+Q	PM	PL+PB	P+Q	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	4.8 20.7%	5.5 15.8%	5.5 7.9%	23.1	34.7	69.3	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	4.2 18.0%	6.6 18.9%	6.6 9.5%	23.1	34.7	69.3	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	2.0 8.6%	7.0 20.1%	7.0 10.1%	23.1	34.7	69.3	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	1.8 8.1%	4.1 12.6%	4.1 6.3%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	4.8 21.9%	6.3 19.3%	6.3 9.7%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	2.2 10.3%	5.0 15.4%	5.0 7.7%	21.8	32.6	65.3	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	0.8 3.3%	1.8 5.1%	1.8 2.6%	23.1	34.7	69.3	34.8	70	23.1

Table A.2.13.1-16
NCT Stress Results–Load Case 11–One Foot Side Drop

Load Case 11			NCT–One Foot Side Drop								
			Max Stress [ksi] Stress Ratio			Allowable Stress [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL+PB	P+Q	PM	PL+PB	P+Q	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	17.7 76.8%	27.5 79.4%	27.5 39.7%	23.1	34.7	69.3	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	14.1 61.0%	16.8 48.4%	16.8 24.2%	23.1	34.7	69.3	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	4.9 21.0%	15.9 45.9%	15.9 23.0%	23.1	34.7	69.3	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	16.9 77.5%	24.0 73.7%	24.0 36.8%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	10.7 49.1%	12.5 38.5%	12.5 19.2%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	9.1 41.8%	9.3 28.5%	9.3 14.3%	21.8	32.6	65.3	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	0.7 2.8%	1.7 5.0%	1.7 2.5%	23.1	34.7	69.3	34.8	70	23.1

Table A.2.13.1-17
NCT Stress Results–Load Case 12–1G Gravity

Load Case 12			NCT–1G Gravity								
			Max Stress [ksi] Stress Ratio			Allowable Stress [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL+PB	P+Q	PM	PL+PB	P+Q	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	1.51 6.5%	3.58 10.3%	3.58 5.2%	23.1	34.7	69.3	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	0.59 2.6%	0.95 2.7%	0.95 1.4%	23.1	34.7	69.3	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	0.04 0.2%	0.13 0.4%	0.13 0.2%	23.1	34.7	69.3	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	1.0 4.6%	1.5 4.7%	1.5 2.4%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	0.57 2.6%	0.94 2.9%	0.94 1.4%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	0.30 1.4%	0.41 1.3%	0.41 0.6%	21.8	32.6	65.3	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	0.01 0.06%	0.03 0.09%	0.03 0.04%	23.1	34.7	69.3	34.8	70	23.1

Table A.2.13.1-18
NCT Stress Results -Load Combination 13–(Loads 1+2+4+12)

Load Combination 13			Hot Environment (100 °F ambient) +Preload + 1G Gravity + Internal Pressure								
			Max Stress [ksi] Stress Ratio			Allowable Stress [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL+PB	P+Q	PM	PL+PB	P+Q	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	2.0 8.5%	4.6 13.4%	18.5 26.8%	23.1	34.7	69.3	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	1.6 6.9%	2.2 6.3%	23.1 33.3%	23.1	34.7	69.3	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	6.4 27.6%	15.3 44.1%	30.8 44.4%	23.1	34.7	69.3	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	5.3 24.2%	12.0 36.7%	34.0 52.1%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	1.0 4.8%	2.4 7.5%	26.3 40.4%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	2.2 10.3%	6.3 19.3%	22.2 34.0%	21.8	32.6	65.3	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	0.4 1.8%	1.4 4.1%	15.3 22.1%	23.1	34.7	69.3	34.8	70	23.1

Table A.2.13.1-19
NCT Stress Results–Load Combination 14–(Loads 1+3+5B+12)

Load Combination 14			Cold Environment (-40 °F Ambient) + Preload + 1G Gravity +External Pressure								
			Max Stress [ksi] Stress Ratio			Allowable Stress [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL+PB	P+Q	PM	PL+PB	P+Q	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	2.0 8.7%	4.7 13.6%	17.2 24.9%	23.1	34.7	69.3	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	1.4 6.0%	2.2 6.2%	21.6 31.2%	23.1	34.7	69.3	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	6.1 26.4%	14.8 42.6%	31.7 45.7%	23.1	34.7	69.3	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	5.0 22.8%	11.8 36.2%	34.0 52.1%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	1.0 4.7%	2.2 6.6%	20.6 31.5%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	2.2 10.0%	6.1 18.7%	16.2 24.8%	21.8	32.6	65.3	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	0.3 1.4%	1.1 3.3%	9.0 13.0%	23.1	34.7	69.3	34.8	70	23.1

Table A.2.13.1-20
NCT Stress Results–Load Combination 15–(Loads 1+3+5A+12)

Load Combination 15			Cold Environment (-20 °F Ambient) + Preload + 1G Gravity + External Pressure								
			Max Stress [ksi] Stress Ratio			Allowable Stress [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL+PB	P+Q	PM	PL+PB	P+Q	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	2.0 8.7%	4.7 13.6%	18.6 26.8%	23.1	34.7	69.3	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	1.4 6.0%	2.2 6.2%	22.9 33.0%	23.1	34.7	69.3	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	6.1 26.4%	14.8 42.6%	28.4 41.0%	23.1	34.7	69.3	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	5.0 22.8%	11.8 36.2%	32.5 49.8%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	1.0 4.7%	2.2 6.6%	26.0 39.8%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	2.2 10.0%	6.1 18.7%	22.4 34.3%	21.8	32.6	65.3	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	0.3	1.1	15.6	23.1	34.7	69.3	34.8	70	23.1

Table A.2.13.1-21
NCT Stress Results–Load Combination 16–(Loads 1+2+4+12)

Load Combination 16			Hot Environment + Preload + 1G Gravity + Internal Pressure								
			Max Stress [ksi] Stress Ratio			Allowable Stress [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL+PB	P+Q	PM	PL+PB	P+Q	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	2.0 8.5%	4.6 13.4%	18.5 26.8%	23.1	34.7	69.3	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	1.6 6.9%	2.2 6.3%	23.1 33.3%	23.1	34.7	69.3	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	6.4 27.6%	15.3 44.1%	30.8 44.4%	23.1	34.7	69.3	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	5.3 24.2%	12.0 36.7%	34.0 52.1%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	1.0 4.8%	2.4 7.5%	26.3 40.4%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	2.2 10.3%	6.3 19.3%	22.2 34.0%	21.8	32.6	65.3	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	0.4 1.8%	1.4 4.1%	15.3 22.1%	23.1	34.7	69.3	34.8	70	23.1

Table A.2.13.1-22
NCT Stress Results–Load Combination 17–(Loads 1+2+4+max (8A, 8B))

Load Case 17			Rail Car Vibration Envelope + Preload + Hot Environment + Internal Pressure								
			Max Stress [ksi] Stress Ratio			Allowable Stress [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL+PB	P+Q	PM	PL+PB	P+Q	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	1.3 5.6%	2.7 7.9%	16.6 24.0%	23.1	34.7	69.3	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	1.4 5.8%	1.7 5.0%	22.6 32.6%	23.1	34.7	69.3	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	6.4 27.8%	15.7 45.3%	31.2 45.0%	23.1	34.7	69.3	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	4.8 22.2%	11.4 34.8%	33.4 51.1%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	0.8 3.5%	2.1 6.3%	26.0 39.8%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	2.1 9.8%	6.3 19.2%	22.1 33.9%	21.8	32.6	65.3	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	0.4 1.8%	1.4 4.0%	15.3 22.1%	23.1	34.7	69.3	34.8	70	23.1

Table A.2.13.1-23
NCT Stress Results–Load Combination 18–(Loads 1+3+max (5A, 5B)+max (8A, 8B))

Load Combination 18			Rail Car Vibration Envelope + Preload + Cold Environment (-20 °F Ambient) + External Pressure								
			Max Stress [ksi] Stress Ratio			Allowable Stress [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL+PB	P+Q	PM	PL+PB	P+Q	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	1.3 5.7%	2.8 8.2%	16.7 24.1%	23.1	34.7	69.3	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	1.1 5.0%	1.7 4.9%	22.4 32.3%	23.1	34.7	69.3	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	6.1 26.6%	15.2 43.8%	32.1 46.3%	23.1	34.7	69.3	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	4.5 20.8%	11.2 34.3%	33.3 51.1%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	0.7 3.4%	1.8 5.5%	25.6 39.2%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	2.1 9.5%	6.1 18.6%	22.3 34.2%	21.8	32.6	65.3	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	0.3 1.3%	1.1 3.3%	15.6 22.5%	23.1	34.7	69.3	34.8	70	23.1

Table A.2.13.1-24
NCT Stress Results–Load Combination 19–(Loads 1+2+4+max (7A, 7B, 7C, 7D))

Load Combination 19			Rail Car Shock Envelope + Preload + Hot Environment + Internal Pressure								
			Max Stress [ksi] Stress Ratio			Allowable Stress [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL+PB	P+Q	PM	PL+PB	P+Q	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	7.4 32.0%	13.9 40.1%	27.8 40.1%	23.1	34.7	69.3	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	5.4 23.4%	7.3 21.2%	28.2 40.7%	23.1	34.7	69.3	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	8.6 37.1%	28.1 81.1%	43.6 62.9%	23.1	34.7	69.3	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	7.7 35.5%	16.0 49.2%	38.0 58.3%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	4.4 20.1%	10.3 31.5%	34.2 52.4%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	4.2 19.2%	13.3 40.7%	29.2 44.7%	21.8	32.6	65.3	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	0.7 3.2%	2.1 6.2%	16.0 23.1%	23.1	34.7	69.3	34.8	70	23.1

Table A.2.13.1-25
NCT Stress Results–Load Combination 20–(Loads 1+3+max (5A, 5B)+max (7A, 7B, 7C, 7D))

Load Combination 20			Rail Car Shock Envelope + Preload + Cold Environment (-20 °F Ambient) + External Pressure								
			Max Stress [ksi] Stress Ratio			Allowable Stress [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL+PB	P+Q	PM	PL+PB	P+Q	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	7.4 32.2%	14.0 40.4%	27.8 40.2%	23.1	34.7	69.3	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	5.2 22.5%	7.3 21.1%	28.0 40.4%	23.1	34.7	69.3	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	8.3 35.9%	27.6 79.6%	44.5 64.3%	23.1	34.7	69.3	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	7.4 34.2%	15.9 48.6%	38.0 58.3%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	4.4 20.0%	10.0 30.6%	33.8 51.8%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	4.1 18.9%	13.1 40.1%	29.3 45.0%	21.8	32.6	65.3	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	0.6 2.7%	1.9 5.4%	16.3 23.6%	23.1	34.7	69.3	34.8	70	23.1

Table A.2.13.1-26
NCT Stress Results–Load Combination 21–(Loads 1+2+4+9)

Load Combination 21			One Ft End Drop on Lid End + Preload + Hot Environment + Internal Pressure								
			Max Stress [ksi] Stress Ratio			Allowable Stress [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL+PB	P+Q	PM	PL+PB	P+Q	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	5.1 22.0%	8.3 24.0%	22.2 32.1%	23.1	34.7	69.3	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	5.6 24.2%	10.2 29.6%	31.2 45.0%	23.1	34.7	69.3	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	9.2 39.7%	25.6 73.8%	41.0 59.2%	23.1	34.7	69.3	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	12.9 59.2%	20.6 63.2%	42.6 65.3%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	2.9 13.5%	5.8 17.7%	29.7 45.5%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	3.1 14.5%	10.4 31.8%	26.3 40.2%	21.8	32.6	65.3	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	2.0 8.8%	6.2 17.8%	20.1 29.0%	23.1	34.7	69.3	34.8	70	23.1

Table A.2.13.1-27
NCT Stress Results–Load Combination 22–(Loads 1+3+max (5A, 5B)+9)

Load Combination 22			One Ft End Drop on Lid End + Preload + Cold Environment (-20 °F Ambient) + External Pressure								
			Max Stress [ksi] Stress Ratio			Allowable Stress [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL+PB	P+Q	PM	PL+PB	P+Q	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	5.1 22.2%	8.4 24.3%	22.3 32.1%	23.1	34.7	69.3	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	5.4 23.3%	10.2 29.5%	30.9 44.6%	23.1	34.7	69.3	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	8.9 38.5%	25.1 72.3%	42.0 60.6%	23.1	34.7	69.3	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	12.6 57.9%	20.4 62.6%	42.6 65.3%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	2.9 13.5%	5.5 16.9%	29.3 44.9%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	3.1 14.2%	10.2 31.2%	26.4 40.5%	21.8	32.6	65.3	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	1.9 8.3%	5.9 17.1%	20.4 29.4%	23.1	34.7	69.3	34.8	70	23.1

Table A.2.13.1-28
NCT Stress Results–Load Combination 23–(Loads 1+2+4+10)

Load Combination 23			One Ft End Drop on Bottom End + Preload + Hot Environment + Internal Pressure								
			Max Stress [ksi] Stress Ratio			Allowable Stress [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL+PB	P+Q	PM	PL+PB	P+Q	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	5.2 22.7%	6.5 18.9%	20.4 29.5%	23.1	34.7	69.3	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	5.2 22.4%	7.8 22.5%	28.7 41.4%	23.1	34.7	69.3	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	8.3 36.0%	22.1 63.8%	37.6 54.2%	23.1	34.7	69.3	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	6.0 27.7%	14.5 44.6%	36.6 56.0%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	5.2 24.1%	7.8 23.9%	31.7 48.6%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	4.2 19.2%	10.9 33.5%	26.8 41.1%	21.8	32.6	65.3	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	1.2 5.1%	3.1 9.1%	17.0 24.6%	23.1	34.7	69.3	34.8	70	23.1

Table A.2.13.1-29
NCT Stress Results–Load Combination 24–(Loads 1+3+max (5A, 5B)+10)

Load Combination 24			One Ft End Drop on Bottom End + Preload + Cold Environment (-20 °F Ambient) + External Pressure								
			Max Stress [ksi] Stress Ratio			Allowable Stress [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL+PB	P+Q	PM	PL+PB	P+Q	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	5.3 22.9%	6.6 19.1%	20.5 29.5%	23.1	34.7	69.3	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	5.0 21.5%	7.8 22.4%	28.5 41.1%	23.1	34.7	69.3	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	8.0 34.8%	21.6 62.3%	38.5 55.6%	23.1	34.7	69.3	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	5.7 26.3%	14.4 44.0%	36.5 56.0%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	5.2 24.0%	7.5 23.0%	31.3 48.0%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	4.1 19.0%	10.7 32.8%	27.0 41.3%	21.8	32.6	65.3	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	1.1 4.6%	2.9 8.3%	17.3 25.0%	23.1	34.7	69.3	34.8	70	23.1

Table A.2.13.1-30
NCT Stress Results–Load Combination 25–(Loads 1+2+4+11)

Load Combination 25(1)			One Ft Side Drop + Preload + Hot Environment + Internal Pressure								
			Max Stress [ksi] Stress Ratio			Allowable Stress [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL+PB	P+Q	PM	PL+PB	P+Q	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	17.9 77.6%	28.1 81.1%	42.0 60.6%	23.1	34.7	69.3	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	14.5 62.8%	17.3 50.0%	38.2 55.1%	23.1	34.7	69.3	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	6.7 29.2%	19.2 55.5%	34.7 50.1%	23.1	34.7	69.3	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	18.4 84.5%	27.6 84.7%	49.7 76.1%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	11.1 51.2%	14.0 42.8%	37.9 58.1%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	9.4 43.4%	10.8 33.0%	26.6 40.8%	21.8	32.6	65.3	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	1.0 4.2%	3.0 8.6%	16.9 24.3%	23.1	34.7	69.3	34.8	70	23.1

Notes: 1. Preload stresses (Load 1) and Side Drop Load stresses (Load 11) combined in ANSYS. Resultant maximum stress combined with Internal Pressure load maximum stress (Load 2) for each component.

Table A.2.13.1-31
NCT Stress Results–Load Combination 26–(Loads 1+3+max (5A, 5B)+11)

Load Combination 26[1]			One Ft Side Drop + Preload + Cold Environment (-20 °F Ambient) + External Pressure								
			Max Stress [ksi] Stress Ratio			Allowable Stress [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL+PB	P+Q	PM	PL+PB	P+Q	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	18.0 77.7%	28.2 81.4%	42.0 60.6%	23.1	34.7	69.3	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	14.3 61.9%	17.3 49.9%	38.0 54.8%	23.1	34.7	69.3	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	6.5 28.0%	18.7 54.0%	35.6 51.4%	23.1	34.7	69.3	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	18.1 83.1%	27.5 84.2%	49.6 76.1%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	11.1 51.1%	13.7 42.0%	37.5 57.5%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	9.4 43.1%	10.5 32.3%	26.8 41.1%	21.8	32.6	65.3	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	0.9 3.8%	2.7 7.9%	17.2 24.8%	23.1	34.7	69.3	34.8	70	23.1

Notes: 1. Preload stresses (Load 1) and Side Drop Load stresses (Load 11) combined in ANSYS. Resultant maximum stress combined with External Pressure load maximum stress (Load 2) for each component

Table A.2.13.1-32
HAC Stress Results–Load Case 27–End Drop on Bottom End–Int. Pressure 30 psig

Load Case 27			HAC–End Drop on Bottom End 55G–Internal Pressure 30 psig								
			Max Stress [ksi] Stress Ratio			Allowable [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL	PL+PB	PM	PL	PL+PB	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	9.7 19.8%	10.5 16.7%	10.5 16.7%	49.0	63.0	63.0	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	8.4 17.2%	12.9 20.5%	12.9 20.5%	49.0	63.0	63.0	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	1.5 3.1%	15.9 25.2%	15.9 25.2%	49.0	63.0	63.0	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	2.8 5.7%	4.8 7.6%	4.8 7.6%	49.0	63.0	63.0	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	9.8 19.9%	12.4 19.7%	12.4 19.7%	49.0	63.0	63.0	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	4.6 9.4%	10.5 16.7%	10.5 16.7%	49.0	63.0	63.0	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	1.2 2.4%	3.4 5.4%	3.4 5.4%	49.0	63.0	63.0	34.8	70	23.1

Table A.2.13.1-33
HAC Stress Results–Load Case 28–End Drop on Bottom End–Ext. Pressure 25 psig

Load Case 28			HAC–End Drop on Bottom End 55G–External Pressure 25 psig								
			Max Stress [ksi] Stress Ratio			Allowable [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL	PL+PB	PM	PL	PL+PB	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	9.7 19.8%	10.4 16.6%	10.4 16.6%	49.0	63.0	63.0	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	8.9 18.2%	12.5 19.9%	12.5 19.9%	49.0	63.0	63.0	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	1.9 4.0%	20.3 32.2%	20.3 32.2%	49.0	63.0	63.0	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	2.9 5.9%	6.2 9.8%	6.2 9.8%	49.0	63.0	63.0	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	9.3 18.9%	12.0 19.0%	12.0 19.0%	49.0	63.0	63.0	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	4.4 9.1%	8.9 14.1%	8.9 14.1%	49.0	63.0	63.0	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	0.8 1.5%	2.8 4.5%	2.8 4.5%	49.0	63.0	63.0	34.8	70	23.1

Table A.2.13.1-34
HAC Stress Results–Load Case 29–End Drop on Lid–Int. Pressure 30 psig

Load Case 29			HAC–End Drop on Lid 55G–Internal Pressure 30 psig								
			Max Stress [ksi] Stress Ratio			Allowable [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL	PL+PB	PM	PL	PL+PB	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	9.7 19.8%	15.8 25.1%	15.8 25.1%	49.0	63.0	63.0	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	8.0 16.3%	18.4 29.2%	18.4 29.2%	49.0	63.0	63.0	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	6.7 13.7%	29.8 47.3%	29.8 47.3%	49.0	63.0	63.0	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	18.5 37.7%	21.2 33.7%	21.2 33.7%	49.0	63.0	63.0	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	4.7 9.6%	8.7 13.8%	8.7 13.8%	49.0	63.0	63.0	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	2.3 4.7%	8.3 13.1%	8.3 13.1%	49.0	63.0	63.0	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	0.2 0.4%	0.9 1.4%	0.9 1.4%	49.0	63.0	63.0	34.8	70	23.1

Table A.2.13.1-35
HAC Stress Results–Load Case 30–End Drop on Lid–Ext. Pressure 25 psig

Load Case 30			HAC–End Drop on Lid 55G–External Pressure 25 psig								
			Max Stress [ksi] Stress Ratio			Allowable [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL	PL+PB	PM	PL	PL+PB	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	9.6 19.7%	15.9 25.2%	15.9 25.2%	49.0	63.0	63.0	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	8.5 17.3%	18.7 29.7%	18.7 29.7%	49.0	63.0	63.0	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	6.2 12.6%	24.7 39.2%	24.7 39.2%	49.0	63.0	63.0	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	18.1 37.0%	21.1 33.5%	21.1 33.5%	49.0	63.0	63.0	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	5.5 11.2%	11.0 17.4%	11.0 17.4%	49.0	63.0	63.0	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	2.8 5.6%	10.6 16.9%	10.6 16.9%	49.0	63.0	63.0	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	0.5 1.0%	2.9 4.6%	2.9 4.6%	49.0	63.0	63.0	34.8	70	23.1

Table A.2.13.1-36
HAC Stress Results–Load Case 31–Side Drop–Int. Pressure 30 psig

Load Case 31			HAC–Side Drop 55G–Internal Pressure 30 psig								
			Max Stress [ksi] Stress Ratio			Allowable [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL	PL+PB	PM	PL	PL+PB	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	34.4 70.2%	41.3 65.6%	41.3 65.6%	49.0	63.0	63.0	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	32.1 65.6%	40.5 64.3%	40.5 64.3%	49.0	63.0	63.0	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	10.2 20.7%	28.5 45.2%	28.5 45.2%	49.0	63.0	63.0	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	33.6 68.7%	39.3 62.4%	39.3 62.4%	49.0	63.0	63.0	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	22.5 46.0%	25.9 41.1%	25.9 41.1%	49.0	63.0	63.0	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	20.6 42.0%	21.2 33.6%	21.2 33.6%	49.0	63.0	63.0	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	2.0 4.0%	7.1 11.2%	7.1 11.2%	49.0	63.0	63.0	34.8	70	23.1

Table A.2.13.1-37
HAC Stress Results–Load Case 32–Side Drop–Ext. Pressure 25 psig

Load Case 32			HAC–Side Drop 55G Load–External Pressure 25 psig								
			Max Stress [ksi] Stress Ratio			Allowable [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL	PL+PB	PM	PL	PL+PB	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	34.5 70.4%	41.4 65.7%	41.4 65.7%	49.0	63.0	63.0	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	32.2 65.8%	40.8 64.7%	40.8 64.7%	49.0	63.0	63.0	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	10.4 21.3%	26.5 42.1%	26.5 42.1%	49.0	63.0	63.0	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	33.2 67.8%	38.8 61.7%	38.8 61.7%	49.0	63.0	63.0	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	22.3 45.5%	26.7 42.3%	26.7 42.3%	49.0	63.0	63.0	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	20.1 41.1%	20.9 33.2%	20.9 33.2%	49.0	63.0	63.0	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	2.0 4.0%	6.9 11.0%	6.9 11.0%	49.0	63.0	63.0	34.8	70	23.1

Table A.2.13.1-38
HAC Stress Results–Load Case 33–CG Over Corner Drop on Bottom End–Int. Pressure 30 psig

Load Case 33			HAC–CG Over Corner Drop on Bottom End 45G – Internal Pressure 30 psig–65° Impact Angle								
			Max Stress [ksi] Stress Ratio			Allowable [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL	PL+PB	PM	PL	PL+PB	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	19.4 39.5%	28.1 44.6%	28.1 44.6%	49.0	63.0	63.0	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	20.2 41.2%	23.5 37.4%	23.5 37.4%	49.0	63.0	63.0	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	1.2 2.4%	11.0 17.5%	11.0 17.5%	49.0	63.0	63.0	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	4.8 9.8%	8.5 13.5%	8.5 13.5%	49.0	63.0	63.0	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	16.8 34.2%	33.8 53.7%	33.8 53.7%	49.0	63.0	63.0	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	13.7 28.0%	30.5 48.4%	30.5 48.4%	49.0	63.0	63.0	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	3.0 6.2%	7.4 11.7%	7.4 11.7%	49.0	63.0	63.0	34.8	70	23.1

Table A.2.13.1-39
HAC Stress Results–Load Case 34–CG Over Corner Drop on Bottom End–Ext. Pressure 25 psig

Load Case 34			HAC–CG Over Corner Drop on Bottom End 45G – External Pressure 25 psig–65° Impact Angle								
			Max Stress [ksi] Stress Ratio			Allowable [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL	PL+PB	PM	PL	PL+PB	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	19.3 39.4%	28.6 45.3%	28.6 45.3%	49.0	63.0	63.0	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	20.7 42.3%	24.3 38.5%	24.3 38.5%	49.0	63.0	63.0	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	1.6 3.3%	15.3 24.3%	15.3 24.3%	49.0	63.0	63.0	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	4.8 9.9%	9.4 14.9%	9.4 14.9%	49.0	63.0	63.0	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	17.0 34.7%	35.9 57.0%	35.9 57.0%	49.0	63.0	63.0	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	13.4 27.3%	26.8 42.5%	26.8 42.5%	49.0	63.0	63.0	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	2.3 4.7%	5.5 8.7%	5.5 8.7%	49.0	63.0	63.0	34.8	70	23.1

Table A.2.13.1-40
HAC Stress Results–Load Case 35–CG Over Corner Drop on Lid End–Int. Pressure 30 psig

Load Case 35			HAC–CG Over Corner Drop on Lid End 45G–Internal Pressure. 30 psig–65° Impact Angle								
			Max Stress [ksi] Stress Ratio			Allowable [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL	PL+PB	PM	PL	PL+PB	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	23.0 47.0%	32.5 51.7%	32.5 51.7%	49.0	63.0	63.0	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	26.6 54.2%	28.0 44.4%	28.0 44.4%	49.0	63.0	63.0	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	10.1 20.7%	32.7 51.9%	32.7 51.9%	49.0	63.0	63.0	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	26.7 54.4%	34.1 54.2%	34.1 54.2%	49.0	63.0	63.0	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	4.2 8.5%	9.5 15.0%	9.5 15.0%	49.0	63.0	63.0	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	2.3 4.7%	6.7 10.6%	6.7 10.6%	49.0	63.0	63.0	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	0.3 0.6%	0.8 1.2%	0.8 1.2%	49.0	63.0	63.0	34.8	70	23.1

Table A.2.13.1-41
HAC Stress Results–Load Case 36–CG Over Corner Drop on Lid End–Ext. Pressure 25 psig

Load Case 36			HAC–CG Over Corner Drop on Lid End 45G Load–External Pressure 25 psig–65° Impact Angle								
			Max Stress [ksi] Stress Ratio			Allowable [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL	PL+PB	PM	PL	PL+PB	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	23.1 47.2%	32.9 52.2%	32.9 52.2%	49.0	63.0	63.0	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	26.9 54.9%	28.6 45.3%	28.6 45.3%	49.0	63.0	63.0	34.8 0	70 0	23.1 0
3	Lid	SA-203 Grade E Carbon Steel Plate	9.3 19.0%	29.3 46.5%	29.3 46.5%	49.0	63.0	63.0	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	27.0 55.0%	33.7 53.5%	33.7 53.5%	49.0	63.0	63.0	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	5.0 10.2%	11.7 18.6%	11.7 18.6%	49.0	63.0	63.0	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	2.7 5.6%	8.8 13.9%	8.8 13.9%	49.0	63.0	63.0	32.6 0	70 0	21.75 0
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	0.5 1.0%	2.7 4.3%	2.7 4.3%	49.0	63.0	63.0	34.8	70	23.1

Table A.2.13.1-42
HAC Stress Results–Load Case 37–Slap Down Drop on Bottom End–Int. Pressure 30 psig

Load Case 37			HAC–Slap Down Drop on Bottom End 45G–Internal Pressure 30 psig–10° Impact Angle								
			Max Stress [ksi] Stress Ratio			Allowable [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL	PL+PB	PM	PL	PL+PB	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	40.4 82.5%	44.2 70.1%	44.2 70.1%	49.0	63.0	63.0	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	40.0 81.7%	43.2 68.5%	43.2 68.5%	49.0	63.0	63.0	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	7.5 15.3%	31.5 50.0%	31.5 50.0%	49.0	63.0	63.0	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	9.8 20.1%	14.6 23.2%	14.6 23.2%	49.0	63.0	63.0	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	36.0 73.5%	39.4 62.6%	39.4 62.6%	49.0	63.0	63.0	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	21.9 44.7%	29.6 47.0%	29.6 47.0%	49.0	63.0	63.0	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	4.5 9.3%	17.2 27.3%	17.2 27.3%	49.0	63.0	63.0	34.8	70	23.1

Table A.2.13.1-43
HAC Stress Results–Load Case 38–Slap Down Drop on Bottom End–Ext. Pressure 25 psig

Load Case 38			HAC–Slap Down Drop on Bottom End 45G–External Pressure 25 psig–10° Impact Angle								
			Max Stress [ksi] Stress Ratio			Allowable [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL	PL+PB	PM	PL	PL+PB	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	40.5 82.6%	44.2 70.2%	44.2 70.2%	49.0	63.0	63.0	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	39.9 81.4%	43.2 68.6%	43.2 68.6%	49.0	63.0	63.0	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	7.3 14.8%	30.4 48.2%	30.4 48.2%	49.0	63.0	63.0	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	9.9 20.2%	14.4 22.9%	14.4 22.9%	49.0	63.0	63.0	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	35.9 73.4%	38.8 61.5%	38.8 61.5%	49.0	63.0	63.0	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	21.5 43.8%	29.7 47.2%	29.7 47.2%	49.0	63.0	63.0	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	4.7 9.7%	17.6 28.0%	17.6 28.0%	49.0	63.0	63.0	34.8	70	23.1

Table A.2.13.1-44
HAC Stress Results–Load Case 39–Slap Down Drop on Lid End–Int. Pressure 30 psig

Load Case 39			HAC–Slap Down Drop on Lid End 45G–Internal Pressure 30 psig–10° Impact Angle								
			Max Stress [ksi] Stress Ratio			Allowable [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL	PL+PB	PM	PL	PL+PB	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	41.7 85.1%	47.2 74.9%	47.2 74.9%	49.0	63.0	63.0	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	41.6 84.9%	44.9 71.2%	44.9 71.2%	49.0	63.0	63.0	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	11.5 23.4%	29.2 46.3%	29.2 46.3%	49.0	63.0	63.0	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	38.8 79.2%	41.1 65.2%	41.1 65.2%	49.0	63.0	63.0	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	5.7 11.7%	12.0 19.1%	12.0 19.1%	49.0	63.0	63.0	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	3.6 7.3%	9.7 15.4%	9.7 15.4%	49.0	63.0	63.0	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	1.8 3.7%	5.4 8.5%	5.4 8.5%	49.0	63.0	63.0	34.8	70	23.1

Table A.2.13.1-45
HAC Stress Results–Load Case 40–Slap Down Drop on Lid End–Ext. Pressure 25 psig

Load Case 40			HAC–Slap Down Drop on Lid End 45g Load–External Pressure 25 psig–10° Impact Angle								
			Max Stress [ksi] Stress Ratio			Allowable [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL	PL+PB	PM	PL	PL+PB	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	41.7 85.2%	47.3 75.0%	47.3 75.0%	49.0	63.0	63.0	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	41.6 84.8%	44.9 71.3%	44.9 71.3%	49.0	63.0	63.0	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	12.5 25.5%	32.9 52.2%	32.9 52.2%	49.0	63.0	63.0	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	38.8 79.1%	41.1 65.2%	41.1 65.2%	49.0	63.0	63.0	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	5.4 10.9%	11.0 17.4%	11.0 17.4%	49.0	63.0	63.0	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	3.1 6.4%	11.6 18.4%	11.6 18.4%	49.0	63.0	63.0	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	1.8 3.7%	5.7 9.1%	5.7 9.1%	49.0	63.0	63.0	34.8	70	23.1

Table A.2.13.1-46
HAC Stress Results–Load Case 41–Immersion–Ext. Pressure 290 psig & Weight

Load Case 41			HAC–Immersion External Pressure 290 psig & Weight								
			Max Stress [ksi] Stress Ratio			Allowable [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL	PL+PB	PM	PL	PL+PB	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	3.0 6.0%	7.5 13.1%	7.5 13.1%	49.0	57.1	57.1	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	3.9 8.0%	5.0 8.8%	5.0 8.8%	49.0	57.1	57.1	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	2.2 4.6%	22.7 39.8%	22.7 39.8%	49.0	57.1	57.1	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	4.2 8.5%	10.3 16.5%	10.3 16.5%	49.0	62.5	62.5	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	4.4 9.1%	13.1 21.0%	13.1 21.0%	49.0	62.5	62.5	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	3.0 6.0%	12.7 20.2%	12.7 20.2%	49.0	62.5	62.5	32.6	70	21.75
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	1.7 3.6%	9.7 17.0%	9.7 17.0%	49.0	57.1	57.1	34.8	70	23.1

Table A.2.13.1-47
HAC Stress Results–Load Case 42–Fire–Temperature 620 °F–Int. Pressure 120 psig & Weight

Load Case 42			HAC–Fire–Temperature 620 °F Internal Pressure 120 psig & Weight								
			Max Stress [ksi] Stress Ratio			Allowable [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL	PL+PB	PM	PL	PL+PB	Sy	Su	Sm
1	Outer Shell	SA-203 Grade E Carbon Steel Plate	1.5 3.0%	3.2 5.6%	3.2 5.6%	48.5	57.1	57.1	29.4	69.3	NA
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	1.9 3.9%	2.2 3.8%	2.2 3.8%	48.5	57.1	57.1	29.4	69.3	NA
3	Lid	SA-203 Grade E Carbon Steel Plate	2.0 4.2%	10.6 18.6%	10.6 18.6%	48.5	57.1	57.1	29.4	69.3	NA
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	2.2 4.5%	2.8 4.4%	2.8 4.4%	48.5	62.5	62.5	27.62	69.3	18.62
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	2.0 4.1%	5.9 9.5%	5.9 9.5%	48.5	62.5	62.5	27.62	69.3	18.62
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	1.4 2.8%	7.7 12.4%	7.7 12.4%	48.5	62.5	62.5	27.62	69.3	18.62
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	1.0 2.1%	4.3 7.5%	4.3 7.5%	48.5	57.1	57.1	29.4	69.3	NA

Table A.2.13.1-48
Rear Impact Limiter–Reaction Forces

REAR IMPACT LIMITER–REACTION FORCES											
Case		**Side Drop**		**Corner Drop/Slap Down Drop on Bottom End**						**End Drop on Bottom End**	
Impact Angle	[deg]	0.0	0.0	10.0	20.0	40.0	55.0	65.0	75.0	90.0	90.0
Axial G-load	[G]	0.0	0.0	7.8	15.4	28.9	36.9	40.8	43.5	25.0	55.0
Transverse G-load	[G]	25.0	55.0	44.3	42.3	34.5	25.8	19.0	11.6	0.0	0.0
Axial Forces											
R_{EA} Flange Interface	[kip]	0.0	0.0	1324.5	2608.7	4902.8	6248.0	6912.8	7367.5	4237.5	9322.4
R_{IA} Bottom Plate Face	[kip]	0.0	0.0	980.2	1930.6	3628.3	4623.8	5115.8	5452.3	3135.9	6899.0
Total Axial Force	[kip]	0.0	0.0	2304.7	4539.3	8531.1	10871.8	12028.6	12819.8	7373.4	16221.4
Transverse Forces											
R_{ER} Limiter Outer Part	[kip]	827.2	1819.9	3089.4	2947.8	2403.1	1799.3	1325.8	811.9	0.0	0.0
R_{IR} Limiter Inner Part	[kip]	2672.6	5879.6	9981.0	9523.8	7763.9	5813.2	4283.2	2623.1	0.0	0.0
R_F Total Transverse Force	[kip]	3499.8	7699.5	13070.3	12471.7	10167.0	7612.5	5609.0	3435.1	0.0	0.0
Total Reaction Force											
Total Reaction Force	[kip]	3499.8	7699.5	13272.1	13272.1	13272.1	13272.1	13272.1	13272.1	7373.4	16221.4
Pressure Load Magnitudes											
Average Axial Pressure(1) Flange Interface	[psi]	0.0	0.0	777.1	1530.7	2876.7	3666.0	4056.1	4322.9	2486.3	5469.9
Average Axial Pressure(1) Bottom Plate Interface	[psi]	0.0	0.0	302.1	595.1	1118.4	1425.2	1576.9	1680.6	966.6	2126.5
Peak Radial P_{MAX} Outer Part	[psi]	2133.7	4694.1	6108.0	5831.1	4753.5	3559.2	2622.5	1606.1	0.0	0.0
Peak Radial P_{MAX} Inner Part	[psi]	2133.7	4694.1	6108.0	5831.1	4753.5	3559.2	2622.5	1606.1	0.0	0.0

Note 1: Axial pressure varies linearly along transverse coordinate.

Table A.2.13.1-49
Front Impact Limiter–Reaction Forces

FRONT IMPACT LIMITER–REACTION FORCES											
Case		**Side Drop**		**Corner Drop/Slap Down Drop on Lid End**						**End Drop on Lid End**	
Impact Angle	[deg]	0.0	0.0	10.0	20.0	40.0	55.0	65.0	75.0	90.0	90.0
Axial G-load	[G]	0.0	0.0	7.8	15.4	28.9	36.9	40.8	43.5	25.0	55.0
Transverse G-load	[G]	25.0	55.0	44.3	42.3	34.5	25.8	19.0	11.6	0.0	0.0
Axial Forces											
R_{EA} Flange Interface	[kip]	0.0	0.0	1332.7	2625.0	3837.5	4933.4	6287.0	6955.9	4263.9	9380.5
R_{IA} Bottom Plate Face	[kip]	0.0	0.0	971.9	1914.3	2798.5	3597.7	4584.9	5072.7	3109.5	6840.9
Total Axial Force	[kip]	0.0	0.0	2304.7	4539.3	6636.0	8531.1	10871.8	12028.6	7373.4	16221.4
Transverse Forces											
R_{ER} Limiter Outer Part	[kip]	568.4	1250.5	2138.8	2040.8	1663.7	1245.7	917.8	562.1	0.0	0.0
R_{IR} Limiter Inner Part	[kip]	2905.2	6391.4	10931.6	10430.8	8503.3	6366.8	4691.2	2873.0	0.0	0.0
R_F Total Transverse Force	[kip]	3473.6	7641.9	13070.3	12471.7	10167.0	7612.5	5609.0	3435.1	0.0	0.0
Total Reaction Force											
Total Reaction Force	[kip]	3473.6	7641.9	13272.1	13272.1	13272.1	13272.1	13272.1	13272.1	7373.4	16221.4
Pressure Load Magnitudes											
Average Axial Pressure(1) Flange Interface	[psi]	0.0	0.0	1456.6	2869.0	5391.9	6871.3	7602.4	8102.5	4660.2	8388.3
Average Axial Pressure(1) Lid Interface	[psi]	0.0	0.0	208.1	409.8	770.2	981.5	1085.9	1157.4	665.7	1198.2
Peak Radial Pressure P_{MAX} Outer Part	[psi]	2117.7	4658.9	6108.0	5831.1	4753.5	3559.2	2622.5	1606.1	0.0	0.0
Peak Radial Pressure P_{MAX} Inner Part	[psi]	2117.7	4658.9	6108.0	5831.1	4753.5	3559.2	2622.5	1606.1	0.0	0.0

Note 1: Axial pressure varies linearly along transverse coordinate

Table A.2.13.1-50
Pressure Loads Specifications (Bottom End Impacts)

WEIGHT LOAD MAGNITUDES											
Case		**Side Drop**		**Corner Drops on Bottom End**						**End Drop on Bottom End**	
Impact Angle	[deg]	0.0	0.0	10.0	20.0	40.0	55.0	65.0	75.0	90.0	90.0
Axial G-load	[G]	0.0	0.0	7.8	15.4	28.9	36.9	40.8	43.5	25.0	55.0
Transverse G-load	[G]	25.0	55.0	44.3	42.3	34.5	25.8	19.0	11.6	0.0	0.0
Payload Weight											
Axial Component	[kip]	0.0	0.0	926.0	1823.8	3427.7	4368.1	4832.9	5150.8	2962.5	6517.5
Transverse Component	[kip]	2962.5	6517.5	5251.5	5010.9	4084.9	3058.6	2253.6	1380.2	0.0	0.0
Total Force	[kip]	2962.5	6517.5	5332.5	5332.5	5332.5	5332.5	5332.5	5332.5	2962.5	6517.5
Payload Pressure Load Magnitudes											
Axial at Bottom Plate	[psi]	0.0	0.0	262.7	517.4	972.5	1239.3	1371.2	1461.4	840.5	1849.1
Peak Radial Pressure $2\times P_{MAX}$ (1)	[psi]	298.6	657.0	1058.7	1010.2	823.5	616.6	454.3	278.2	0.0	0.0
Front Impact Limiter Weight											
Axial Component	[kip]	0.0	0.0	125.0	246.3	462.8	589.8	652.5	695.5	400.0	880.0
Transverse Component	[kip]	0.0	0.0	709.1	676.6	551.6	413.0	304.3	186.3	0.0	0.0
Total Force	[kip]	0.0	0.0	720.0	720.0	720.0	720.0	720.0	720.0	400.0	880.0
Front Impact Limiter Pressure Load Magnitudes											
Axial Pressure Whole Interface	[psi]	0.0	0.0	22.4	44.1	82.8	105.6	116.8	124.5	71.6	157.5
Peak Radial Pressure P_{MAX}	[psi]	0.0	0.0	432.3	412.5	336.3	251.8	185.5	113.6	0.0	0.0

Note 1: In corner drop model radial pressure varies linearly along an axial coordinate, magnitude of peak pressure (impact side) is two times larger than an average pressure imposed by payload; in side drop model the pressure gradient in axial direction is zero.

Table A.2.13.1-51
Pressure Loads Specifications (Lid End Impacts)

WEIGHT LOAD MAGNITUDES											
Case		**Side Drop**		**Corner Drops on Lid End**						**End Drop on Lid End**	
Impact Angle	[deg]	0.0	0.0	10.0	20.0	40.0	55.0	65.0	75.0	90.0	90.0
Axial G-load	[G]	0.0	0.0	7.8	15.4	28.9	36.9	40.8	43.5	25.0	55.0
Transverse G-load	[G]	25.0	55.0	44.3	42.3	34.5	25.8	19.0	11.6	0.0	0.0
Payload Weight											
Axial Component	[kip]	0.0	0.0	926.0	1823.8	3427.7	4368.1	4832.9	5150.8	2962.5	6517.5
Transverse Component	[kip]	2962.5	6517.5	5251.5	5010.9	4084.9	3058.6	2253.6	1380.2	0.0	0.0
Total Force	[kip]	2962.5	6517.5	5332.5	5332.5	5332.5	5332.5	5332.5	5332.5	2962.5	6517.5
Payload Pressure Load Magnitudes											
P_{IA} Axial Pressure at Lid	[psi]	0.0	0.0	262.7	517.4	972.5	1239.3	1371.2	1461.4	754.7	1660.4
Peak Radial Pressure $2 \times P_{MAX}$ (1)	[psi]	298.6	657.0	1058.7	1010.2	823.5	616.6	454.3	278.2	0.0	0.0
Front Limiter Weight											
Axial Component	[kip]	0.0	0.0	125.0	246.3	462.8	589.8	652.5	695.5	400.0	880.0
Transverse Component	[kip]	0.0	0.0	709.1	676.6	551.6	413.0	304.3	186.3	0.0	0.0
Total Force	[kip]	0.0	0.0	720.0	720.0	720.0	720.0	720.0	720.0	400.0	880.0
Front Impact Limiter Pressure Load Magnitudes											
Axial Pressure Whole Interface	[psi]	0.0	0.0	25.3	49.8	93.5	119.2	131.9	140.5	80.8	177.8
Peak Radial Pressure P_{MAX}	[psi]	0.0	0.0	432.3	412.5	336.3	251.8	185.5	113.6	0.0	0.0

Note 1: In corner drop model radial pressure varies linearly along an axial coordinate, magnitude of peak pressure (impact side) is two times larger than an average pressure imposed by payload; in side drop model the pressure gradient in axial direction is zero.

Table A.2.13.1-52
HAC Stress Results–Side Drop with Ext. Pressure 25 psig (Elastic Analysis)

Load Case 43			HAC - Side Drop 55G Load - External Pressure 25 psig								
			Max Stress [ksi] Stress Ratio			Allowable [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL	PL+PB	PM	PL	PL+PB	Sy	Su	Sm
1	Outer Shell.	SA-203 Grade E Carbon Steel Plate	35.8 73.1%	56.0 76.3%	56.0 76.3%	49.0	70.0	70.0	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	31.0 63.2%	39.6 53.9%	39.6 53.9%	49.0	70.0	70.0	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	10.7 21.8%	34.5 47.0%	34.5 47.0%	49.0	70.0	70.0	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	30.7 62.6%	44.0 59.9%	44.0 59.9%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	22.2 45.3%	25.8 35.1%	25.8 35.1%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	20.0 40.7%	21.3 29.0%	21.3 29.0%	49.0	70.0	70.0	34.8	70	23.1
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	1.9 4.0%	4.5 6.2%	4.5 6.2%	49.0	70.0	70.0	34.8	70	23.1

Table A.2.13.1-53
HAC Stress Results – Slap Down Drop on Lid End with Ext. Pressure 25 psig (Elastic Analysis)

Load Case 44			HAC - Slap Down Drop on Lid End 45g Load - External Pressure 25 psig - 10° Impact Angle								
			Max Stress [ksi] Stress Ratio			Allowable [ksi]			Material Properties [ksi]		
#	Component	Material Specification	PM	PL	PL+PB	PM	PL	PL+PB	Sy	Su	Sm
1	Outer Shell.	SA-203 Grade E Carbon Steel Plate	54.3(1) 110.7%	81.3(1) 116.2%	81.3(1) 116.2%	49.0	70.0	70.0	34.8	70	23.1
2	Inner Shell	SA-203 Grade E Carbon Steel Plate	46.6 95.1%	55.5 79.2%	55.5 79.2%	49.0	70.0	70.0	34.8	70	23.1
3	Lid	SA-203 Grade E Carbon Steel Plate	9.0 18.4%	29.6 42.3%	29.6 42.3%	49.0	70.0	70.0	34.8	70	23.1
4	Top Flange	SA-350 Grade LF3 Carbon Steel Forging	47.8 97.5%	60.2 86.0%	60.2 86.0%	21.8	32.6	65.3	32.6	70	21.75
5	Bottom Flange	SA-350 Grade LF3 Carbon Steel Forging	6.5 13.2%	10.3 14.7%	10.3 14.7%	21.8	32.6	65.3	32.6	70	21.75
6	Bottom Plate	SA-350 Grade LF3 Carbon Steel Forging	3.1 6.4%	5.0 7.1%	5.0 7.1%	49.0	70.0	70.0	34.8	70	23.1
7	RAM Closure Plate	SA-203 Grade E Carbon Steel Plate	2.1 4.2%	4.3 6.1%	4.3 6.1%	49.0	70.0	70.0	34.8	70	23.1

Note 1: The Outer Shell is not a containment boundry of the cask. Moreover, the outer shell component has been shown to meet the ASME Code Allowable Stress Limit for Plastic Analysis as shown in Table A.2.13.1-45.

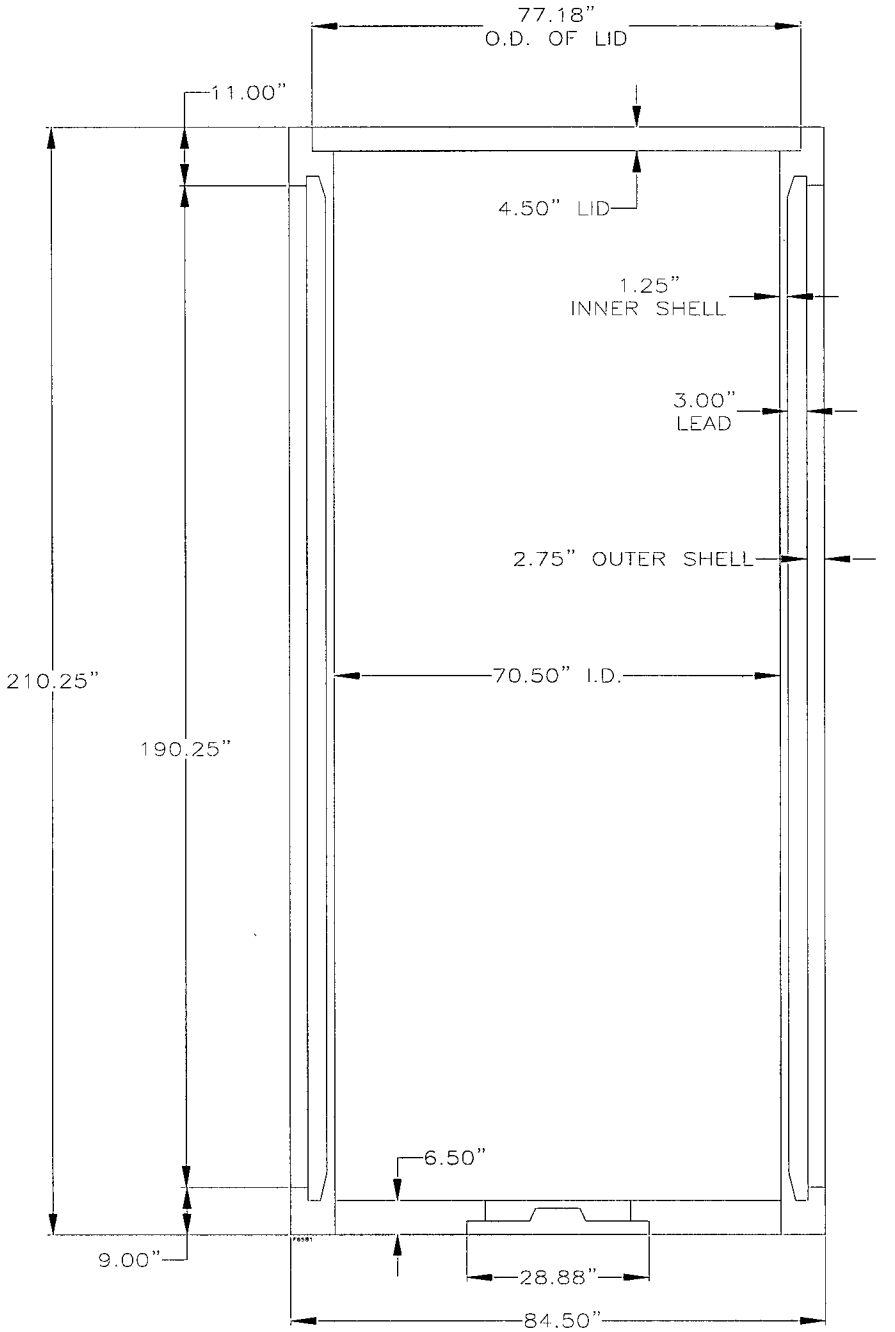


Figure A.2.13.1-1
NUHOMS – MP197HB Key Dimensions

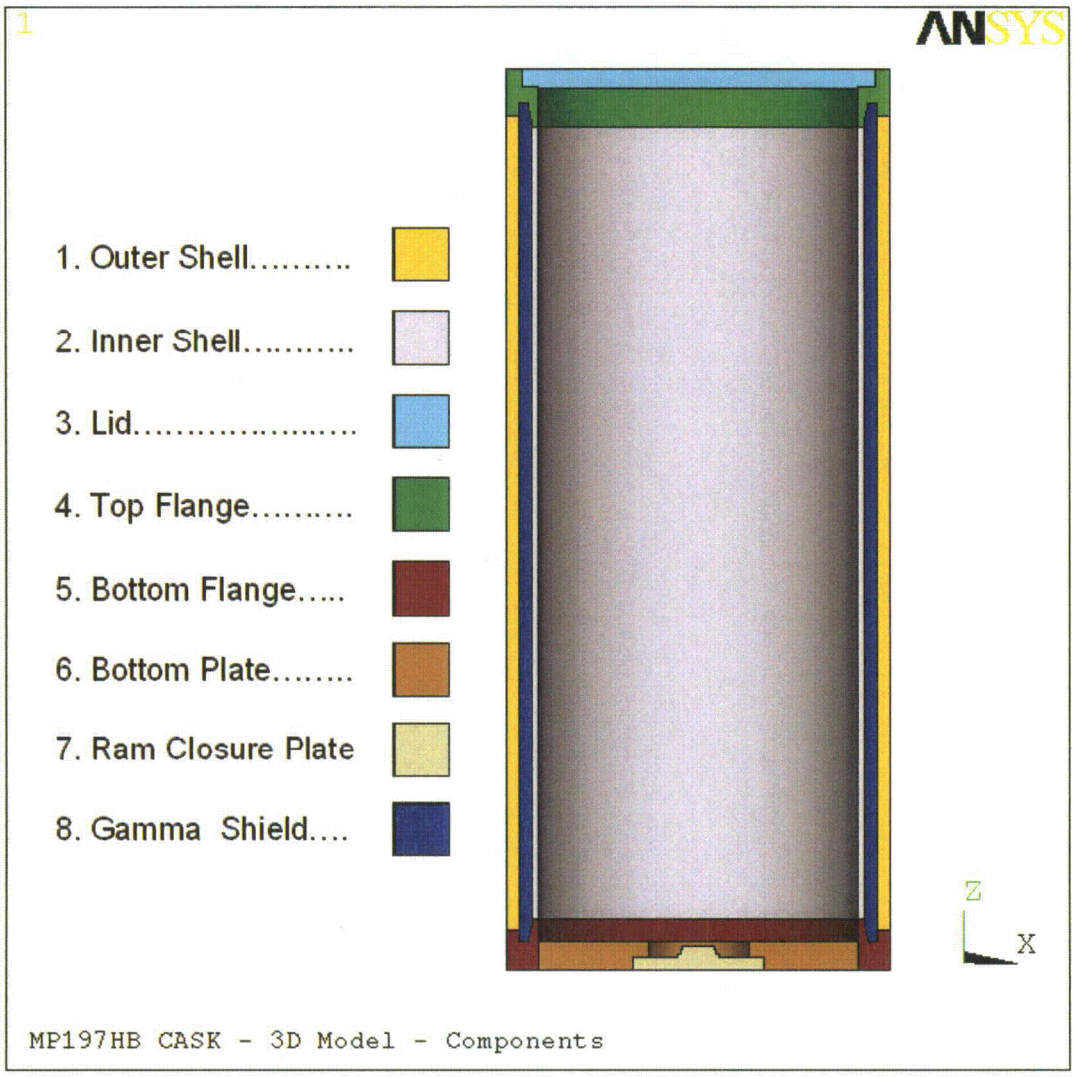


Figure A.2.13.1-2
NUHOMS – MP197HB Structural Components Analyzed

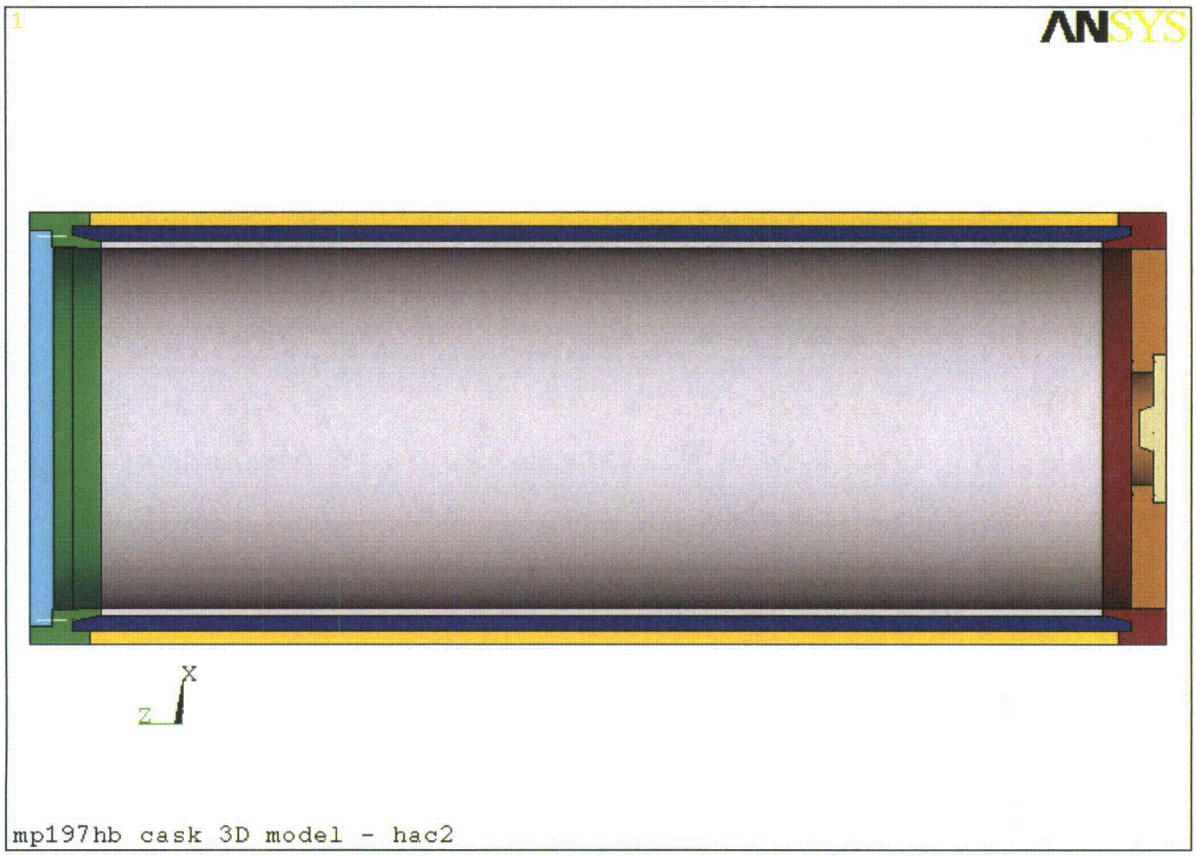


Figure A.2.13.1-3
NUHOMS – MP197HB Model MOD20

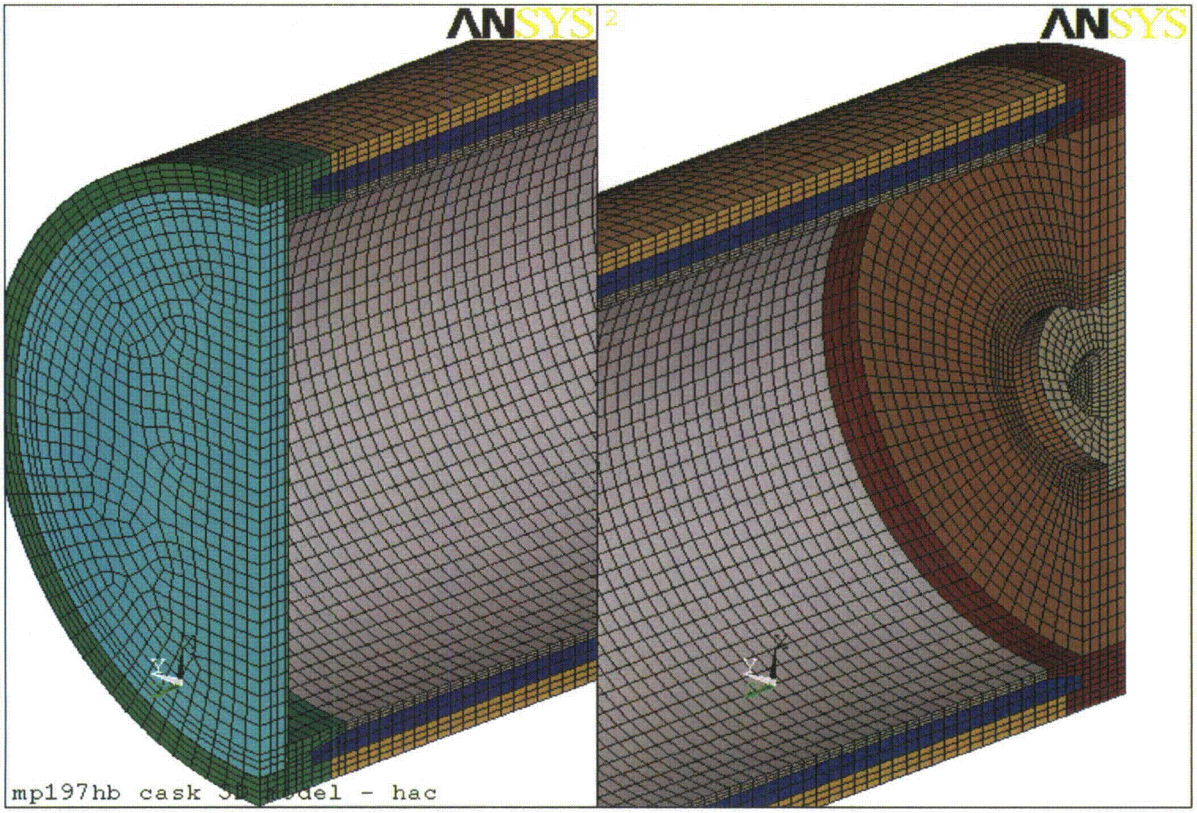


Figure A.2.13.1-4
NUHOMS – MP197HB Model MOD20 (Top and Bottom Detail View)

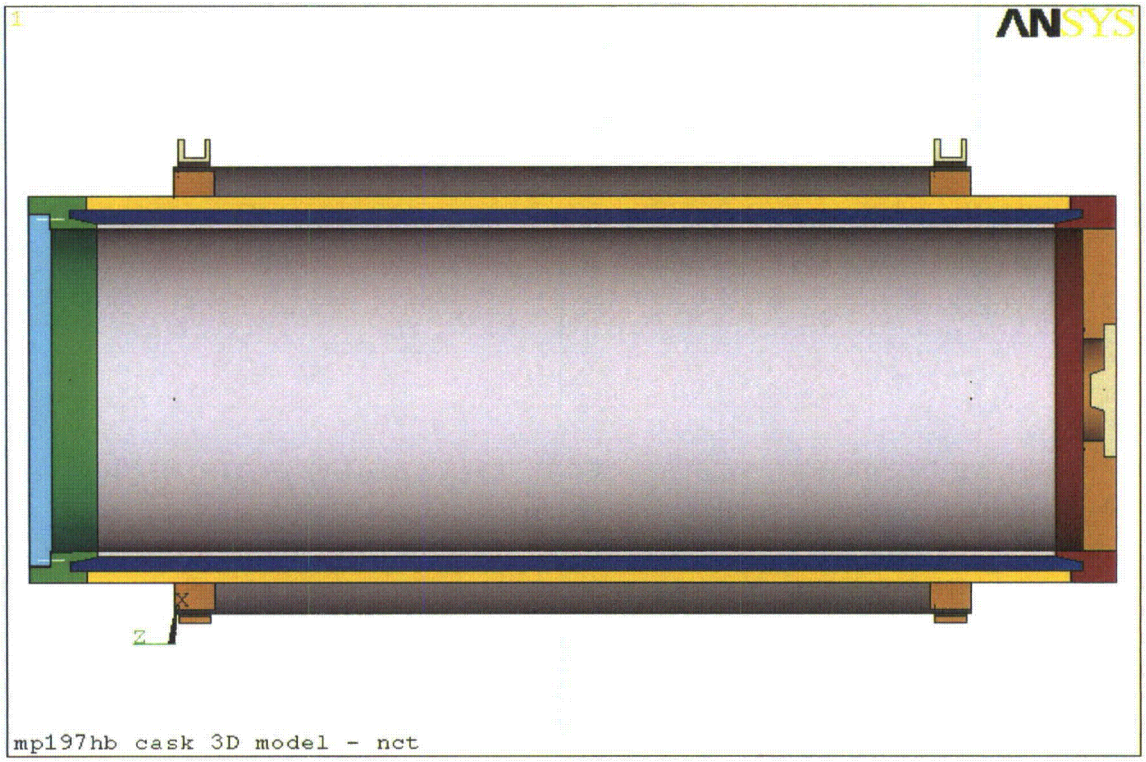


Figure A.2.13.1-5
NUHOMS – MP197HB Model MOD20TI

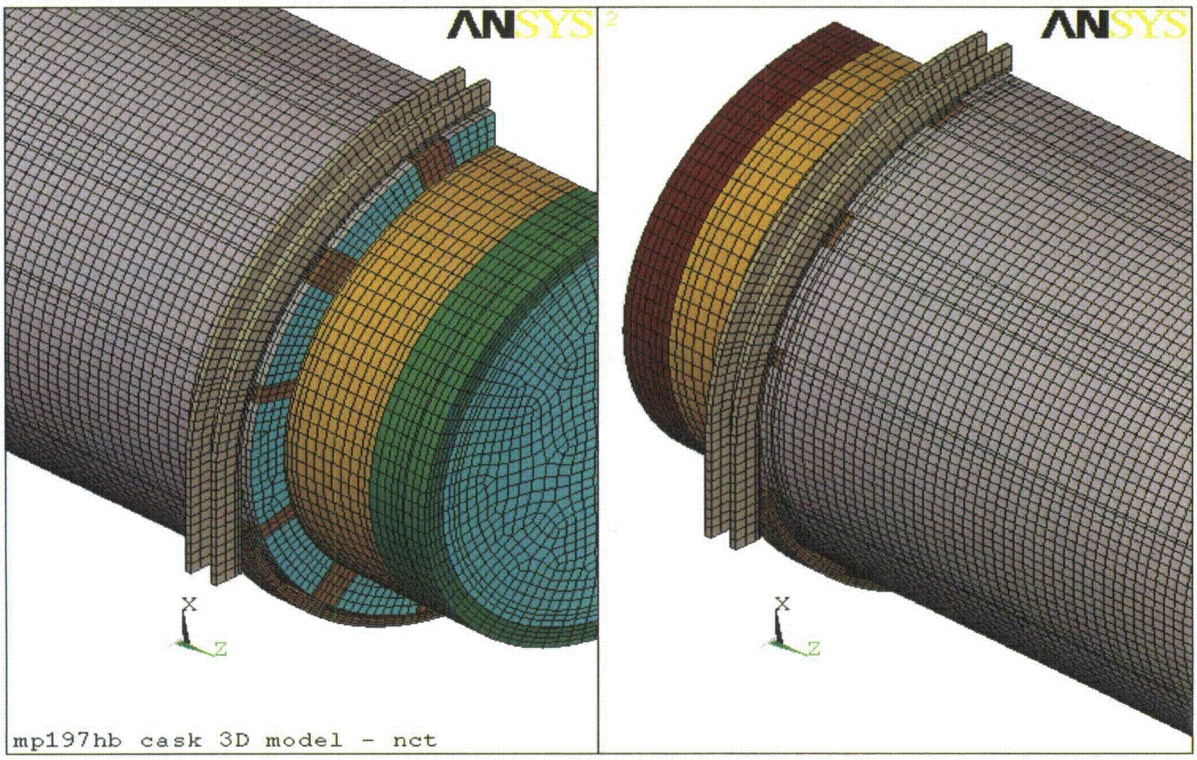


Figure A.2.13.1-6
NUHOMS – MP197HB Model MOD20TI (Top and Bottom Detail View)

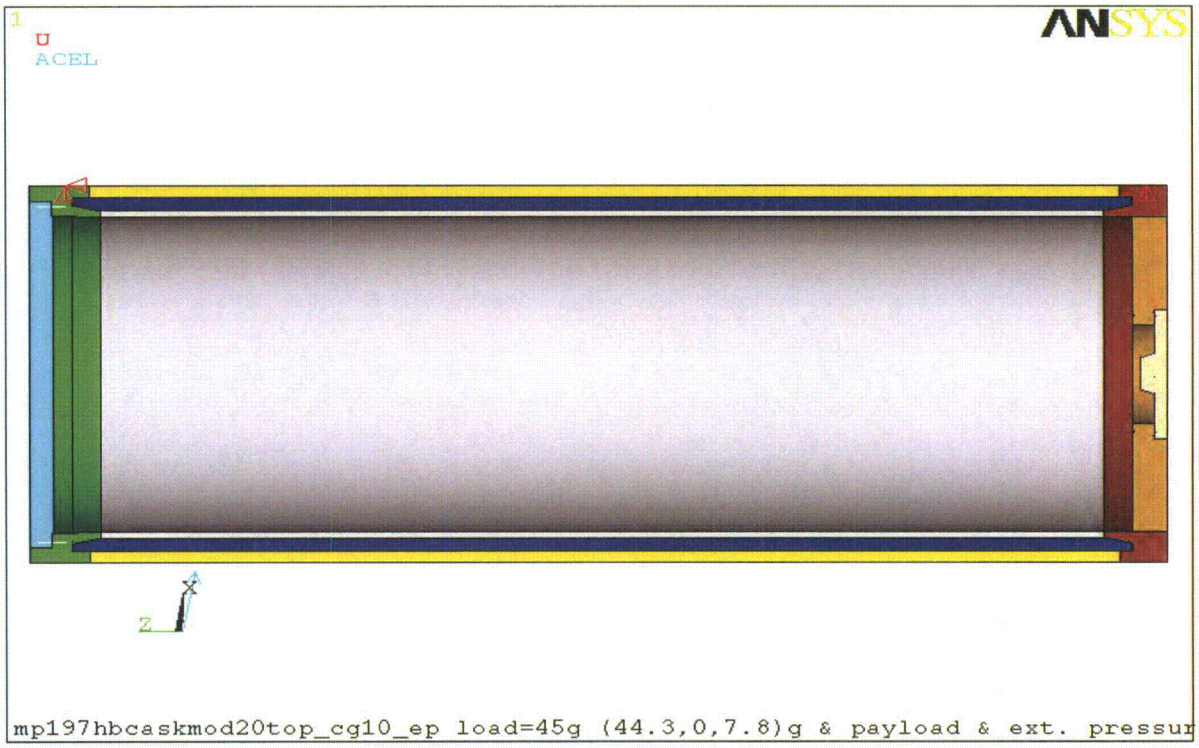


Figure A.2.13.1-7
Boundary Conditions – Side Drop, End and Corner Drop on Lid End Loading

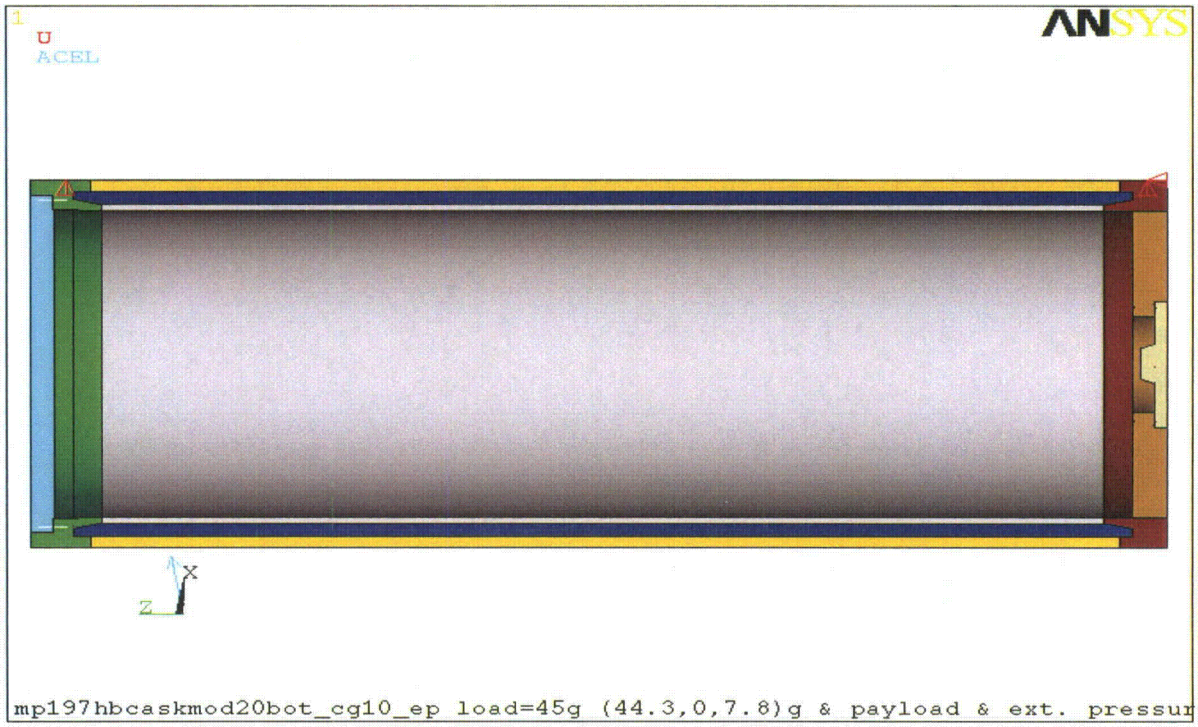


Figure A.2.13.1-8
Boundary Conditions – End Drop and Corner Drop on Bottom End Loading

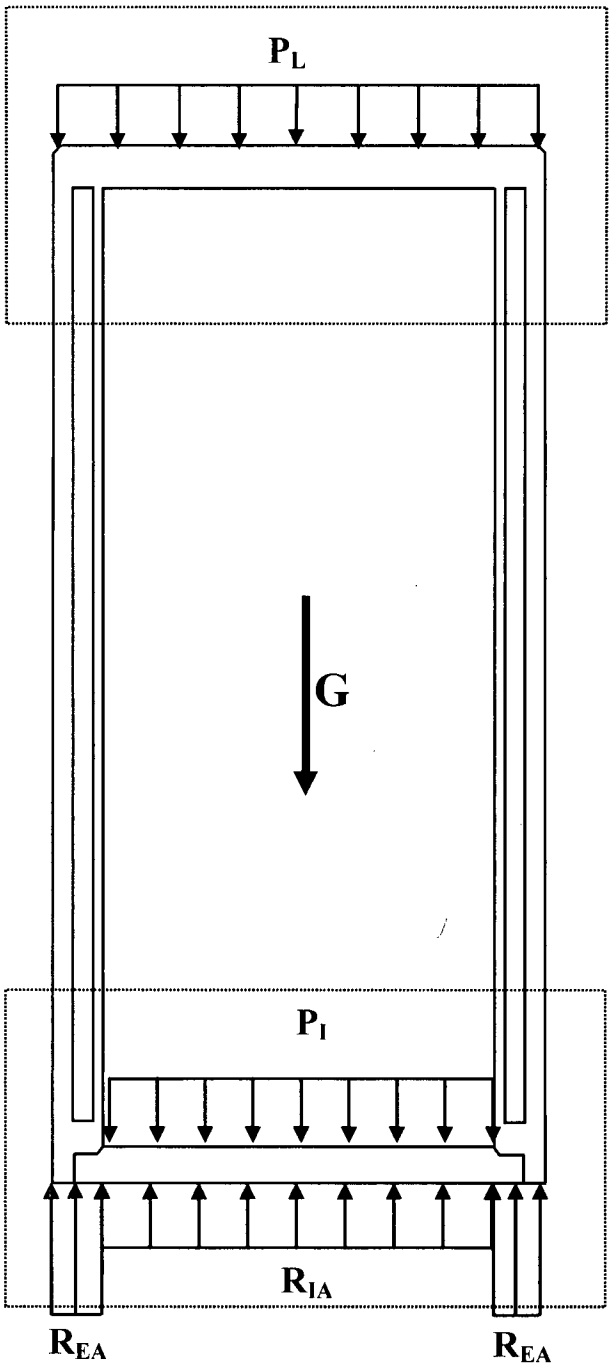


Figure A.2.13.1-9
End Drop on the Lid End Loading

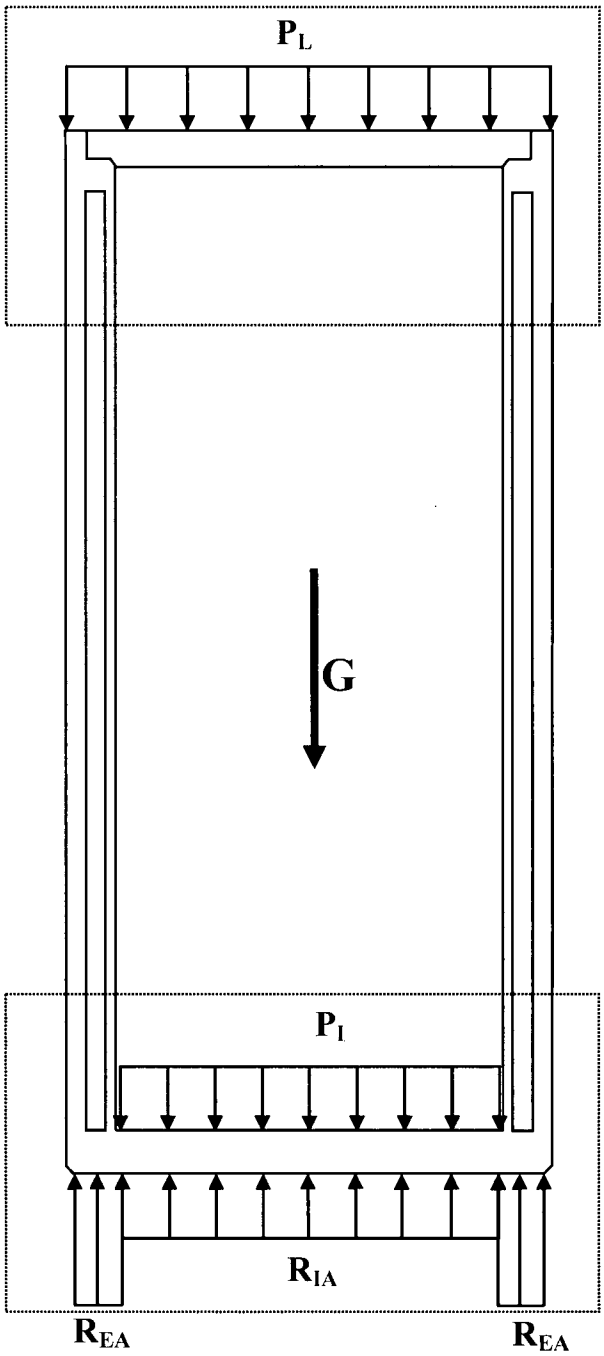


Figure A.2.13.1-10
End Drop on the Bottom End Loading

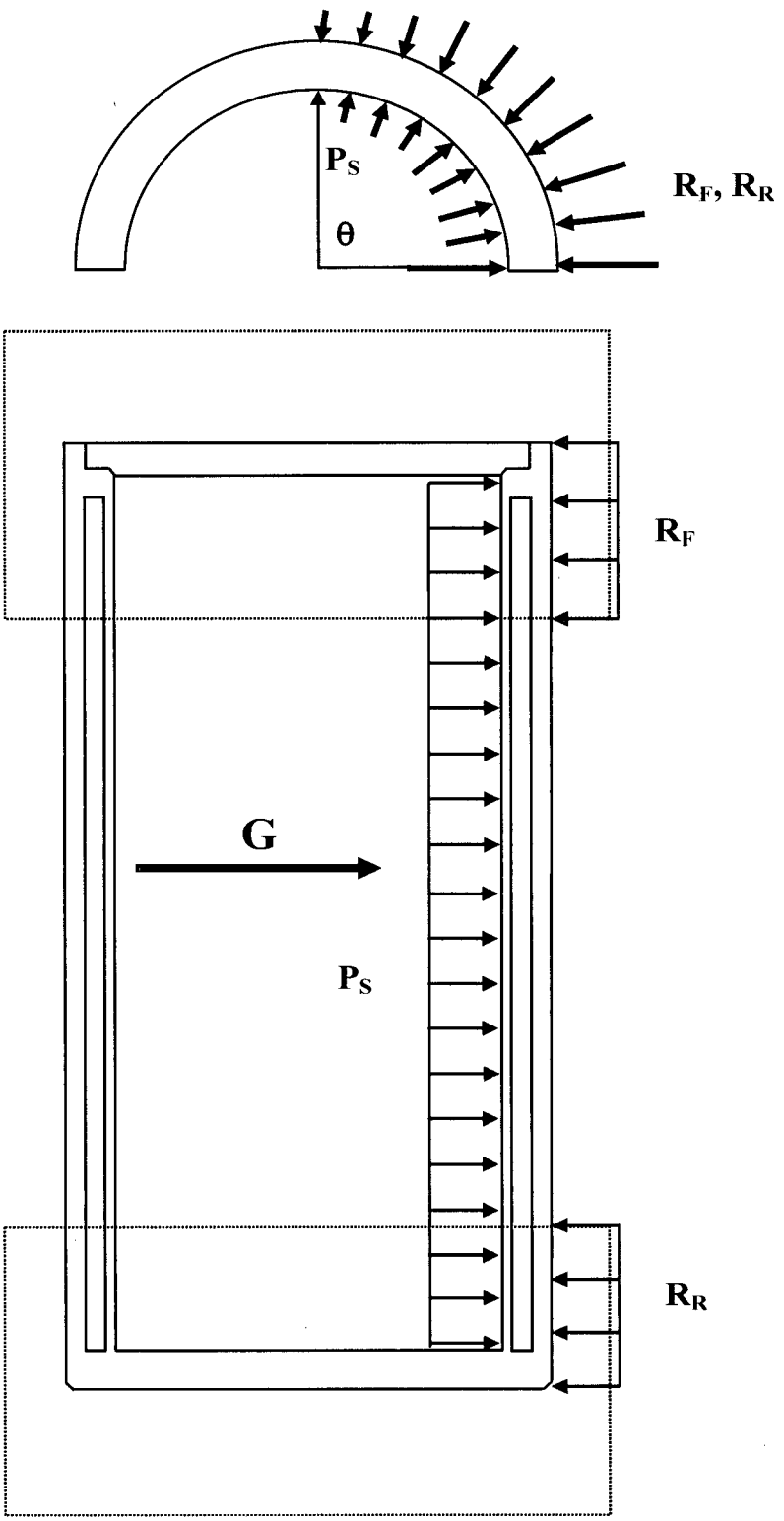


Figure A.2.13.1-11
Side Drop Loading

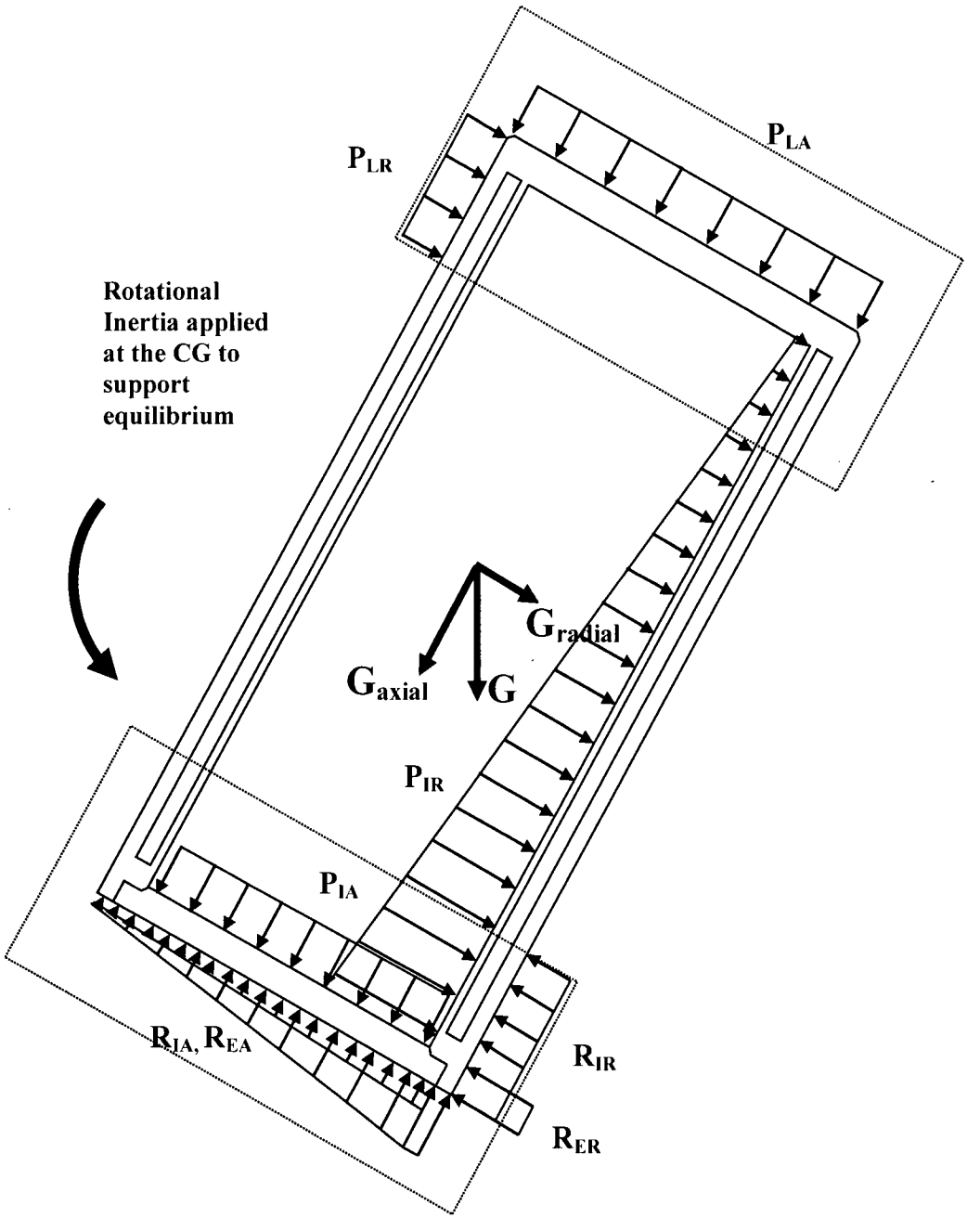


Figure A.2.13.1-12
30 Foot CG Over Corner Drop on Lid End Loading

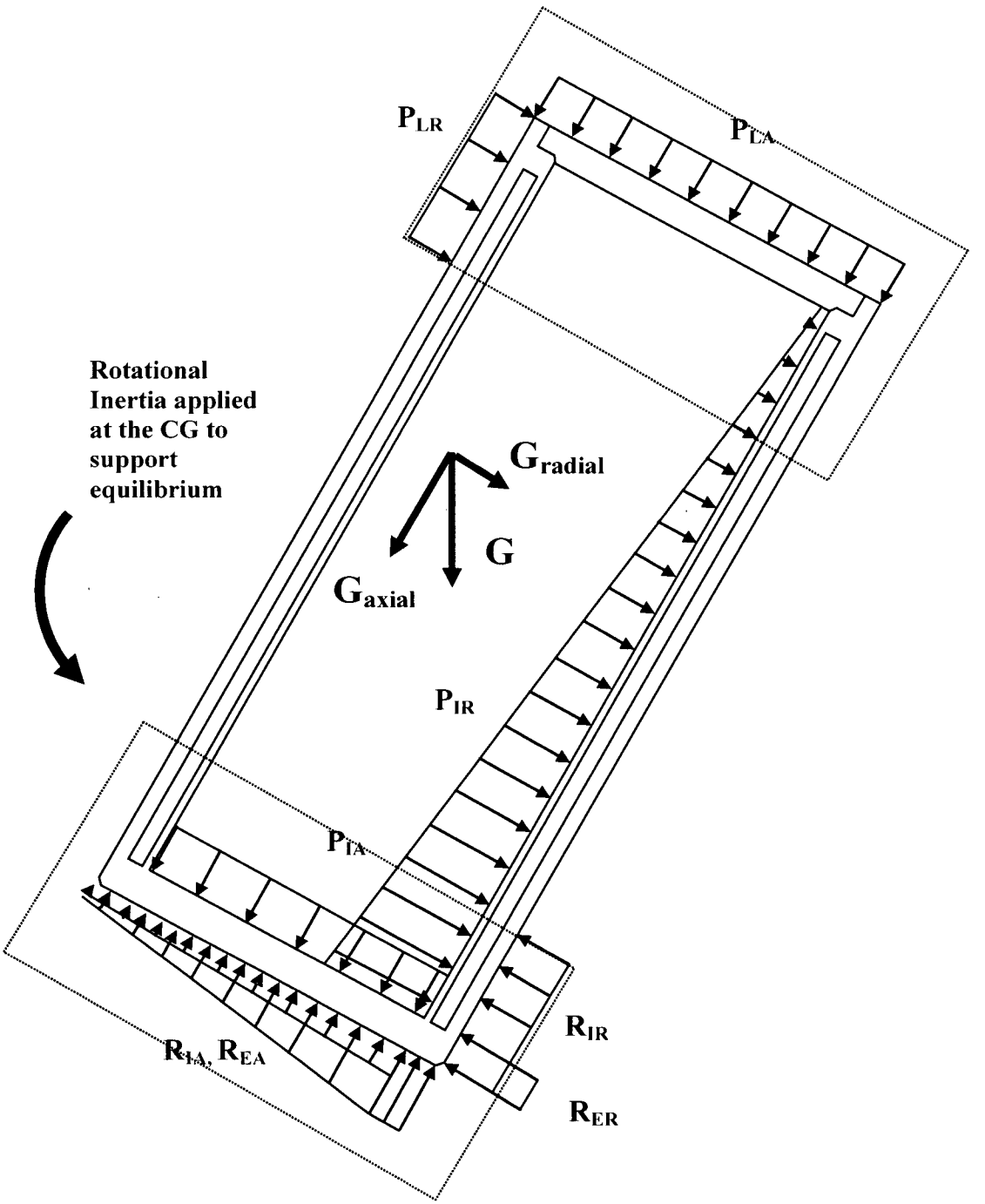


Figure A.2.13.1-13
30 Foot CG Over Corner Drop on Bottom End Loading

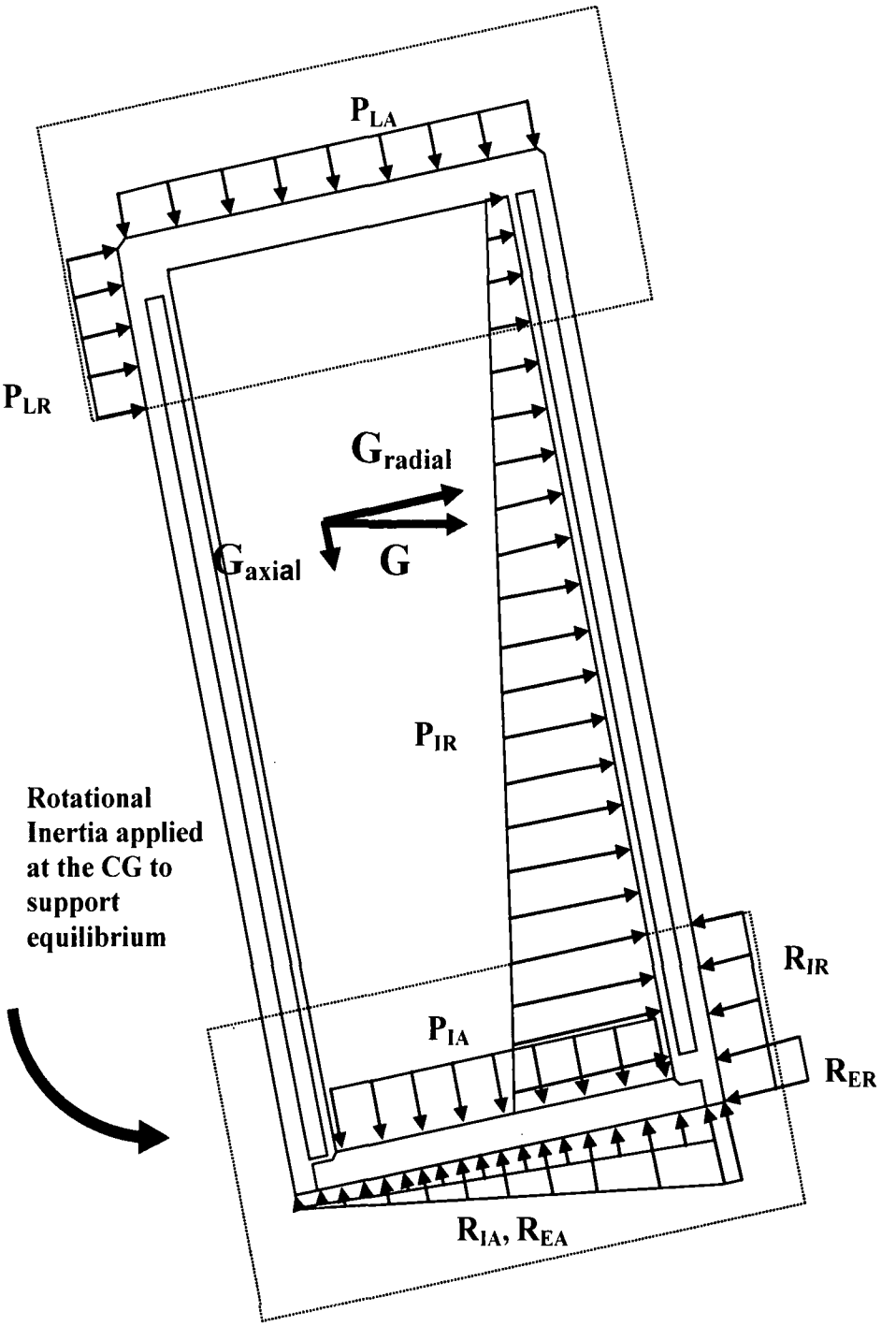


Figure A.2.13.1-14
30 Foot Oblique Impact on Lid End Loading

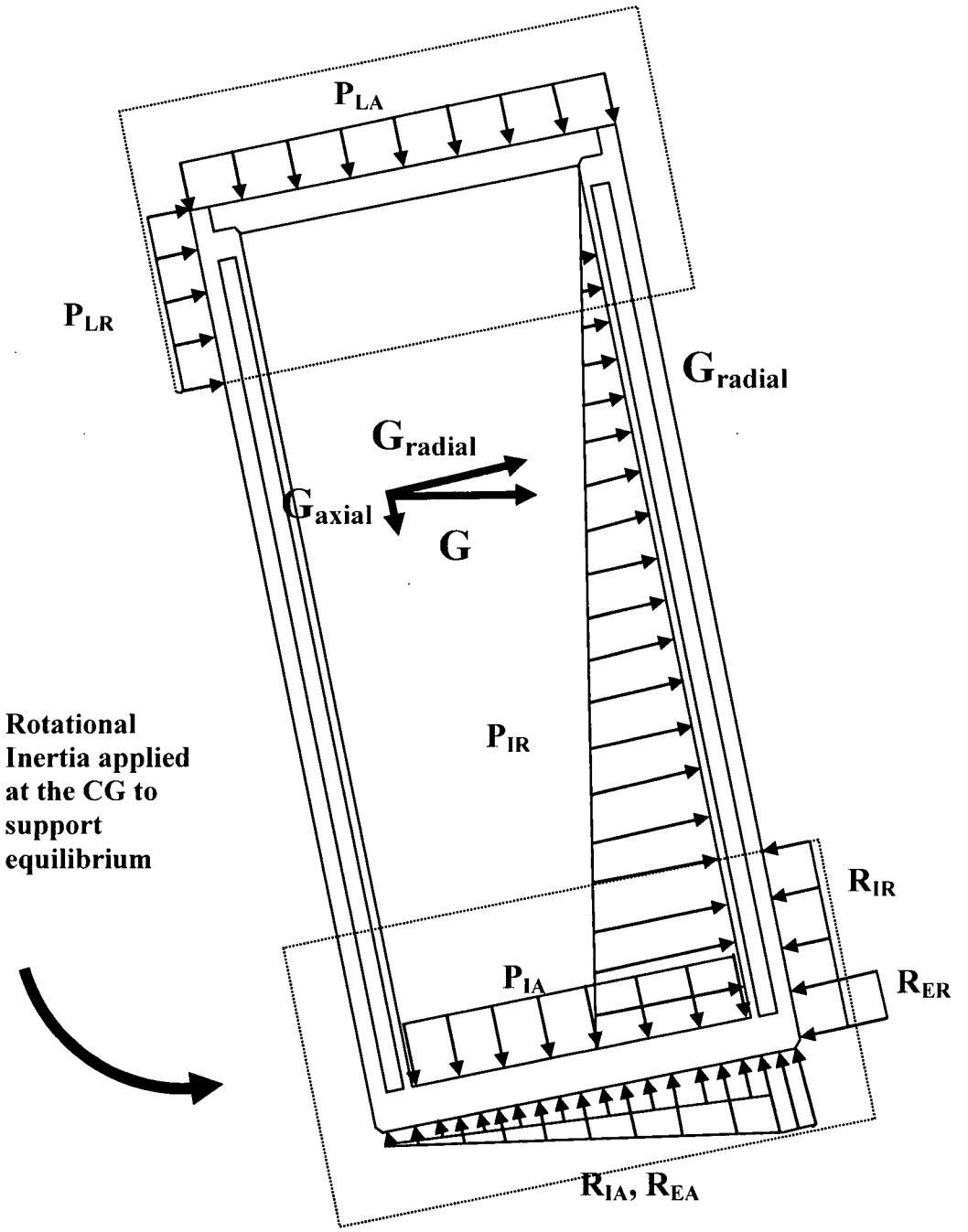


Figure A.2.13.1-15
30 Foot Oblique Impact on Bottom End Loading

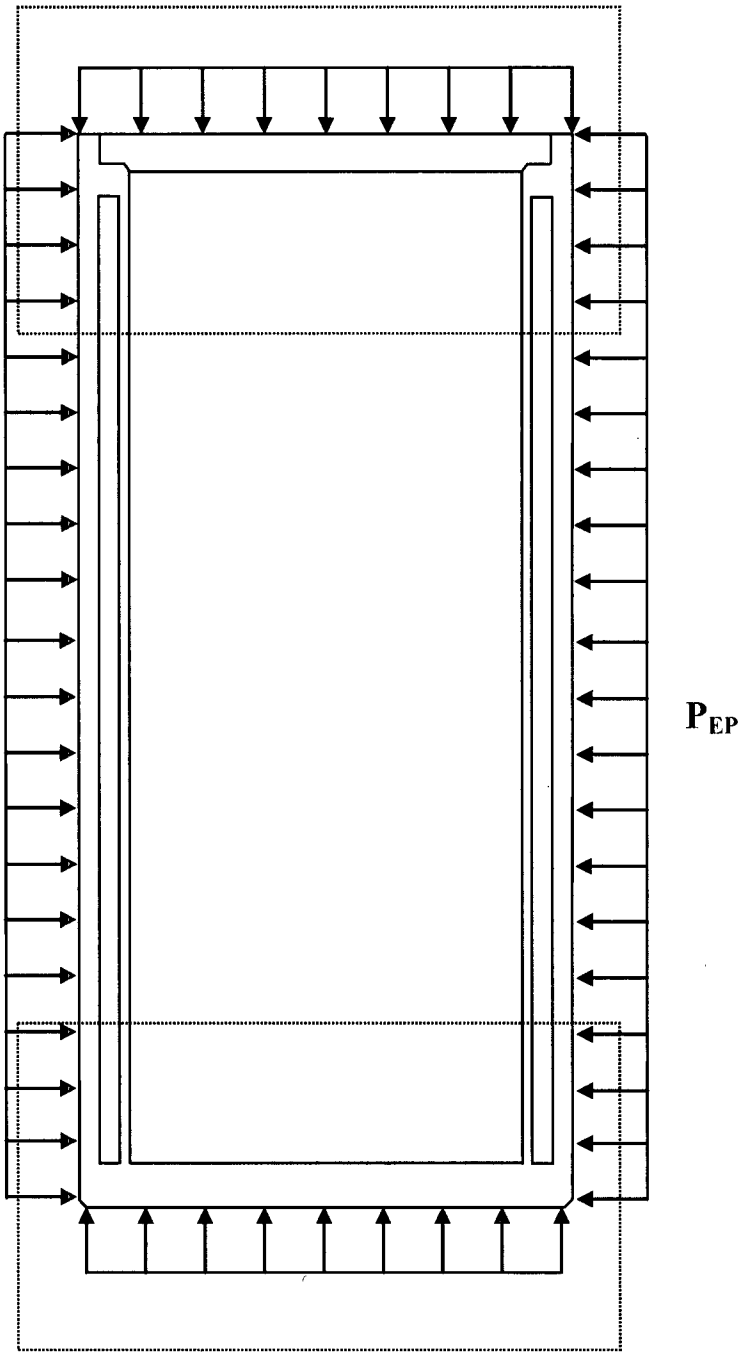


Figure A.2.13.1-16
External Pressure Loading

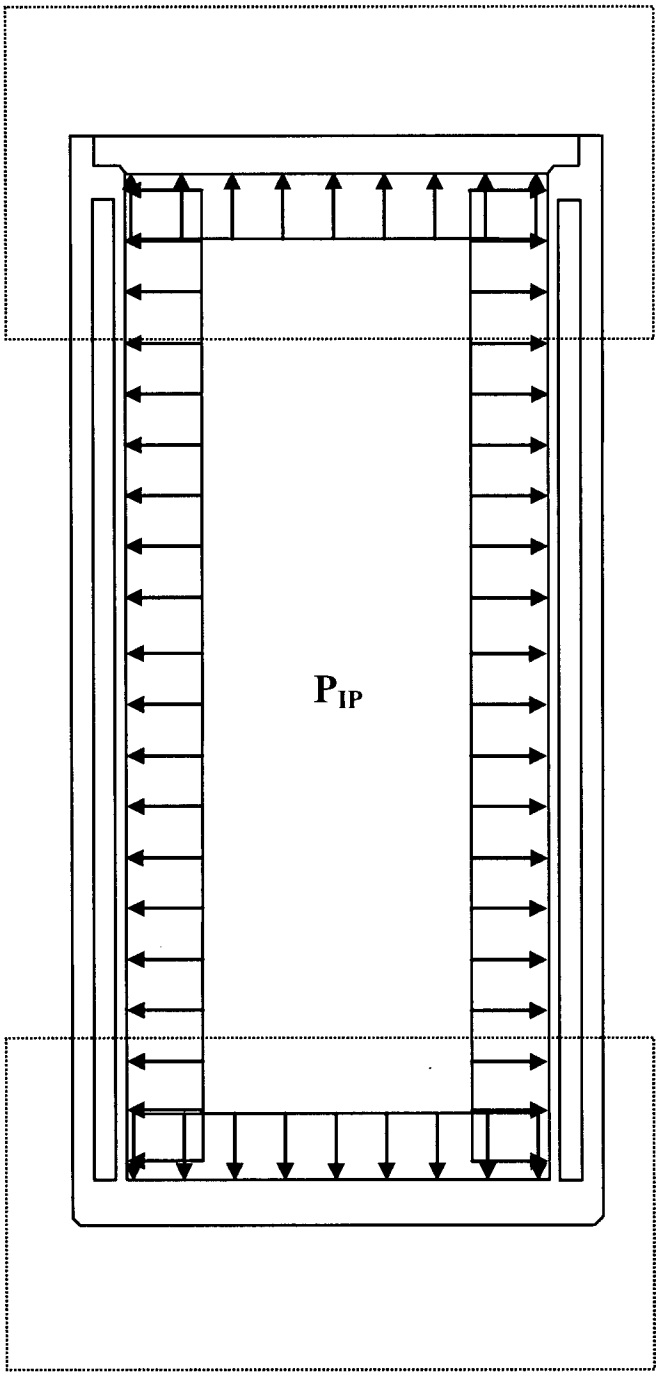


Figure A.2.13.1-17
Internal Pressure Loading

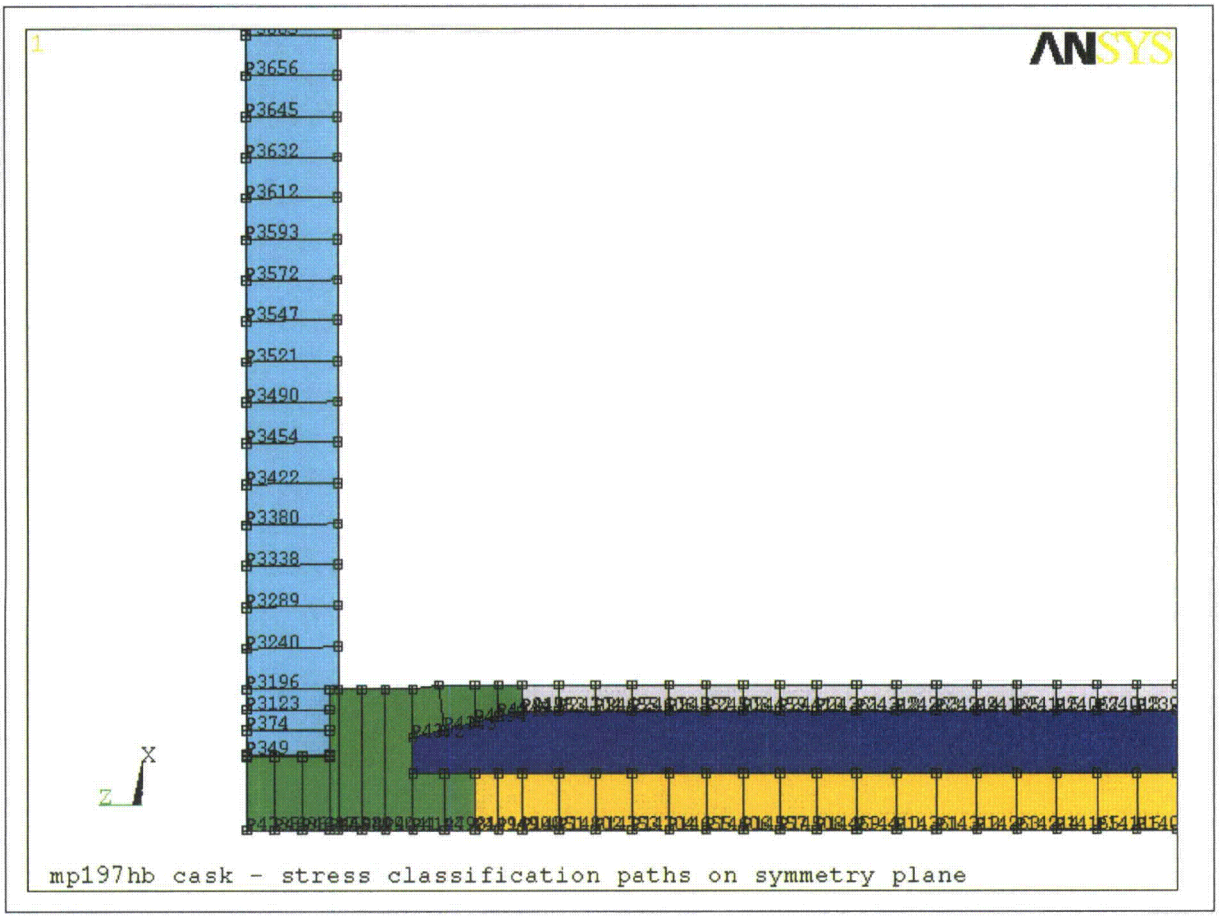


Figure A.2.13.1-18
Stress Classification paths at symmetry plane (cask top end)

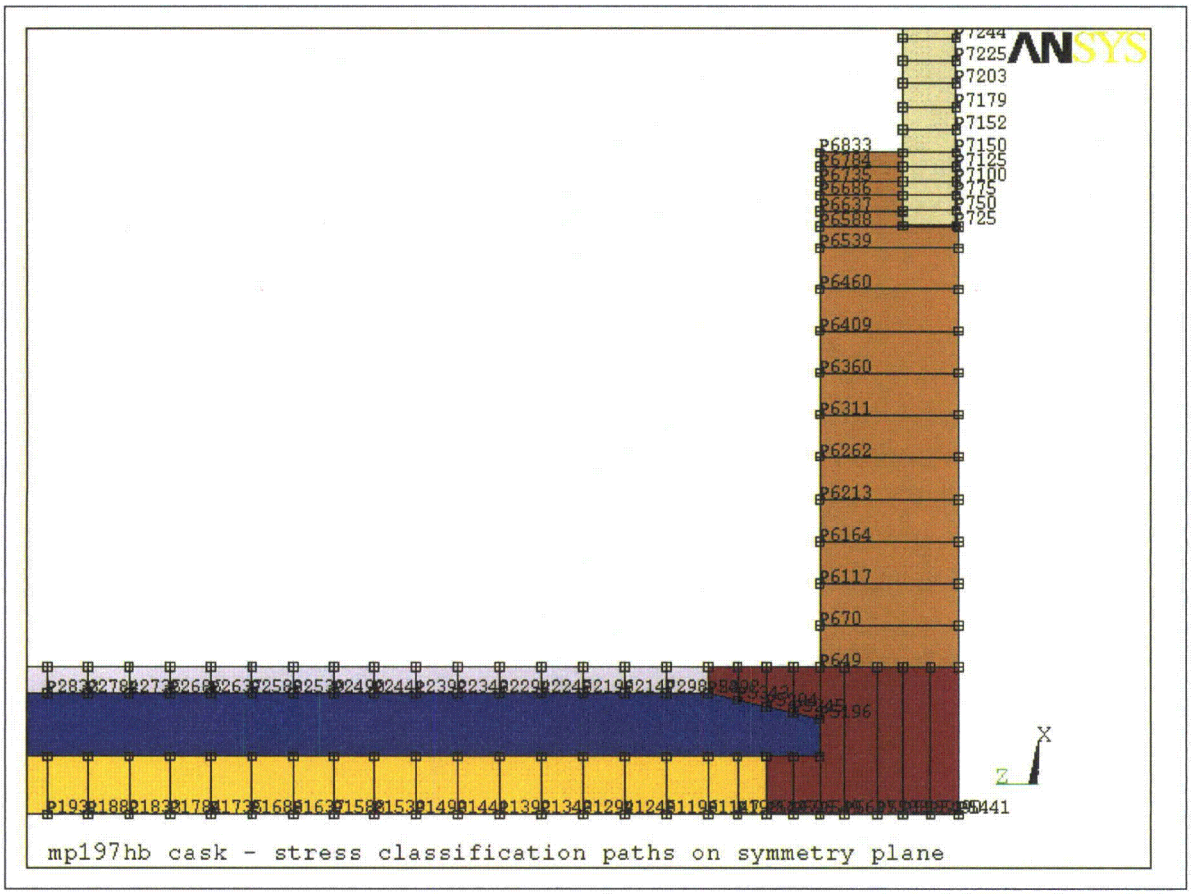
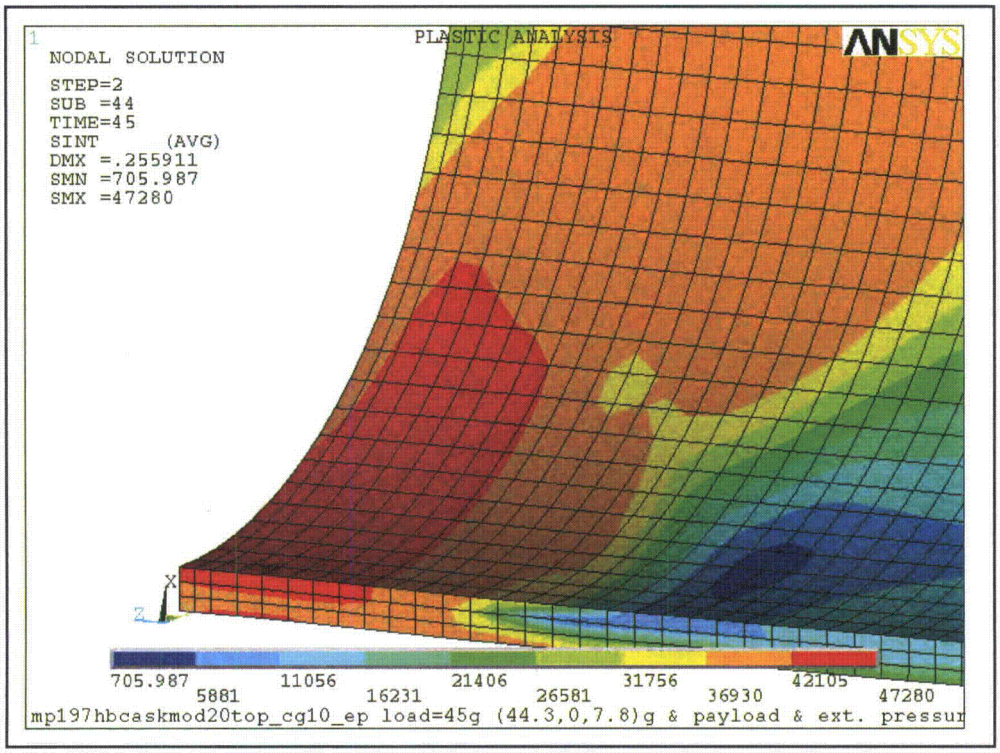


Figure A.2.13.1-19
Stress Classification paths at symmetry plane (cask bottom end)



Path Stress Information:

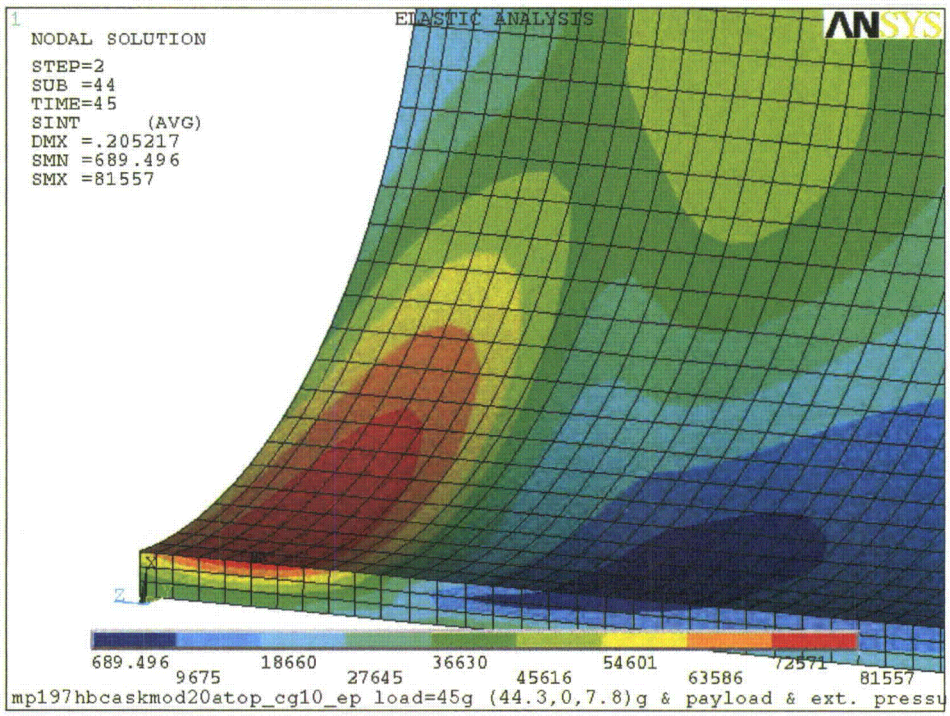
PM stress

Maximum: **41732 psi**
Location:
Axial Coordinate: **186.3 in**
Angle Coordinate: **180.0°**
Path Nodes: **35895, 32275**

Max Stress Intensity

Maximum: **47280 psi**
Location:
Axial Coordinate: **193.4 in**
Angle Coordinate: **180.0°**
Path Nodes: **35891, 32271**,,

Figure A.2.13.1-20
Outer Shell Stress Linearization-10° Slap Down Drop on Lid End
(Plastic Analysis)



Path Stress Information:

PM stress

Maximum: **54252 psi**.
Location:
Axial Coordinate: **191.7**
Angle Coordinate: **180.0**,
Path Nodes: **35892, 32272**.

PM+PB Stress

Maximum: **81349 psi**
Location:
Axial Coordinate: **191.7**
Angle Coordinate: **180.0**
Path Nodes: **35892, 32272**

Figure A.2.13.1-21
Outer Shell Stress Linearization-10° Slap Down Drop on Lid End
(Elastic Analysis)

Appendix A.2.13.2
MP197HB Cask Lid Bolt Analysis

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Appendix A.2.13.2
MP197HB Cask Lid Bolt Analysis

NOTE: References in this *a*ppendix are shown as [1], [2], etc. and refer to the reference list in Section A.2.13.2.11.

A.2.13.2.1 Purpose

This *a*ppendix analyzes the ability of the cask closure bolts to maintain a leak–tight seal under events defined by *n*ormal *c*onditions of *t*ransport (NCT) and the *h*ypothetical *a*ccident *c*onditions (HAC). Also evaluated in this section are the stresses in the bolt threads and in the internal threads, and the lid bolt fatigue. The stress analysis is performed in accordance with NUREG/CR–6007 [1].

Appendix A.1.4.10 contains reference drawings for the lid bolt.

The closure lid has a diameter of 77.18 in. and consists of a 4.50 in. thick plate with a 3.94 in. thick outer flange. The lid is bolted directly to the end of the containment vessel flange by 48 high-strength alloy steel 1.5 in. diameter bolts on a 74.81 in. diameter bolt circle. Close fitting alignment pins ensure that the lid is centered in the vessel. The bolts material is SA–540 Gr. B23 Cl. 1 which has a yield strength of 139.1 ksi and a tensile strength of 165.0 ksi at 350 °F.

The bolt material (SA-540 Gr. B23 Cl. 1) used to fabricate the lid bolt will have a minimum tensile strength of 175 ksi as specified in the SAR drawing (Dwg No. MP197HB-71-1002, sheet 2 of 2, rev. 2, note 16). Fine thread series will be used (1½-12 UNF, Dwg No. MP197HB-71-1002, sheet 1 of 2, rev. 2, item 21), which has a tensile stress area of 1.58 in^2.

The lid bolt analysis presented in this appendix is in accordance with NUREG/CR-6007 and conservatively uses a 1½-6 UNC (coarse thread) lid bolt with a tensile strength of 165 ksi. The lid bolt evaluation due to delayed impact is presented in Appendix A.2.13.14.

The following ways to minimize bolt forces and bolt failures for shipping casks are taken directly from [1], page xiii. All of the following design methods are employed in the NUHOMS® – MP197HB closure system:

- Protect closure lid from direct impact to minimize bolt forces generated by free drops (use impact limiters).
- Use materials with similar thermal properties for the closure bolts, the lid, and the cask wall to minimize the bolt forces generated by a fire accident.
- Apply sufficiently large bolt preload to minimize fatigue and loosening of the bolts by vibration.
- Lubricate bolt threads to reduce required preload torque and to increase the predictability of the achieved preload.
- Use closure lid design which minimizes the prying actions of applied loads.
- When choosing a bolt preload, pay special attention to the interactions between the preload

and thermal load and between the preload and the prying action.

The following evaluations are made in this section:

- Bolt preload
- Gasket seating load
- Internal pressure loads
- Temperature load
- Impact load
- Puncture load
- External pressure loads
- Load combinations for normal and accident conditions
- Bolt stresses and allowable stresses
- Bearing stress
- Lid bolt fatigue
- Thread engagement length evaluation

The design parameters for the closure lid analysis taken from [1] are summarized in Table A.2.13.2-1. The lid bolt data and material allowables are presented in Tables A.2.13.2-2 to A.2.13.2-4. Material properties and allowable stresses for NCT and HAC analyses are based on 350 °F, which bound -40 °F, -20 °F, and 100 °F ambient conditions.

The following load cases are considered in the analysis:

1. Preload + *t*emperature *l*oad (NCT)
2. Internal *p*ressure + 30 *f*oot *c*orner *d*rop (HAC)
3. Internal *p*ressure + *p*uncture *l*oad (HAC)

A.2.13.2.2 Lid Bolt Load Calculations

A.2.13.2.2.1 Bolt Preload

The method of analysis is described in Table 4.1 of [1].

A bolt torque range of 950 to 1,040 ft.lb is required to ensure leak tightness against normal and accident loadings.

Bolt preload for the minimum torque is:

$$F_a = \frac{Q}{K \times D_b} = \frac{950 \times 12}{0.135 \times 1.5} = 56{,}296 \text{ lb/bolt}$$

Bolt preload for the maximum torque is:

$$F_a = \frac{Q}{K \times D_b} = \frac{1{,}040 \times 12}{0.135 \times 1.5} = 61{,}630 \text{ lb/bolt}$$

Residual torsional moment for the minimum torque is:

$$M_{tr} = 0.5 \times Q = 0.5 \times 950 \times 12 = 5{,}700 \text{ in.lb/bolt}$$

Residual torsional moment for the maximum torque is:

$$M_{tr} = 0.5 \times Q = 0.5 \times 1{,}040 \times 12 = 6{,}240 \text{ in.lb/bolt}$$

Residual tensile bolt force:

$$F_{ar} = F_a = 61{,}630 \text{ lb/bolt}$$

A.2.13.2.2.2 Gasket Seating Load

The analysis is described in Table 4.2 of [1].

An elastomer O–ring is used, therefore the gasket seating load is negligible, and $F_s = 0$.

A.2.13.2.2.3 Internal Pressure Load

The analysis is described in Table 4.3 of [1].

The axial force per bolt due to internal pressure is:

$$F_a = \frac{\pi \times D_{lg}^2 \times (P_{li} - P_{lo})}{4N_b}$$

D_{lg} for outer seal is conservatively taken equal to the outer diameter of the outer seal groove and is equal to (see Appendix A.1.4.12):

D_{lg} = 72.267 (seal groove I. D.) +2 × 0.235 (groove width) = 72.737 in.

Therefore:

$$F_a = \frac{\pi \times 72.737^2 \times (30 - 0)}{4 \times 48} = 2{,}598 \text{ lb/bolt}$$

The fixed edge closure lid force is:

$$F_f = \frac{D_{lb} \times (P_{li} - P_{lo})}{4} = \frac{74.81 \times (30 - 0)}{4} = 562 \text{ lb/in}$$

The fixed edge closure lid moment is:

$$M_f = \frac{(P_{li} - P_{lo}) \times D_{lb}^2}{32} = \frac{30 \times 74.81^2}{32} = 5{,}247 \text{ in.lb/in}$$

The shear bolt force per bolt is:

$$S_s = \frac{\pi \times E_l \times t_l \times (P_{li} - P_{lo}) \times D_{lb}^2}{2 \times N_b \times E_c \times t_c \times (1 - N_{ul})}$$

$$S_s = \frac{\pi \times 27.9 \times 10^6 \times 4.5 \times (30 - 0) \times 74.81^2}{2 \times 48 \times 27.9 \times 10^6 \times 7 \times (1 - 0.3)} = 5{,}046 \text{ lb/bolt}$$

The lid shoulder takes this shear force, so $F_s = 0$.

A.2.13.2.2.4 Temperature Load

The analysis is described in Table 4.4 of [1].

The bolt material is SA–540 Gr. B23 Cl. 1; the lid and its flange are made of SA–203 Grade E or SA–350 Grade LF3, and the cask walls are made of SA–350 Grade LF3.

The coefficient of thermal expansion of the bolts at 350°F is 7.0×10^{-6} in/in/°F, and the coefficient of thermal expansion of the lid, its flange and of the cask is 7.0×10^{-6} in/in/°F.

Since the lid, its flange and the cask walls are made of the same material, the only load caused by thermal expansion is the non–prying tensile bolt force per bolt F_a. Since the coefficients of thermal expansion of the lid and the bolts is identical, $F_a = 0$ lb/bolt.

A.2.13.2.2.5 Impact Load

The analysis is described in Tables 4.5 and 4.6 of [1].

The non-prying tensile bolt force per bolt, F_a, is:

$$F_a = \frac{1.34 \times \sin(xi) \times DLF \times ai \times (W_l + W_c)}{N_b}$$

The drop angle xi is 60.3°. Only the accident conditions drop is considered in this Appendix. The acceleration ai is 40 g for the accident conditions. This g load used is higher than the baseline g load calculated of 37g in Appendix A.2.13.12, Section A.2.13.12.10.

The weight W_c of the payload is 118,500 lbs. The maximum weight W_l of the lid is 6,100 lbs. These weights bound the maximum weight specified in Chapter A.2, Section A.2.1.3 (112,000 lbs for payload and 6,000 lbs for lid)

$$F_a = \frac{1.34 \times \sin(60.3°) \times 1.1 \times 40 \times (6{,}100 + 118{,}500)}{48} = 132{,}944 \text{ lb/bolt}$$

The gap between the lid and the cask walls is smaller than the gap between the lid bolts and the lid bolt holes, during a side drop, the lid comes into contact with the cask walls before the lid bolts are loaded in shear, and the lid shoulder takes the shear force during these drops. Therefore, $F_s = 0$.

The fixed-edge closure lid force F_f is:

$$F_f = \frac{1.34 \times \sin(xi) \times DLF \times ai \times (W_l + W_c)}{\pi \times D_{lb}}$$

$$F_f = \frac{1.34 \times \sin(60.3) \times 1.1 \times 40 \times (6{,}100 + 118{,}500)}{\pi \times 74.81} = 27{,}152 \text{ lb/in}$$

The fixed-edge closure lid moment M_f is:

$$M_f = \frac{1.34 \times \sin(xi) \times DLF \times ai \times (W_l + W_c)}{8\pi}$$

$$M_f = \frac{1.34 \times \sin(60.3) \times 1.1 \times 40 \times (6{,}100 + 118{,}500)}{8\pi} = 253{,}905 \text{ in.lb/in}$$

A.2.13.2.2.6 Puncture Load

Impact limiters are assumed to protect the ends of the cask body and to absorb the puncture load energy to such an extent that no indirect prying force is generated by the six inch diameter puncture bar.

A.2.13.2.2.7 External Pressure Load of 290 psig

The analysis is described in Table 4.3 of [1].

The axial force per bolt due to external pressure is:

$$F_a = \frac{\pi \times D_{lg}^2 \times (P_{li} - P_{lo})}{4N_b}$$

D_{lg} for outer seal (conservatively taken equal to the outer diameter of the outer seal groove):

D_{lg} = 72.267 (seal groove I. D.) +2 × 0.235 (groove width) = 72.737 in.

Therefore:

$$F_a = \frac{\pi \times 72.737^2 \times (0-290)}{4 \times 48} = -25{,}105 \text{ lb/bolt}$$

Since this force is negative (inward acting), the actual resulting bolt force, $F_a = 0$, because the applied load is supported by the cask wall and not by the bolts.

The fixed edge closure lid force is:

$$F_f = \frac{D_{lb} \times (P_{li} - P_{lo})}{4} = \frac{74.81 \times (0-290)}{4} = -5{,}424 \text{ lb/in}$$

The fixed edge closure lid moment is:

$$M_f = \frac{(P_{li} - P_{lo}) \times D_{lb}^2}{32} = \frac{(0-290) \times 74.81^2}{32} = -50{,}719 \text{ in.lb/in}$$

The shear bolt force per bolt is:

$$S_s = \frac{\pi \times E_l \times t_l \times (P_{li} - P_{lo}) \times D_{lb}^2}{2 \times N_b \times E_c \times t_c \times (1 - N_{ul})} = \frac{\pi \times 27.90 \times 10^6 \times 4.5 \times (0-290) \times 74.81^2}{2 \times 48 \times 27.9 \times 10^6 \times 7 \times (1-0.3)} = -48{,}777 \text{ lb/bolt}$$

The lid shoulder takes this shear force, so $F_s = 0$.

The loads calculated in this section are summarized in Table A.2.13.2-5.

A.2.13.2.3 Lid Bolt Load Combinations

A summary of normal and accident condition load combinations is presented in table A.2.13.2-6. The method used for the following combination is taken from [1], Table 4.9.

A.2.13.2.3.1 Additional Prying Bolt Force

The analysis is described in Table 2.1 of [1].

Since the prying forces applied in load case 3 act inward, normal to the cask lid, an additional prying bolt force, F_{ap}, is generated (Table 2.1 of [1]). No additional prying bolt force is generated for the outward loadings because of the gap between the lid and flange at the outer edge.

F_{ap} for an inward force is calculated in the following way:

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

Where $C_1 = 1$, and:

$$C_2 = \frac{8}{3 \times (D_{li} - D_{lb})^2} \frac{L_b}{N_b \times D_b^2 \times E_b} \left[\frac{E_l \times t_l^3}{1 - N_{ul}} + \frac{(D_{lo} - D_{li}) \times E_{lf} \times t_{lf}^3}{D_{lb}} \right]$$

The bolt length between the top and bottom surfaces of the lid is:

$$L_b = 4.50\,(\text{lid thickness}) - .56\,(\text{gap}) - [1.70\,(\text{counter bore}) - .17\,(\text{washer})] = 2.41\,\text{in}.$$

$$C_2 = \frac{8}{3 \times (70.44 - 74.81)^2} \frac{2.41 \times 26.45 \times 10^6}{48 \times 1.5^2 \times 26.45 \times 10^6} \left[\frac{4.5^3}{1 - 0.3} + \frac{(77.18 - 70.44) \times 3.94^3}{74.81} \right]$$

$$C_2 = 0.4228.$$

B is the non-prying tensile bolt force, and P is the bolt preload; both are derived from the load applied to each bolt in normal operating conditions (bolt preload + temperature load + internal pressure load). Conservatively, the fixed-edge closure lid moment is considered for the case of the external pressure load, for which $M_f = -50{,}719$ in.lb/in.

$$P = \frac{F_{ap} \times N_b}{\pi \times D_{lb}} = \frac{61{,}630 \times 48}{\pi \times 74.81} = 12{,}587\ \text{lb/in}$$

For all inward loadings such as a puncture load, F_f is supported by the cask wall and thus has no effect on both the non–prying and prying bolt forces, B and R. Therefore, $F_f = 0$.

$B = F_f$ if $F_f > P$ and $B = P$ otherwise. Since $F_f = 0 < P$, $B = P = 12{,}587$ lb/in.

Furthermore, the pressure load is not included because it decreases the magnitude of the applied prying moment, which is less conservative.

Therefore:

$$F_{ap} = \frac{\pi \times 74.81}{48} \times \left[\frac{\frac{2 \times (-50{,}719)}{70.44 - 74.81} - 1 \times (12{,}587 - 0) - 0.4228 \times (12{,}587 - 12{,}587)}{1 + 0.4228} \right]$$

$$F_{ap} = 36{,}565 \text{ lb/bolt.}$$

It is observed that the additional tensile bolt force due to prying for the external pressure load is less than the accident impact force. The external pressure load is therefore not critical for bolt stress evaluation.

A.2.13.2.3.2 Bending Moment Bolt Force

The analysis is described in Table 2.2 of [1].

The maximum bending bolt moment M_{bb} generated by the applied load is evaluated as follows:

$$M_{bb} = \frac{\pi \times D_{lb}}{N_b} \frac{K_b}{K_b + K_l} \times M_f$$

The coefficients K_b and K_l are based on geometry and material properties and are defined in Table 2.2 of [1]. By substituting the values given above:

$$K_b = \frac{N_b}{L_b} \frac{E_b}{D_{lb}} \frac{D_b^4}{64} = \frac{48}{2.41} \frac{26.45 \times 10^6}{74.81} \frac{1.5^4}{64} = 5.571 \times 10^5$$

$$K_l = \frac{E_l \times t_l^3}{3\left[\left(1 - N_{ul}^2\right) + \left(1 - N_{ul}\right)^2 \left(\frac{D_{lb}}{D_{lo}}\right)^2\right] D_{lb}} = \frac{26.45 \times 10^6 \times 4.5^3}{3\left[\left(1 - 0.3^2\right) + \left(1 - 0.3\right)^2 \left(\frac{74.81}{77.18}\right)^2\right] 74.81} = 7.837 \times 10^6$$

Therefore:

$$M_{bb} = \frac{\pi \times 74.81}{48} \times \frac{5.571 \times 10^5}{5.571 \times 10^5 + 7.837 \times 10^6} \times M_f$$

In the case of the internal pressure load, M_f = 5,247 in.lb.

Substituting this value into the equation above gives:

$$M_{bb} = 1{,}705 \text{ in.lb/bolt}$$

A.2.13.2.4 Bolt Stress Calculations

The formulas for the bolt stress calculations are described in Table 5.1 of [1].

A.2.13.2.4.1 Average Tensile Stress

The bolt preload is calculated to withstand the worst case load combination and to maintain a clamping (compressive) force on the closure joint, under both normal and accident conditions.

Based upon the load combination results (see Table A.2.13.2-6), it is shown that a positive (compressive) load is maintained on the clamped joint for all load combinations except for the accident condition impact plus pressure load. A more detailed finite element analysis is performed in Section A.2.13.2.7 of this Appendix to evaluate closure of the lid during this event.

The maximum non–prying tensile force for normal conditions is F_a = 61,630 lbs, from load case 1.B (maximum torque preload + temperature load). The maximum non–prying tensile force for accident conditions is F_a = 135,542 lbs, from load case 2 (internal pressure load + impact force).

The average tensile stress caused by the tensile bolt force F_a is:

$$S_{ba} = 1.2732 \times \frac{F_a}{D_{ba}^2}$$

D_{ba} is the bolt diameter for tensile stress calculation: $D_{ba} = D_b - 0.9743 \times p$, where p is the pitch of the bolt[1]. According to Table 1, p. 1714 of [3], p = 0.1667 in. Therefore, D_{ba} = 1.3376 in. This value is conservatively used for all bolt stress calculations.

Normal conditions:

$$S_{ba} = 1.2732 \times \frac{61{,}630}{1.3376^2} = 43{,}856 \text{ psi}$$

Accident conditions:

$$S_{ba} = 1.2732 \times \frac{135{,}542}{1.3376^2} = 96{,}452 \text{ psi}$$

A.2.13.2.4.2 Bending Stress

The bending stress caused by the bending bolt moment M_{bb} is:

$$S_{bb} = 10.186 \times \frac{M_{bb}}{D_{ba}^3}$$

Normal conditions:

$$S_{bb} = 10.186 \times \frac{1{,}705}{1.3376^3} = 7{,}256 \text{ psi}$$

[1] For inch–series threads only; the coefficient is equal to 0.9382 for metric–series threads

A.2.13.2.4.3 Shear Stress

For both normal and accident conditions, the average shear stress caused by shear bolt force F_s is:

$$S_{bs} = 0.$$

The maximum shear stress caused by the torsional moment M_t is:

$$S_{bt} = 5.093 \times \frac{M_t}{D_{ba}^3}$$

For both normal and accident conditions:

$$S_{bt} = 5.093 \times \frac{6{,}240}{1.3376^3} = 13{,}279 \text{ psi}$$

A.2.13.2.4.4 Maximum Combined Stress Intensity

The maximum combined stress intensity is calculated in the following way ([1], Table 5.1):

$$S_{bi} = \sqrt{(S_{ba} + S_{bb})^2 + 4 \times (S_{bs} + S_{bt})^2}$$

For normal conditions, it combines tension, shear, bending, and residual torsion:

$$S_{bi} = \sqrt{(43{,}856 + 7{,}256)^2 + 4 \times (0 + 13{,}279)^2} = 57.6 \text{ ksi}.$$

A.2.13.2.4.5 Stress Ratios

In order to meet the stress ratio requirement, the following relationship must hold for both normal and accident conditions:

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

Where R_t is the ratio of average tensile stress to allowable average tensile stress F_{tb} and R_s is the ratio of average shear stress to allowable average shear stress F_{vb}.

For NCT:

$$R_t = \frac{S_{ba}}{F_{tb,NCT}} = \frac{43.9}{92.7} = 0.474,$$

$$R_s = \frac{S_{bt}}{F_{vb,NCT}} = \frac{13.3}{55.6} = 0.239,$$

$$R_t^2 + R_s^2 = 0.474^2 + 0.239^2 = 0.282 < 1.$$

For HAC:

$$R_t = \frac{S_{ba}}{F_{tb,HAC}} = \frac{96.4}{115.5} = .835,$$

$$R_s = \frac{S_{bt}}{F_{vb,HAC}} = \frac{13.3}{69.3} = 0.192,$$

$$R_t^2 + R_s^2 = 0.835^2 + 0.192^2 = 0.734 < 1.$$

A.2.13.2.4.6 Bearing Stress Under Bolt Head

The maximum NCT axial force is 61,630 lb. A washer of outer diameter 2.35" is used. The diameter of the bolt hole is 1.69 in. Therefore, the bearing area is:

$$A = 0.25 \times \pi \times (2.35^2 - 1.69^2) = 2.094 \text{ in}^2$$

Therefore, the bearing stress is:

$$\frac{61{,}630}{2.094} = 29.4 \text{ ksi}$$

The allowable normal condition bearing stress on the lid is taken to be the yield stress of the lid material at 350°F. The lid is manufactured out of SA–350 Gr. LF3 or SA–203 Gr. E, which has a minimum yield stress of 32.60 ksi at 350°F.

A.2.13.2.5 Results

A summary of the lid bolt stresses calculated above is listed in Table A.2.13.2-7.

The calculated bolt stresses are all less than the specified allowable stresses.

A.2.13.2.6 Lid Bolt Fatigue Analysis

The purpose of the fatigue analysis is to show quantitatively that the fatigue damage to the lid bolts during NCT is acceptable. This is done by considering the fatigue damage factor for each NCT event. For this analysis it is assumed that the bolts are replaced after 250 round trip shipments.

Since the bolt preload stress applied to the MP197HB cask lid bolts is higher than all of the other NCT condition loads, the stress in the bolts will never exceed the bolt preload stress.

Consequently, the application and removal of preload is the only real cyclic loading that occurs in the lid bolts.

Assuming that the bolts are replaced after 250 round trips, the number of preload cycles is two times the number of trips, or 500 cycles. For each round trip, the cask will be with payload for one cycle (or one one–way trip) and the applied bolt torque is in the 1,000 -1,040 ft.lb range. However, for the return trip, the cask will be empty and the applied bolt toque is in the 600 - 640 ft.lb range.

For the loaded cask, the maximum normal condition bolt stress intensity (due to preload and temperature) is 57.6 ksi (Section A.2.13.2.4.4) for 250 cycles.

For the empty cask, the maximum normal condition bolt stress intensity (due to preload and temperature) is:

$$\frac{640}{1{,}040} \times 57.6 = 35.4 \text{ ksi (for 250 cycles)}$$

It is shown below that this reduced preload stress is also higher than the rail shock or vibrations stresses.

A.2.13.2.6.1 Vibration/Shock

Since the MP197HB package will be shipped by truck or rail car, the bounding shock and vibration loadings are considered.

Rail car shock:

Reference [5] specifies a peak shock loading of 4.7 g in the longitudinal direction for rail car transport. Consequently, the bolt force due to rail car shock is:

$$\frac{(118{,}500 + 6{,}100 \text{ lb}) \times (4.7 \text{ g})}{(48 \text{ bolts}) \times (1.4052 \text{ in}^2 \text{ per bolt})} = 8{,}682 \text{ psi}$$

Truck vibration:

According to reference [7], the peak vibration load on the deck of a truck in the longitudinal direction is 0.3 g. This results in a stress of less than 600 psi, which is negligible for high–strength bolt.

A.2.13.2.6.2 Damage Factor Calculation

The damage factors are computed in Table A.2.13.2–8 based on the stresses and cyclic history described above, a fatigue strength reduction factor K_F of 4, and the fatigue curve shown in Table I–9.4 and tabulated in Table I–9.1 of [2] for Maximum Nominal Stress MNS = 57.6 ksi $\leq$ $2.7 \times S_m = 2.7 \times 45.5 = 122.85$ ksi.

Here, n is the number of cycles, N is taken from Figure I–9.4 of [2], and S_a is defined in the following way:

If one cycle goes from 0 to $+S.I.$, then $S_a = 0.5 \times S.I. \times K_F \times K_E$.

If one cycle goes from $-S.I$ to $+S.I.$, then $S_a = S.I. \times K_F \times K_E$.

Where K_E is the correction factor for modulus of elasticity:

$$K_E = \frac{30 \times 10^6}{26.45 \times 10^6} = 1.13$$

Since the total damage factor is less than one, the MP197HB cask lid bolts will not fail due to fatigue.

A.2.13.2.7 Lid Seal Contact Evaluation

The lid seal analysis was conducted in order to determine the lid / cask seal status when subject to a CG over lid corner impact 30 foot drop since section A.2.13.2.3 above shows that during accident conditions, the preload is not enough to maintain a compressive force on the seal.

An elastic finite element analysis is performed to determine the status of the lid / cask seal during a CG over corner 30 foot drop.

A.2.13.2.7.1 Assumptions

- The details of the finite element model, material properties and other details are described in detail in Appendix A.2.13.1.
- The lid / cask seal is investigated in this section, so CG over corner drop towards the lid end is deemed critical.
- The force to seat the seals is 0 lb.
- The maximum allowable decompression of the seal is 0.040 in.
- A spring stiffness value of 10 lb/in. is assumed for the real elastomer.

A.2.13.2.7.2 Analysis

The 3D finite element model from Appendix A.2.13.1 is modified to include the seal elastomer modeling using contact elements (CONTAC52). A pressure of 30 psig is applied on all internal surfaces. Bolt preload is applied using link and pretension elements.

A.2.13.2.7.3 Results

Figure A.2.13.2-1 plots the decompression of the seal as a function of circumferential location. As can be seen there is no decompression of the seal; *based on preload of 50 kips (minimum preload is 56.3 kips).* Figure A.2.13.2-2 shows the zoomed deformation plot near the lid-flange region.

From the analysis results it can be concluded that there is no decompression in the seal during the CG over corner drop impact scenario with internal pressure and bolt preload. Since the seal exists all along the circumference of the MP197HB Transport cask, the internal contents will not leak during the worst case loading condition.

A.2.13.2.8 Minimum Engagement Length for Bolt and Flange

For the 1 ½–6UNC bolt, the material is SA–540 Gr. B23 Cl. 1 which has a yield strength of 139.1 ksi and a tensile strength of 165.0 ksi at 350°F. The flange material is SA–350 LF3 or SA–203 Gr. E, with S_u = 70.00 ksi (at 350°F).

The minimum engagement length L_e for the bolt and flange is ([3], page 1490):

$$L_e = \frac{2 \times A_t}{3.1416 \times K_{n\max} \times \left[\frac{1}{2} + .57735 \times n \times \left(E_{s,\min} - K_{n\max}\right)\right]}$$

A_t is the tensile–stress area of the screw and is given by the following formula:

$$A_t = \pi \times \left(\frac{E_{s,\min}}{2} - \frac{0.16238}{n}\right)^2$$

According to [3]:

n = number of threads per inch = 6.

$E_{s,\min}$ = minimum pitch diameter of external threads = 1.3772 in.

Therefore, A_t = 1.375 in^2.

$K_{n\max}$ = maximum minor diameter of internal threads = 1.3500 in.

$D_{s\min}$ = minimum major diameter of external threads = 1.4703 in.

Substituting the values given above:

$$L_e = \frac{2 \times 1.375}{3.1416 \times 1.3500 \times \left[\frac{1}{2} + .57735 \times 6 \times (1.3772 - 1.3500)\right]} = 1.09 \text{ in}$$

According to [3], page 1490:

$$J = \frac{A_s \times S_{ue}}{A_n \times S_{ui}}.$$

Where S_{ue} is the tensile strength of external thread material, and S_{ui} is the tensile strength of internal thread material. Therefore, S_{ue} = 165 ksi and S_{ui} = 70.00 ksi.

A_s is the shear area of external threads:

$$A_s = 3.1416 \times n \times L_e \times K_{n\max} \times \left[\frac{1}{2n} + 0.57735 \times (E_{s\min} - K_{n\max})\right]$$

A_n is the shear area of internal threads:

$$A_n = 3.1416 \times n \times L_e \times D_{s\min} \times \left[\frac{1}{2n} + 0.57735 \times (D_{s\min} - E_{n\max})\right]$$

For the bolt / flange insert connection:

$E_{n\max}$ = maximum pitch diameter of internal threads = 1.4075 in.(see [3], page 1728).

Therefore:

$$A_s = 3.1416 \times 6 \times 1.09 \times 1.3500 \times \left[\frac{1}{2 \times 6} + 0.57735 \times (1.3772 - 1.3500)\right] = 2.750 \text{ in}^2$$

$$A_n = 3.1416 \times 6 \times 1.09 \times 1.4703 \times \left[\frac{1}{2 \times 6} + 0.57735 \times (1.4703 - 1.4075)\right] = 3.616 \text{ in}^2$$

So:

$$J = \frac{2.750 \times 165.0}{3.616 \times 70.0} = 1.79.$$

Therefore, the minimum required engagement length $Q = J \times L_e$ = 1.79 × 1.09 = 1.96 in.

The actual minimum engagement length is equal to:

5.00 (bolt length) – 2.24 (thickness of the closure lid under the screw head) – 0.17 (washer

thickness) = 2.59 in > 2.25 in (length of lid bolt insert) > 1.96 in.

The above calculation bounds the minimum required engagement length if inserts are used because S_u of inserts is higher than the S_u for the lid, thus lowering the J value.

A.2.13.2.9 Ram Closure Plate Bolts Analysis

This section analyzes the ability of the ram closure plate bolts to maintain a leak–tight seal under events defined by Normal Conditions of Transport (NCT) and the Hypothetical Accident Conditions (HAC). Also evaluated in this section are the stresses in the bolt threads and in the internal threads. The stress analysis is performed in accordance with NUREG/CR–6007 [1].

The ram closure plate has a diameter of 28.88 in. and consists of a 5.00–inch thick plate with a 2.50–inch thick outer flange. The ram closure plate is bolted directly to the bottom of the containment vessel by 12 high–strength alloy steel 1–inch diameter bolts on a 27.00 in. diameter bolt circle. The bolts material is SA–540 Gr. B23 Cl. 1 which has a yield strength of 139.1 ksi and a tensile strength of 165.0 ksi at 350°F.

The following evaluations are made in this section:

- Bolt preload
- Gasket seating load
- Internal pressure loads
- Temperature load
- Impact load
- Puncture load
- External pressure loads
- Load combinations for normal and accident conditions
- Bolt stresses and allowable stresses
- Thread engagement length evaluation
- Bearing stress

The design parameters for the ram closure plate analysis taken from [1] are summarized in Table A.2.13.2-1. The ram closure plate bolt data and material allowables are presented in Tables A.2.13.2-2 to A.2.13.2-4. A temperature of 350°F is used in the bolts region during NCT and HAC based on results of thermal analyses.

The following load cases are considered in the analysis:

1. Preload + Temperature Load (NCT);
2. Internal Pressure + 30 Foot Corner Drop (HAC);
3. Internal Pressure + Puncture Load (HAC).

A.2.13.2.9.1 Bolt Load Calculations

Bolt Preload

The method of analysis is described in Table 4.1 of [1].

A bolt torque range of 100 to 125 ft.lb is required to ensure leak tightness against normal and accident loadings.

Bolt preload for the minimum torque is:

$$F_a = \frac{Q}{K \times D_b} = \frac{100 \times 12}{0.135 \times 1.0} = 8{,}889 \text{ lb/bolt}$$

Bolt preload for the maximum torque is:

$$F_a = \frac{Q}{K \times D_b} = \frac{125 \times 12}{0.135 \times 1.0} = 11{,}111 \text{ lb/bolt}$$

Residual torsional moment for the minimum torque is:

$$M_{tr} = 0.5 \times Q = 0.5 \times 100 \times 12 = 600 \text{ in.lb/bolt}$$

Residual torsional moment for the maximum torque is:

$$M_{tr} = 0.5 \times Q = 0.5 \times 125 \times 12 = 750 \text{ in.lb/bolt}$$

Residual tensile bolt force:

$$F_{ar} = F_a = 11{,}111 \text{ lb/bolt.}$$

Gasket Seating Load

An elastomer O–ring is used, therefore the gasket seating load is negligible, and $F_s = 0$.

Internal Pressure Load

The analysis is described in Table 4.3 of [1].

The axial force per bolt due to internal pressure is:

$$F_a = \frac{\pi \times D_{lg}^2 \times (P_{li} - P_{lo})}{4N_b}$$

D_{lg} for outer seal is conservatively taken equal to the outer diameter of the outer seal groove and is equal to:

D_{lg} = 24.788 (seal groove I. D.) +2 × 0.235 (groove width) = 25.258 in.

Therefore:

$$F_a = \frac{\pi \times 25.258^2 \times (30-0)}{4 \times 12} = 1{,}253 \text{ lb/bolt}$$

The fixed edge cover plate force is:

$$F_f = \frac{D_{lb} \times (P_{li} - P_{lo})}{4} = \frac{27 \times (30-0)}{4} = 203 \text{ lb/in}$$

The fixed edge cover plate moment is:

$$M_f = \frac{(P_{li} - P_{lo}) \times D_{lb}^2}{32} = \frac{30 \times 27^2}{32} = 683 \text{ in.lb/in}$$

The cask bottom wall takes the shear force, so the shear bolt force per bolt F_s is 0.

Temperature Load

The analysis is described in Table 4.4 of [1].

The cover plate bolt material is SA-540 Gr. B23 Cl. 1, the cask bottom is made of SA-350 Gr. LF3, and the ram cover plate is made of SA-203 Gr. E.

The coefficient of thermal expansion of the bolts at 350°F is 7.00×10^{-6} in/in/°F, and the coefficient of thermal expansion of the cask bottom and of the ram cover plate is 7.00×10^{-6} in/in/°F.

Since the coefficients of thermal expansion of the ram cover plate and cask bottom are identical, the only load caused by thermal expansion is the non–prying tensile bolt force per bolt F_a. Since the coefficients of thermal expansion of the ram cover plate and the bolts are identical, F_a = 0 lb/bolt.

Impact Load

The analysis is described in Tables 4.5 and 4.6 of [1].

The non-prying tensile bolt force per bolt, F_a, is:

$$F_a = \frac{1.34 \times \sin(xi) \times DLF \times ai \times (W_l + W_c)}{N_b}$$

The drop angle xi is 60.3°. Only the accident conditions drop is considered in this Appendix. The acceleration ai is 40 g for the accident conditions.

Only the weight of the ram closure plate W_p is considered since the contents of the cask do not weigh on the plate.

The weight of the plate is conservatively taken equal to the sum of the weights of two plates, both of them 2.5–inches thick, one of them having a 28.88–inch diameter, and the other one a 9–inch diameter.

The resulting volume is equal to:

$$V = 0.25 \times \pi \times 2.5 \times (28.88^2 + 9^2) = 1{,}796.71 \text{ in}^3$$

The resulting ram cover plate weight W_p is equal to:

$$W_p = V \times \rho = 1{,}796.71 \times 0.29 = 522 \text{ lb}$$

The weight of the plate is conservatively taken equal to 530 lb.

$$F_a = \frac{1.34 \times \sin(60.3°) \times 1.1 \times 40 \times 530}{12} = 2{,}262 \text{ lb/bolt}$$

The gap between the cask bottom wall and the ram access cover plate is smaller than the gap between the ram access cover plate bolts and the ram access cover plate, during a side drop, the ram access cover plate comes into contact with the cask bottom wall before the ram access cover plate bolts are loaded in shear, and the cask bottom wall takes the shear force during these drops. Therefore, $F_s = 0$.

The fixed-edge closure lid force F_f is:

$$F_f = \frac{1.34 \times \sin(xi) \times DLF \times ai \times W_p}{\pi \times D_{lb}}$$

$$F_f = \frac{1.34 \times \sin(60.3) \times 1.1 \times 40 \times 530}{\pi \times 27} = 320 \text{ lb/in}$$

The fixed-edge closure lid moment M_f is:

$$M_f = \frac{1.34 \times \sin(xi) \times DLF \times ai \times W_p}{8\pi}$$

$$M_f = \frac{1.34 \times \sin(60.3) \times 1.1 \times 40 \times 530}{8\pi} = 1{,}080 \text{ in.lb/in}$$

Puncture Load

The puncture load is not considered because of the protection provided by the impact limiters.

External Pressure Load of 290 psig

The analysis is described in Table 4.3 of [1].

The axial force per bolt due to external pressure is:

$$F_a = \frac{\pi \times D_{lg}^2 \times (P_{li} - P_{lo})}{4N_b}$$

D_{lg} for outer seal (conservatively taken equal to the outer diameter of the outer seal groove):

D_{lg} = 24.788 (seal groove I. D.) +2 × 0.235 (groove width) = 25.258 in.

Therefore:

$$F_a = \frac{\pi \times 25.258^2 \times (0 - 290)}{4 \times 12} = -12{,}109 \text{ lb/bolt}$$

Since this force is negative (inward acting), the actual resulting bolt force, $F_a = 0$, because the applied load is supported by the cask wall and not by the bolts.

The fixed edge cover plate force is:

$$F_f = \frac{D_{lb} \times (P_{li} - P_{lo})}{4} = \frac{27.00 \times (0 - 290)}{4} = -1{,}958 \text{ lb/in}$$

The fixed edge cover plate moment is:

$$M_f = \frac{(P_{li} - P_{lo}) \times D_{lb}^2}{32} = \frac{(0 - 290) \times 27.00^2}{32} = -6{,}607 \text{ in.lb/in}$$

The ram cover plate shoulder takes the shear force, so the shear bolt force per bolt is $F_s = 0$.

The loads calculated in this section are summarized in Table A.2.13.2–9.

A.2.13.2.9.2 Load Combinations

A summary of normal and accident condition load combinations is presented in table A.2.13.2–10. The method used for the following combination is taken from [1], Table 4.9.

Additional Prying Bolt Force

The analysis is described in Table 2.1 of [1].

Although the methodology developed in [1] applies to full cover plates that extend to the entire diameter of the cask, it can also be applied to the ram cover plate analyzed in this calculation, even though its bolt diameter does not extend all the way to the cask walls. The contents of the cask provide the bottom part of the cask with a rigid seating surface, rigid enough to consider that the ram cover plate is bolted on the walls of a thick cylindrical shell, the inner diameter of which is the diameter of the ram opening through the cask bottom.

Since the prying forces applied in load case 3 act inward, normal to the cask lid, an additional prying bolt force, F_{ap}, is generated (Table 2.1 of [1]). The additional force generated for the outward loadings is considered negligible since its main source – the contents of the cask – can not be in contact with the ram cover plate.

F_{ap} for an inward force is calculated in the following way:

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

Where $C_1 = 1$, and:

$$C_2 = \frac{8}{3 \times (D_{li} - D_{lb})^2} \frac{L_b}{N_b \times D_b^2 \times E_b} \left[\frac{E_l \times t_l^3}{1 - N_{ul}} + \frac{(D_{lo} - D_{li}) \times E_{lf} \times t_{lf}^3}{D_{lb}} \right]$$

$$C_2 = \frac{8}{3 \times (22.00 - 27.00)^2} \frac{1.25 \times 26.45 \times 10^6}{12 \times 1.0^2 \times 26.45 \times 10^6} \left[\frac{5.0^3}{1 - 0.3} + \frac{(28.88 - 22.00) \times 2.50^3}{27.00} \right]$$

$$C_2 = 2.0284.$$

B is the non-prying tensile bolt force, and P is the bolt preload; both are derived from the load applied to each bolt in normal operating conditions (bolt preload + temperature load + internal pressure load). Conservatively, the fixed-edge closure lid moment is considered for the case of the external pressure load, for which $M_f = -6{,}607$ in.lb/in./bolt.

$$P = \frac{F_a \times N_b}{\pi \times D_{lb}} = \frac{14{,}019 \times 12}{\pi \times 27.00} = 1{,}983 \text{ lb/in}$$

For all inward loadings such as the external pressure load, F_f is supported by the cask wall and thus has no effect on both the non–prying and prying bolt forces, B and R. Therefore, $F_f = 0$.

$B = F_f$ if $F_f > P$ and $B = P$ otherwise. Since $F_f = 0 < P$, $B = P = 1{,}983$ lb/in.

Furthermore, the internal pressure load is not included because it decreases the magnitude of the applied prying moment, which is less conservative.

Therefore:

$$F_{ap} = \frac{\pi \times 27.00}{12} \times \left[\frac{\frac{2 \times (-6{,}607)}{22.00 - 27.00} - 1 \times (1{,}983 - 0) - 2.0284 \times (1{,}983 - 1{,}983)}{1 + 2.0284} \right]$$

$$F_{ap} = -1{,}539 \text{ lb/bolt.}$$

Since this bolt load is less than the load generated by the minimum bolt preload, the prying force generated by the external pressure load is not critical with respect to bolt stress, and will not result in loss of the ram cover plate closure seal.

Bending Moment Bolt Force

The analysis is described in Table 2.2 of [1].

The maximum bending bolt moment M_{bb} generated by the applied load is evaluated as follows:

$$M_{bb} = \frac{\pi \times D_{lb}}{N_b} \frac{K_b}{K_b + K_l} \times M_f$$

The coefficients K_b and K_l are based on geometry and material properties and are defined in Table 2.2 of [1]. By substituting the values given above:

$$K_b = \frac{N_b}{L_b} \frac{E_b}{D_{lb}} \frac{D_b^4}{64} = \frac{12}{1.25} \frac{26.45 \times 10^6}{27.00} \frac{1.0^4}{64} = 1.469 \times 10^5$$

$$K_l = \frac{E_l \times t_l^3}{3\left[\left(1 - N_{ul}^2\right) + \left(1 - N_{ul}\right)^2 \left(\frac{D_{lb}}{D_{lo}}\right)^2\right] D_{lb}} = \frac{26.45 \times 10^6 \times 5.00^3}{3\left[\left(1 - 0.3^2\right) + \left(1 - 0.3\right)^2 \left(\frac{27.00}{28.88}\right)^2\right] 27.00} = 3.050 \times 10^7$$

In the case of the internal pressure load, $M_f = 683$ in.lb.

Therefore:

$$M_{bb} = \frac{\pi \times 27.00}{12} \times \frac{1.469 \times 10^5}{1.469 \times 10^5 + 3.050 \times 10^7} \times 683 = 23 \text{ in.lb/bolt} \approx 0$$

The maximum bending bolt moment is considered equal to 0.

A.2.13.2.9.3 Bolt Stress Calculations

The analysis is described in Table 5.1 of [1].

Average Tensile Stress

The bolt preload is calculated to withstand the worst case load combination and to maintain a clamping (compressive) force on the closure joint, under both normal and accident conditions. Based upon the load combination results (see Table A.2.13.2-10), it is shown that a positive (compressive) load is maintained on the clamped joint for all load combinations.

The maximum non–prying tensile force for both normal and accident conditions is F_a = 11,111 lbs, from load case 1.B (maximum torque preload + temperature load).

The average tensile stress caused by the tensile bolt force F_a is:

$$S_{ba} = 1.2732 \times \frac{F_a}{D_{ba}^2}$$

D_{ba} is the bolt diameter for tensile stress calculation: $D_{ba} = D_b - 0.9743 \times p$, where p is the pitch of the bolt. According to Table 1, p. 1714 of [3], p = 0.125 in. Therefore, D_{ba} = 0.8782 in. This value is conservatively used for all bolt stress calculations.

$$S_{ba} = 1.2732 \times \frac{11{,}111}{0.8782^2} = 18{,}342 \text{ psi}$$

Bending Stress

The bending stress caused by the bending bolt moment M_{bb} is null since the bending bolt moment is equal to 0.

$$S_{bb} = 0$$

Shear Stress

For both normal and accident conditions, the average shear stress caused by shear bolt force F_s is:

$$S_{bs} = 0.$$

The maximum shear stress caused by the torsional moment M_t is:

$$S_{bt} = 5.093 \times \frac{M_t}{D_{ba}^3}$$

For both normal and accident conditions:

$$S_{bt} = 5.093 \times \frac{750}{0.8782^3} = 5{,}639 \text{ psi}$$

Maximum Combined Stress Intensity

The maximum combined stress intensity is calculated as follow:

$$S_{bi} = \sqrt{(S_{ba} + S_{bb})^2 + 4 \times (S_{bs} + S_{bt})^2}$$

For normal conditions, it combines tension, shear, bending, and residual torsion:

$$S_{bi} = \sqrt{(18{,}342 + 0)^2 + 4 \times (0 + 5{,}639)^2} = 21.5 \text{ ksi}$$

Stress Ratios

In order to meet the stress ratio requirement, the following relationship must hold for both normal and accident conditions:

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

Where R_t is the ratio of average tensile stress to allowable average tensile stress F_{tb} and R_s is the ratio of average shear stress to allowable average shear stress F_{vb}.

For normal conditions:

$$R_t = \frac{S_{ba}}{F_{tb,NCT}} = \frac{18.3}{92.7} = 0.197,$$

$$R_s = \frac{S_{bt}}{F_{vb,NCT}} = \frac{5.6}{55.6} = 0.101,$$

$$R_t^2 + R_s^2 = 0.197^2 + 0.101^2 = 0.049 < 1.$$

For accident conditions:

$$R_t = \frac{S_{ba}}{F_{tb,HAC}} = \frac{18.3}{115.5} = 0.159,$$

$$R_s = \frac{S_{bt}}{F_{vb,HAC}} = \frac{5.6}{69.3} = 0.081,$$

$$R_t^2 + R_s^2 = 0.159^2 + 0.081^2 = 0.032 < 1.$$

A.2.13.2.9.4 Bearing Stress Under Bolt Head

The maximum axial force is 11,111 lb for both normal and accident conditions. A washer of outer diameter 1.50" is used. The diameter of the bolt hole is 1.16 in.

The bearing area is $0.25 \times \pi \times (1.50^2 - 1.16^2) = 0.71$ in^2.

Therefore, the bearing stress is:

$$\frac{11{,}111}{0.71} = 15.6 \text{ ksi}$$

The allowable normal condition bearing stress on the ram cover plate is taken to be the yield stress of the cover plate material at 350°F, 34.8 ksi.

A.2.13.2.9.5 Results

A summary of the ram closure plate bolt stresses calculated above is listed in Table A.2.13.2–7.

The calculated bolt stresses are all less than the specified allowable stresses.

A.2.13.2.9.6 Minimum Engagement Length for Bolt and Flange

The minimum engagement length L_e for the bolt and flange is ([3], page 1490):

$$L_e = \frac{2 \times A_t}{3.1416 \times K_{n\max} \times \left[\frac{1}{2} + .57735 \times n \times \left(E_{s,\min} - K_{n\max}\right)\right]}$$

A_t is the tensile–stress area of the screw and is given by the following formula[2]:

$$A_t = \pi \times \left(\frac{E_{s,\min}}{2} - \frac{0.16238}{n}\right)^2$$

According to [3]:

n = number of threads per inch = 8.

[2] Formula valid if the ultimate tensile strength of the screw is over 100,000 psi

$E_{s,\min}$ = minimum pitch diameter of external threads = 0.9067 in.

Therefore, A_t = 0.589 in^2.

$K_{n\,\max}$ = maximum minor diameter of internal threads = 0.8900 in.

$D_{s\,\min}$ = minimum major diameter of external threads = 0.9755 in.

Substituting the values given above:

$$L_e = \frac{2 \times 0.589}{3.1416 \times 0.8900 \times \left[\frac{1}{2} + .57735 \times 8 \times (0.9067 - 0.8900)\right]} = 0.73 \text{ in}$$

According to [3], page 1490:

$$J = \frac{A_s \times S_{ue}}{A_n \times S_{ui}}$$

Where S_{ue} is the tensile strength of external thread material, and S_{ui} is the tensile strength of internal thread material. Therefore, S_{ue} = 165 ksi and S_{ui} = 70.00 ksi.

A_s is the shear area of external threads:

$$A_s = 3.1416 \times n \times L_e \times K_{n\,\max} \times \left[\frac{1}{2n} + 0.57735 \times (E_{s\,\min} - K_{n\,\max})\right]$$

A_n is the shear area of internal threads:

$$A_n = 3.1416 \times n \times L_e \times D_{s\,\min} \times \left[\frac{1}{2n} + 0.57735 \times (D_{s\,\min} - E_{n\,\max})\right]$$

For the bolt / flange insert connection:

$E_{n\,\max}$ = maximum pitch diameter of internal threads = 0.9320 in.(see [3], page 1728).

Therefore:

$$A_s = 3.1416 \times 8 \times 0.73 \times 0.8900 \times \left[\frac{1}{2 \times 8} + 0.57735 \times (0.9067 - 0.8900)\right] = 1.178 \text{ in}^2$$

$$A_n = 3.1416 \times 8 \times 0.73 \times 0.9755 \times \left[\frac{1}{2 \times 8} + 0.57735 \times (0.9755 - 0.9320)\right] = 1.569 \text{ in}^2$$

So:

$$J = \frac{1.178 \times 165.0}{1.569 \times 70.0} = 1.77$$

Therefore, the minimum required engagement length $Q = J \times L_e$ = 1.77 x 0.73 = 1.29 in.

The actual minimum engagement length is equal to:

4.00 (bolt length) – 1.25 (thickness of the cover plate under the screw head) – 0.177 (washer thickness) = 2.57 in > 1.50 in (ram cover plate bolts inserts) > 1.29 in.

The above calculation bounds the minimum required engagement length if inserts are used because S_u of inserts is higher than the S_u for the lid, thus lowering the J value.

A.2.13.2.10 Conclusions

A lid bolt torque range of *950* to 1,040 ft.lb is required.

A ram closure plate bolt torque range of 100 to 125 ft.lb is required.

For the required preloads:

1. Bolt stresses meet the acceptance criteria of NUREG/CR-6007 "Stress Analysis of Closure Bolts for Shipping Casks."
2. A positive (compressive) load is maintained during all load combinations, except, for the lid bolts, for the accident condition impact plus pressure load case. A more detailed analysis is performed to evaluate the closure of the lid during this event and shows that there is no decompression in the seal during this event, and therefore no leak of the contents during the worst case loading condition.
3. The bolt and flange thread engagement lengths are acceptable.

The MP197HB cask lid bolts will not fail due to fatigue for 250 round trip shipments.

A.2.13.2.11 References

1. Stress Analysis of Closure Bolts for Shipping Casks, NUREG/CR-6007.

2. American Society of Mechanical Engineers, ASME Boiler and Pressure Vessel Code, Section III, Appendices, 2004 edition including 2006 addenda.1989.

3. Machinery Handbook, 26th Edition, Industrial Press, 2000.

4. Standard Handbook for Mechanical Engineers, Baumeister, Avallone and Baumeister III, 8th Edition, McGraw-Hill, 1978.

5. Shock and Vibration Environments for Large Shipping Containers on Rail Cars and Trucks, NUREG 766510.

6. Norton, Robert L., "Machine Design, An Integrated Approach," Prentice-Hall, 1998.

7. ANSI, Design Basis for Resistance to Shock and Vibration of Radioactive Material Packages Greater than One Ton in Truck Transport, Draft American National Standard, N14.23, 1980.

Table A.2.13.2-1
Design Parameters for Bolts Analysis

	Parameter	Lid	Ram access cover plate
α_b	Thermal coefficient of expansion of the bolts (in/in/°F)	7.0×10^{-6}	
α_c, α_l	Thermal coefficients of expansion of the cask, closure lid and ram cover plate (in/in/°F)	7.5×10^{-6}	
ai	Maximum rigid–body impact acceleration of the cask for Hypothetical Accident Conditions – 30 ft C. G. over corner drop (g)	40	
xi	Impact angle between the cask axis and target surface for Hypothetical Accident Conditions – 30 ft C. G. over corner drop	60.3°	
D_b	Nominal diameter of closure bolt (in)	1.50	1.00
D_{lb}	Bolt circle diameter (in)	74.81	27.00
D_{lg}	Outer seal diameter (in)	72.737	25.258
D_{li}	Inner edge diameter (in)	70.44	22.00
D_{lo}	Outer edge diameter (in)	77.18	28.88
D_{pb}	Puncture bar diameter (in)	6.0	
DLF	Dynamic Load Factor	1.1	
E_b	Young's modulus of bolt material (ksi)	26.45×10^3	
E_c, E_l	Young's modulus of cask flange, cask bottom, closure lid and ram cover plate material (ksi)	26.45×10^3	
K	Nut factor for empirical relation between applied torque and achieved preload	0.135	
L_b	Bolt length between top and bottom surfaces of cover plate at bolt circle (in)	2.41	1.25
N_b	Total number of closure bolts	48	12
N_{ul}	Poisson's ratio of cover plates	0.3	
P_{li}	Pressure inside the cask (psig)	30	
P_{lo}	Pressure outside the cask (psig)	290	
Q	Applied preload bolt torque (ft.lb)	*950*–1,040	100–125
S_{ub}	Ultimate strength of bolt material (ksi)	165.0	
S_{ul}	Ultimate strength of cover plates material (ksi)	70.0	
S_{yb}	Yield strength of bolt material (ksi)	139.1	
S_{yl}	Yield strength of cover plates material (ksi)	32.6	34.8
t_c	Thickness of cask wall (in)	7.0	
t_l	Thickness of plates at center (in)	4.5	5.00
t_{lf}	Thickness of plates flange (in)	3.94	2.50
W_c	weight of contents (lbs)	118,500	N/A
W_l	weight of plate (lbs)	6,100	530

Table A.2.13.2-2
Bolt Data

Parameters necessary to use formulas of reference [1], Table 5.1.

Bolt: 1 ½–6UNC–2A

n = number of threads per inch = 6.

p = pitch = 1/6 = 0.167 in.

D_b = nominal diameter = 1.5 in.

D_{ba} = bolt diameter for tensile stress calculation = $D_b - 0.9743 \times p$ = 1.3376 in.

Table A.2.13.2-3
Allowable Stresses in Closure Bolts for Normal Conditions

(Bolt Material: SA–540 Gr. 23 Cl. 1)

Temperature (°F)	**Yield Stress[3] (ksi)**	**Normal Condition Allowable Stresses (ksi)**		
		F_{tb}[4,6]	**F_{vb}[5,6]**	**S.I.[7]**
300	140.3	93.5	56.1	126.3
350	139.1	92.7	55.6	125.2
400	137.9	91.9	55.2	124.1

[3] Yield stress values are from ASME Code [2].
[4] Allowable tensile stress: F_{tb} = 2/3 S_y ([1]).
[5] Allowable shear stress: F_{vb} = 0.4 S_y ([1]).
[6] Tension and shear stresses must be combined using the following interaction equation:

$$\frac{\sigma_{tb}^2}{F_{tb}^2} + \frac{\tau_{yb}^2}{F_{yb}^2} \leq 1.0 \text{ [1].}$$

[7] Stress intensity from combined tensile, shear and residual torsion loads: S.I. ≤ 0.9 S_y ([1], Table 6.1).

Table A.2.13.2-4
Allowable Stresses in Closure Bolts for Accident Conditions

(Bolt Material: SA–540 Gr. 23 Cl. 1)

Temperature (°F)	**Yield Stress[8] (ksi)**	**Accident Condition Allowable Stresses (ksi)**		
		0.6 S_y	**F_{tb}[9]**	**F_{vb}[10]**
300	140.3	84.2	115.5	69.3
350	139.1	83.5	115.5	69.3
400	137.9	82.7	115.5	69.3

[8] Yield and tensile stress values are from ASME Code [2], note that S_u = 165 ksi at all temperatures of interest.
[9] Allowable Tensile stress, F_{tb} = MINIMUM(0.7 S_u, S_y), where S_u = 165 ksi [1].
[10] Allowable shear stress, F_{vb} = MINIMUM(0.42 S_u, 0.6 S_y), where S_u = 165 ksi [1].

Table A.2.13.2-5
Lid Bolts Individual Summary

Load Case	Applied Load		Non-Prying Tensile Force F_a (lb/bolt)	Torsional Moment M_t (in.lb/bolt)	Prying Force F_f (lb/in)	Prying Moment M_f (in.lb/in)
Preload	Residual torque	Minimum	*56,296*	*5,700*	0	0
		Maximum	61,630	6,240	0	0
Gasket	Seating load		0	0	0	0
Internal Pressure	30 psig internal		2,598	0	562	5,247
Thermal	350°F		0	0	0	0
Impact	30 ft accident conditions drop		132,944	0	27,152	253,905
Puncture	Drop on six inch diameter rod		0	0	0	0
External pressure	290 psig external		0	0	-5,424	-50,719

Table A.2.13.2-6
Lid Bolts Normal and Accident Load Combinations

Load Case	Combination Description		Non-Prying Tensile Force F_a (lb/bolt)	Torsional Moment M_t (in.lb/bolt)	Prying Force F_f (lb/in)	Prying Moment M_f (in.lb/in)
1	Preload + Temperature (Normal Conditions)	A. Min. Torque	*56,296*	*5,700*	0	0
		B. Max. Torque	61,630	6,240	0	0
2	Pressure + Accident Impact (Accident Conditions)		135,542	0	27,714	259,152
3	Pressure + Puncture (Accident Conditions)		0	0	–5,424	–50,719

Table A.2.13.2-7
Lid and Ram Closure Plate Bolt Stresses

	Stress Type	NCT		HAC	
		Stress	**Allowable**	**Stress**	**Allowable**
Lid bolts	Average Tensile	43.9	92.7	96.4	115.5
	Shear	13.3	55.6	13.3	69.3
	Combined	57.6	125.2	*Not Required [1]*	
	Interaction E.Q. $R_t^2 + R_s^2 < 1$	0.281	1	0.734	1
	Bearing	29.4	32.6	*Not Required [1]*	
Ram cover plates bolts	Average Tensile	18.3	92.7	18.3	115.5
	Shear	5.6	55.6	5.6	69.3
	Combined	21.5	125.2	*Not Required [1]*	
	Interaction E.Q. $R_t^2 + R_s^2 < 1$	0.049	1	0.032	1
	Bearing	15.6	34.8	*Not Required [1]*	

Table A.2.13.2-8
Damage Factor Calculation

Event	Stress Intensity (ksi)	S.I. × K_F (ksi)	S_a (ksi)	Cycles		Damage Factor n / N
				n	N	
Operating preload Loaded Cask	57.6	230.4	130.2	250	600	0.42
Operating preload Empty Cask	35.4	141.6	80.0	250	1,500	0.17
Σ						0.59

Table A.2.13.2-9
Ram Closure Plate Bolts Individual Summary

Load Case	Applied Load		Non-Prying Tensile Force F_a (lb/bolt)	Torsional Moment M_t (in.lb/bolt)	Prying Force F_f (lb/in)	Prying Moment M_f (in.lb/in)
Preload (P)	Residual torque	Minimum	8,889	600	0	0
		Maximum	11,111	750	0	0
Gasket (G)	Seating load		0	0	0	0
Internal Pressure (Pi)	30 psig internal		1,253	0	203	683
Thermal (T)	350°F		0	0	0	0
Impact (I)	30 ft accident conditions drop		2,262	0	320	1,080
Puncture (Pu)	Drop on six inch diameter rod		0	0	0	0
External pressure (Pe)	290 psig external		0	0	–1,958	–6,607

Table A.2.13.2-10
Ram Closure Plate Bolts Normal and Accident Load Combinations

Load Case	Combination Description		Non-Prying Tensile Force F_a (lb/bolt)	Torsional Moment M_t (in.lb/bolt)	Prying Force F_f (lb/in)	Prying Moment M_f (in.lb/in)
1.NCT P+T	Preload + Temperature	A. Min. Torque	8,889	600	0	0
		B. Max. Torque	11,111	750	0	0
2.HAC (Pi+I)	Internal Pressure + Impact		3,515	0	523	1,763
3.HAC (P_e)	External Pressure		0	0	–1,958	–6,607

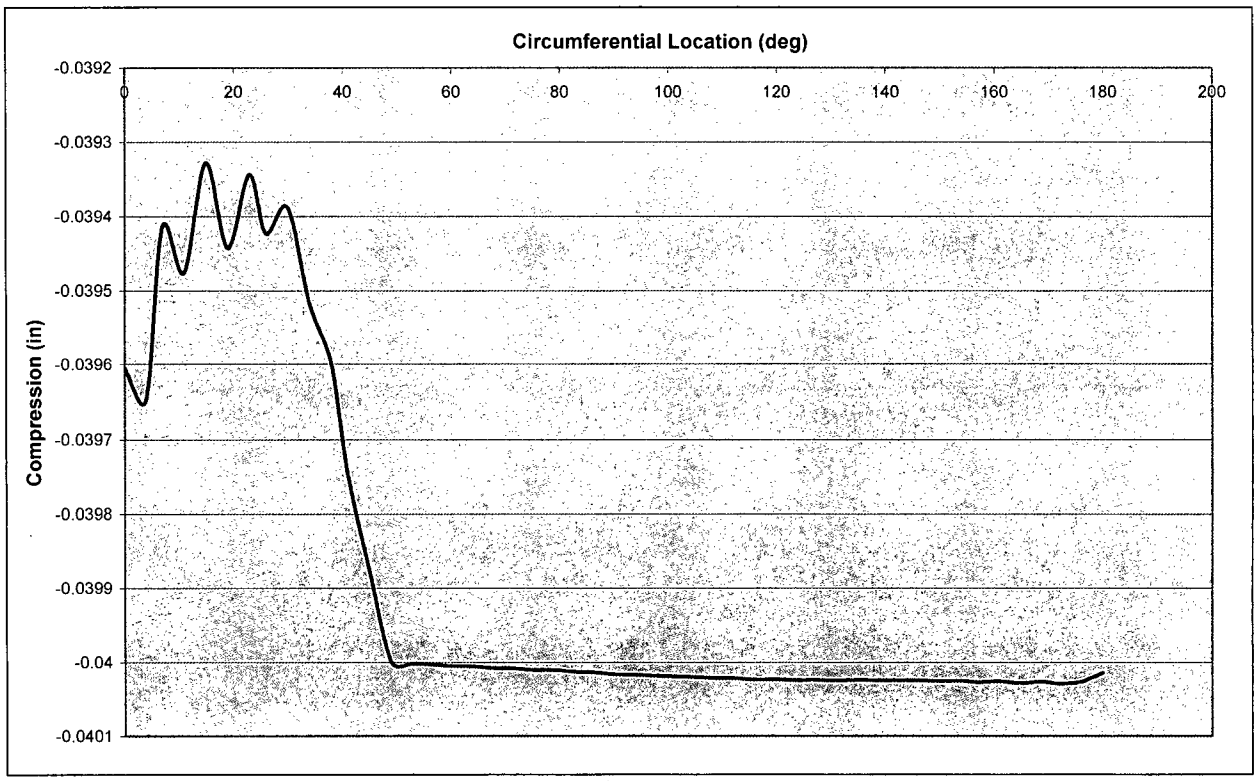

Figure A.2.13.2-1
MP197HB Transport Cask (CG Over Corner Lid Drop–Hot) Seal Decompression as a Function of Circumferential Location

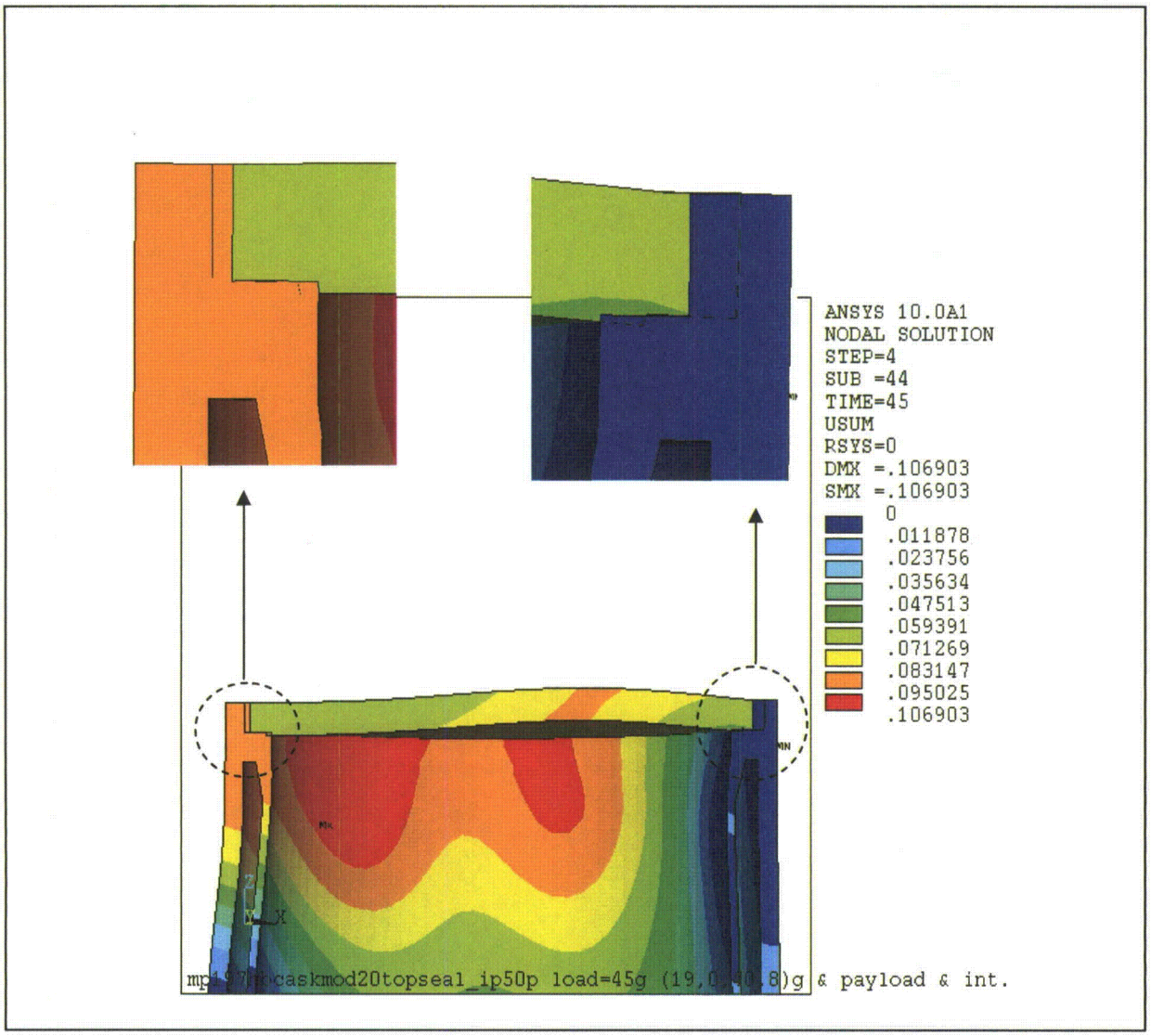

Figure A.2.13.2-2
Deformation Plot Near Lid–Flange Interface

Appendix A.2.13.3
MP197HB Cask Lead Slump and Containment Boundary Buckling Analysis

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A.2.13.3- 7 Displacement Plot at 215g (Lid End Drop with 25 psig External Pressure) A.2.13.3-14
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Appendix A.2.13.3
MP197HB Cask Lead Slump and Containment Boundary Buckling Analysis

NOTE: References in this Appendix are shown as [1], [2], etc. and refer to the reference list in Section A.2.13.3.7.

A.2.13.3.1 Introduction

The purpose of this analysis is to determine the amount of lead slump that occurs in the NUHOMS®-MP197HB cask and containment boundary buckling loads during a hypothetical accident condition end drop. The load cases considered in this calculation are hypothetical accident condition lid and bottom end drops.

During a hypothetical accident condition end drop, permanent deformation of the lead gamma shield may occur. The lead gamma shield is supported by friction between the lead and cask shells, in addition to bearing at the end of the lead column.

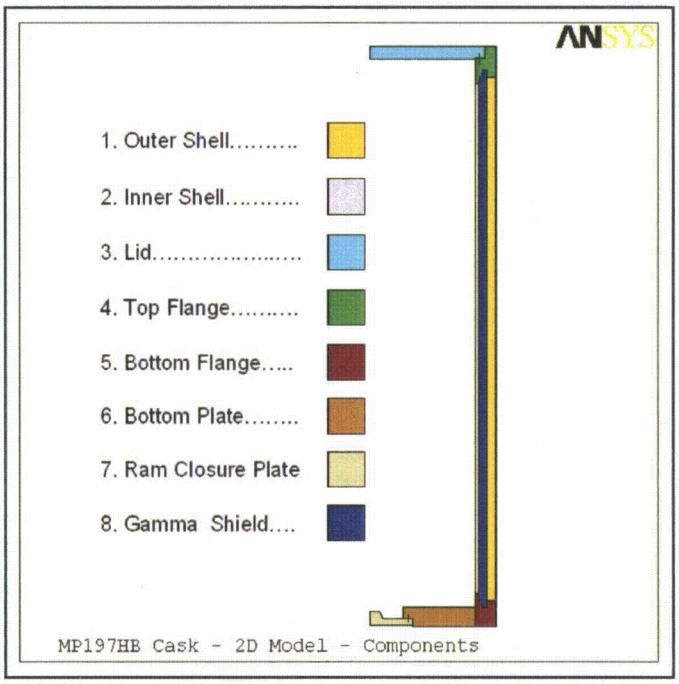
A nonlinear finite element analysis is performed in order to quantify the amount of lead slump generated during an end drop event. A 2-dimensional axisymmetric ANSYS [1] finite element model is constructed for this purpose. The results of the finite element analysis provide both stresses and displacements generated during the end drop event. The displacement results are used in this section to determine the maximum size of the axial gap that develops between the lead gamma shield column and the structural shell of the cask. The effect of this cavity size on the shielding ability of the transport package is evaluated in Chapter A.5. Both stress and displacement distributions computed by the finite element analysis are used to determine the allowable buckling loads of the inner containment shell of the NUHOMS®-MP197HB cask.

A.2.13.3.2 Finite Element Model

Geometry

The schematic of structural components of 2D model of the MP197HB transport cask is presented in the following figure.

The Finite Element Model represents MP197HB transport cask assembly by means of eight structural components: Outer Shell, Inner Shell, Lid, Top Flange, Bottom Flange, Bottom Plate, Ram Closure Plate and Gamma Shield. The Neutron Shield assembly structure is not modeled but its mass is accounted for as a surface mass load.



Schematic of the MP197HB Transport Cask - 2D FEA Model.

ANSYS Elements

Following table lists ANSYS element types used to represent in analyses structural components of cask design.

ANSYS Elements Specifications

Component	Material Type Number	Element Type Number	2D Model Elements
Outer Shell	1	1	SOLID42
Inner Shell	2	2	SOLID42
Lid	3	3	SOLID42
Top Flange	4	4	SOLID42
Bottom Flange	5	5	SOLID42
Bottom Plate	6	6	SOLID42
RAM Closure Plate	7	7	SOLID42
Gamma Shield	8	8	SOLID42
Lid Bolts (Radial Shear Interaction)	9	391	COMBIN39
Lid (Axial Interaction)	9	393	COMBIN39
RAM Closure Bolts (Radial Shear Interaction)	10	394	COMBIN39
RAM Closure Bolts (Axial Interaction)	10	396	COMBIN39
Neutron Shield	14	14	SURF153

The following table shows specifications of the contact model between material components done by means of surface contact elements (elements CONTA171, TARGE169).

ANSYS Elements Specifications –Contact elements

INTERFACE DESCRIPTION	ELEMENT TYPE NUMBER		2D MODEL	
	Target Element	Contact Element	Element Real Constants	Material Type Number
Lid and Top Flange (Top Radial Interface)	1101	101	101	11
Lid and Top Flange (Plate Contact Interface)	1102	102	102	11
Lid and Top Flange (Bottom Radial Interface)	1103	103	103	11
RAM Closure Plate and Bottom Plate–Radial Interface	1111	111	111	12
RAM Closure Plate and Bottom Plate–Plate Contact Interface	1112	112	112	12
Outer Shell and Gamma Shield (Radial) Interface	1201	201	201	13
Top Flange and Gamma Shield (Top Contact Surface)	1202	202	202	13
Top Flange and Gamma Shield (Conical Surface)	1203	203	203	13
Inner Shell and Gamma Shield (Radial) Interface	1204	204	204	13
Bottom Flange and Gamma Shield (Conical Surface)	1205	205	205	13
Bottom Flange and Gamma Shield (Bottom Contact Surface)	1206	206	206	13

Methodology

An ANSYS elastic-plastic buckling analysis with large displacement option was performed to calculate the buckling loads of the cask under each end drop case. A 525g drop load, which is greater than the HAC load of 55g, is applied to each ANSYS cask end drop model. This 525g drop load is ramped in small increments by many load sub-steps. The ANSYS solution was set to stop and exit at any load sub-step that fails to result in a converged solution. When the imposed sub-step load reaches the buckling load, ANSYS will be unable to produce a converged solution. Since the ANSYS database model is very stable, the buckling produces a second mode deformation before non-converged solution occurs. Hence, a time-history post processing is done for select nodes to plot the radial deformation against g-loads to get a conservative value of g-load near the first mode deformation. Lead slump values are calculated at 55g.

A.2.13.3.3 Material Properties

Properties of NUHOMS®-MP197HB cask materials are taken at 350°F for both hot and cold environment cases, which is conservative. The transport cask material properties used for the analysis are the same as used in the elastic-plastic accident analysis of the Appendix A.2.13.1 "NUHOMS®-MP197HB Cask Body Structural Analysis."

A.2.13.3.4 Loading and Boundary Conditions

DSC Weight

DSC impact is applied to the cask model based on the assumption of DSC weight of 118.5 kips. This is the bounding weight for the DSC weight. The DSC weight is imposed as a pressure load distributed uniformly at the area of DSC contact with Lid (End Drop on Lid End) or Bottom Plate (End Drop on Bottom End). The DSC load for End Drop on Lid End and End Drop on Bottom End are illustrated in Figure A.2.13.3-1 and A.2.13.3-2 respectively. The DSC load pressure for these loads is denoted by P_I.

Impact Limiter Weight

Loads applied to the cask model are based on the assumption that the front impact limiter mass is 16,000 lbs and the rear impact limiter mass is 16,000 lbs. These values of impact limiter weights envelop the limiter weights calculated in Chapter A.2.

In the End Drop on Bottom End calculations the full weight of front limiter is imposed as a uniform axial pressure load acting on the effective area of contact of the front impact limiter with cask body.

In the End Drop on Lid End calculations, the full weight of rear impact limiter is imposed as a uniform axial pressure load acting on the effective area of the contact of the rear impact limiter with cask body.

The pressure load due to impact limiter weight for End Drop on Lid End and End Drop on Bottom End cases are illustrated in Figure A.2.13.3-1 (End Drop on Lid End) and Figure A.2.13.3-2 (End Drop on Bottom End). The pressure for these loads is denoted P_L.

Boundary Conditions

There are two boundary conditions imposed on the cask model. The first one is symmetry boundary condition on the cutting plane in radial direction. The cask is assumed to fall on a rigid surface and accordingly contact elements (CONTAC12) are used to model the interface between "cask-rigid surface" with free end nodes of contacts being constrained in axial direction. A total of 4 load cases are analyzed.

- Lid End Drop with 30 psig Internal Pressure
- Lid End Drop with 25 psig External Pressure
- Bottom End Drop with 30 psig Internal Pressure

- Bottom End Drop with 25 psig External Pressure

Loadings and boundary conditions on 2D Finite Element Model for lid end drop with 30 psig internal pressure is shown on Figure A.2.13.3-3.

A.2.13.3.5 FEA Results

Buckling Load

Since the ANSYS database model is very stable under the applied loads, the buckling produces a second mode deformation before non-converged solution occurs (at about 500g) for all the load cases. Hence, a time-history post processing is done for select nodes to plot the radial deformation against g-loads to get a conservative value of g-load near the first mode deformation.

The location of selected nodes is shown in Figure A.2.13.3-4. Since the lid end drop produces higher deformation due to heavier bottom, the radial displacement plots for selected nodes is taken for lid end drop (Figures A.2.13.3-5 and A.2.13.3-6). As can be seen from the figures, there is significant shift in the slope of displacement curves at about 215g. Hence, 215g load has been conservatively taken as the buckling load. The displacement plots at 215g for lid end drop with 25 psig external pressure is shown in Figure A.2.13.3-7.

Lead Slump

Since the Hypothetical Accident Condition g-load is 55g, the lead slump is calculated at 55g.

The following table summarizes the lead slump values for various load cases. The maximum lead slump is 0.32 in. and occurs during bottom end drop with 30 psig internal pressure. The corresponding plot is shown on Figure A.2.13.3-8.

Summary of Lead Slump at 55g

Lead Slump at 55g (inches)		
Load Case	**Internal Pressure**	**External Pressure**
Lid End Drop	0.316	0.310
Bottom End Drop	0.320	0.316

A.2.13.3.6 Conclusions

The table above shows that the maximum longitudinal gap, caused by lead slump, is 0.32 inches, and occurs during accident condition bottom end drop. The effect of the gap on the shielding ability of the NUHOMS®-MP197HB cask is analyzed in Chapter A.5. The allowable buckling load is 215g and the accident g load is 55g, this gives a safety ratio of 4:1.

A.2.13.3.7 References

1. ANSYS Computer Code and User's Manual, Release 10A1.

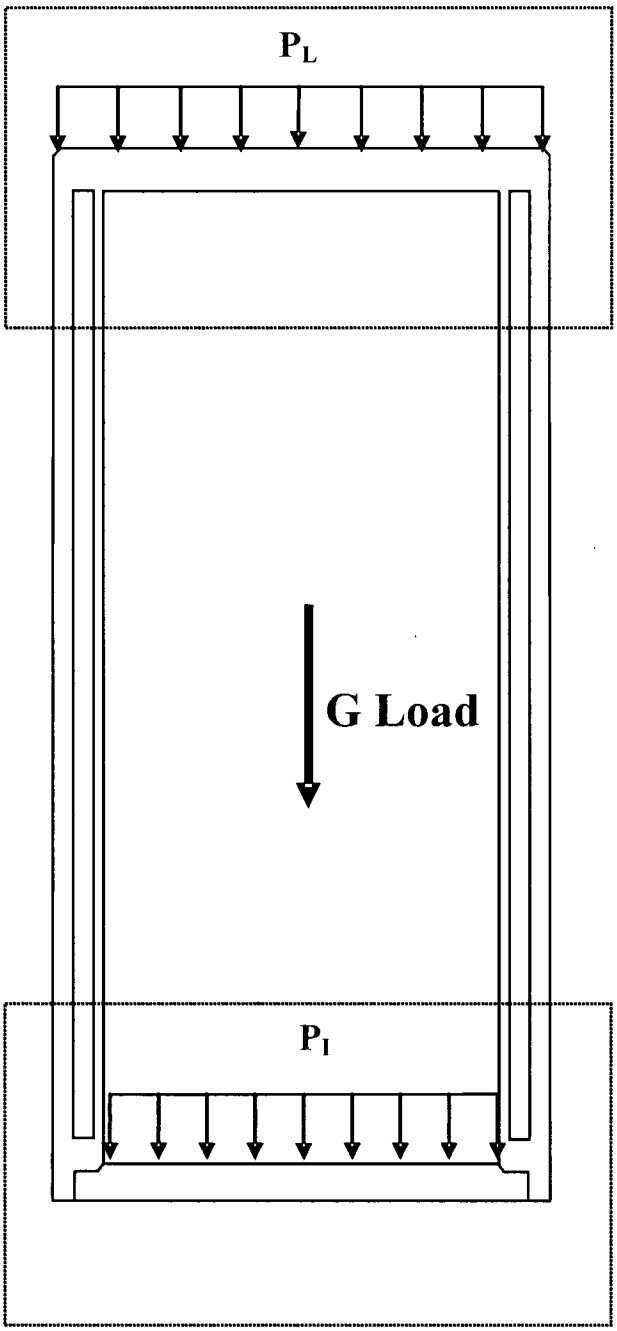


Figure A.2.13.3- 1 Schematic for End Drop on Lid End

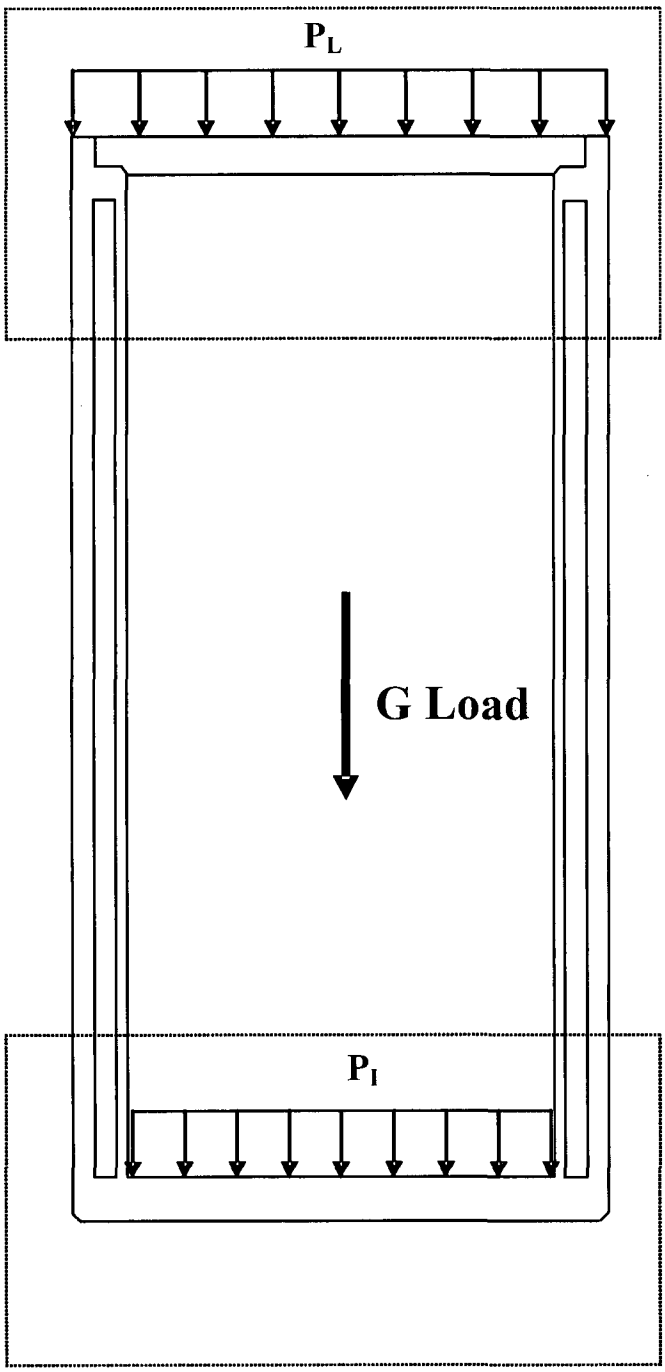


Figure A.2.13.3- 2 Schematic for End Drop on Bottom End

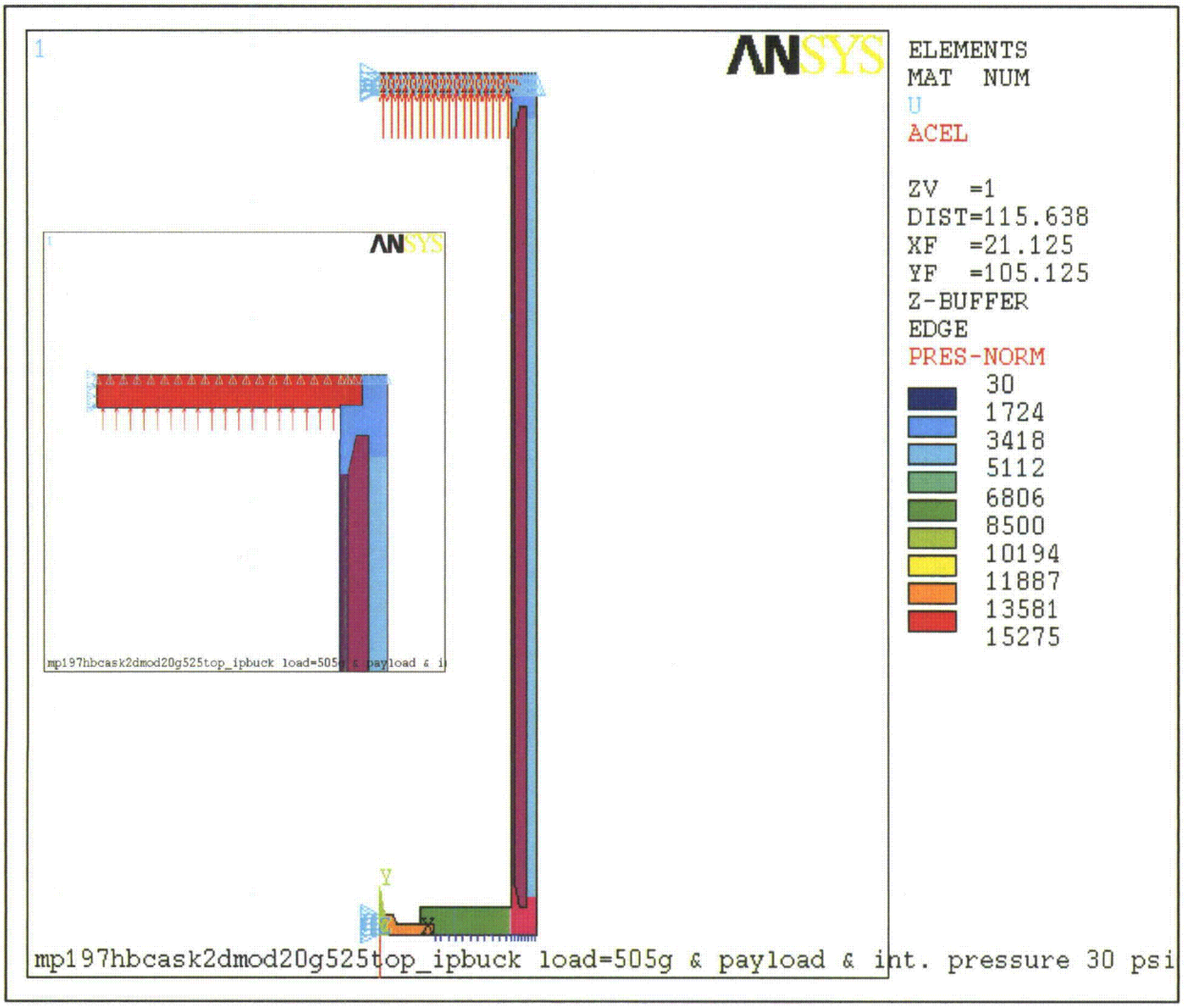


Figure A.2.13.3- 3 Boundary Condition & Loads for Lid End Drop with 30psig Internal Pressure

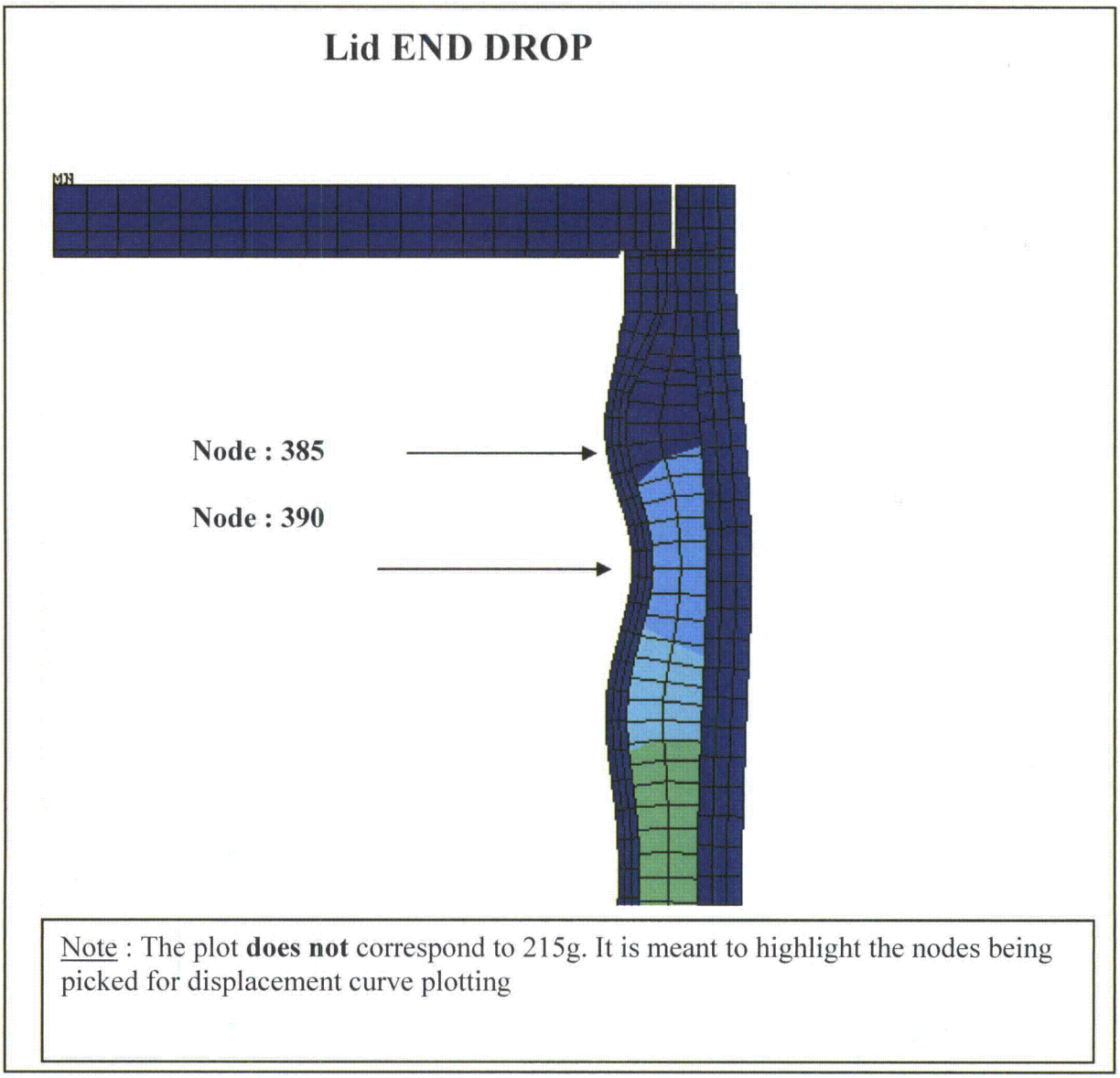
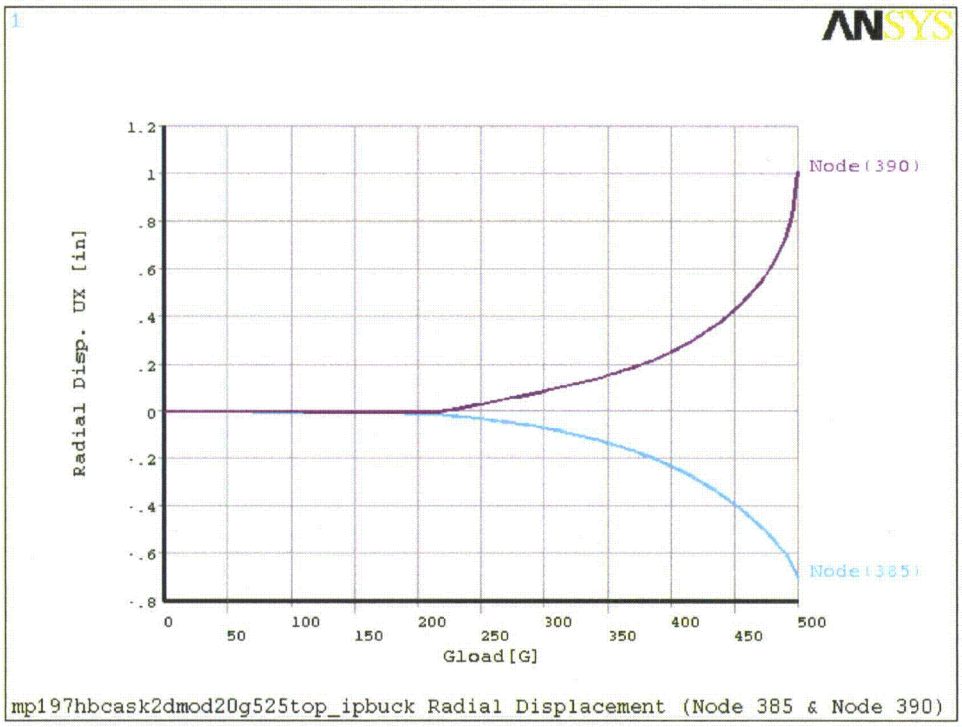


Figure A.2.13.3- 4 Nodes Selected for Time-History Post Processing



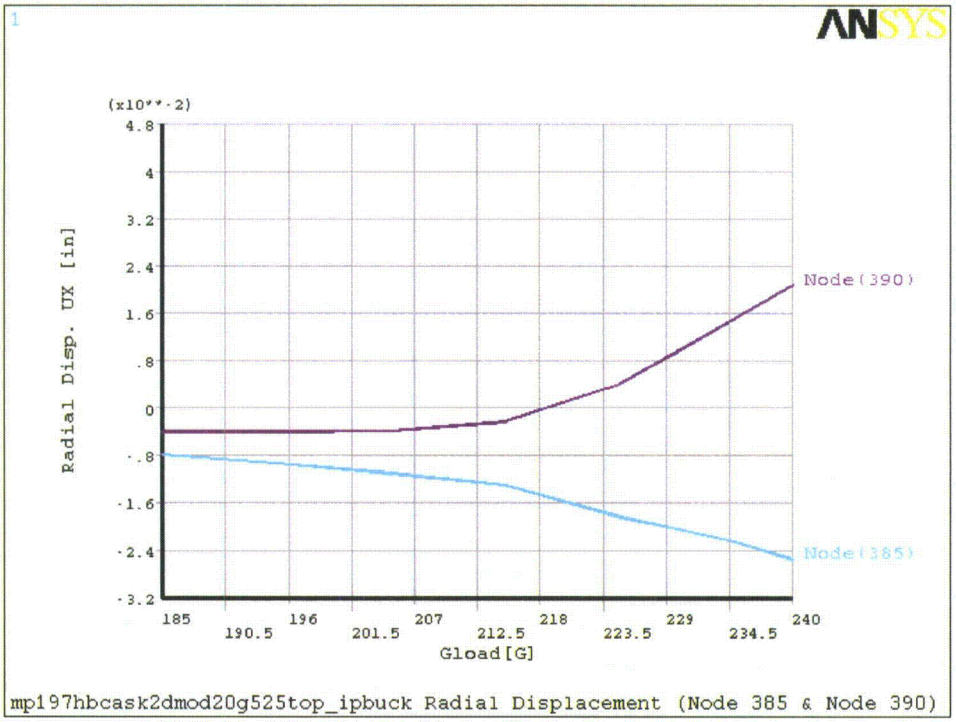
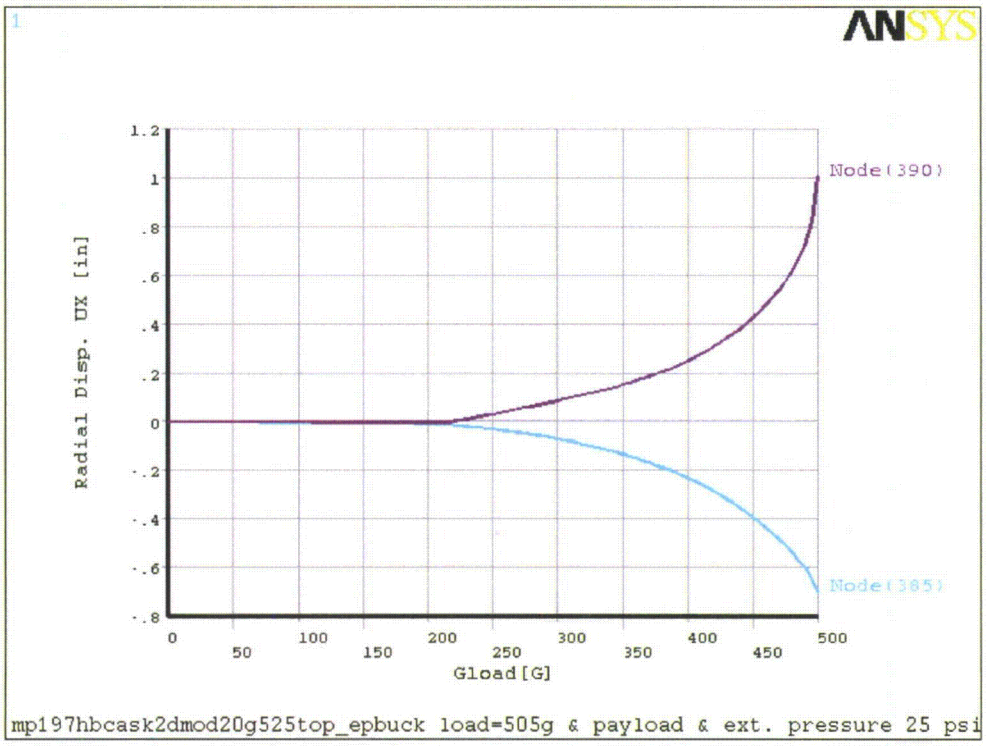


Figure A.2.13.3- 5 Displacement vs. G-Load Curve for Lid End Drop with 30 psig Internal Pressure (Enlarge View is Shown in the Bottom Plot)



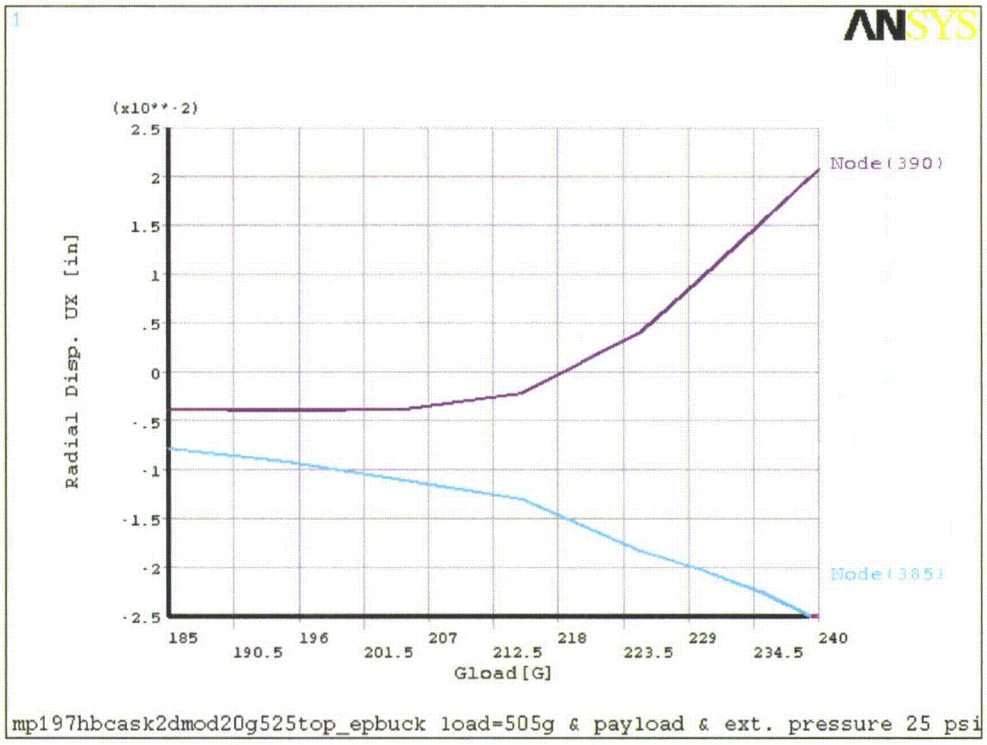


Figure A.2.13.3- 6 Displacement vs. G-Load Curve for Lid End Drop with 25 psig External Pressure (Enlarge View is Shown in the Bottom Plot)

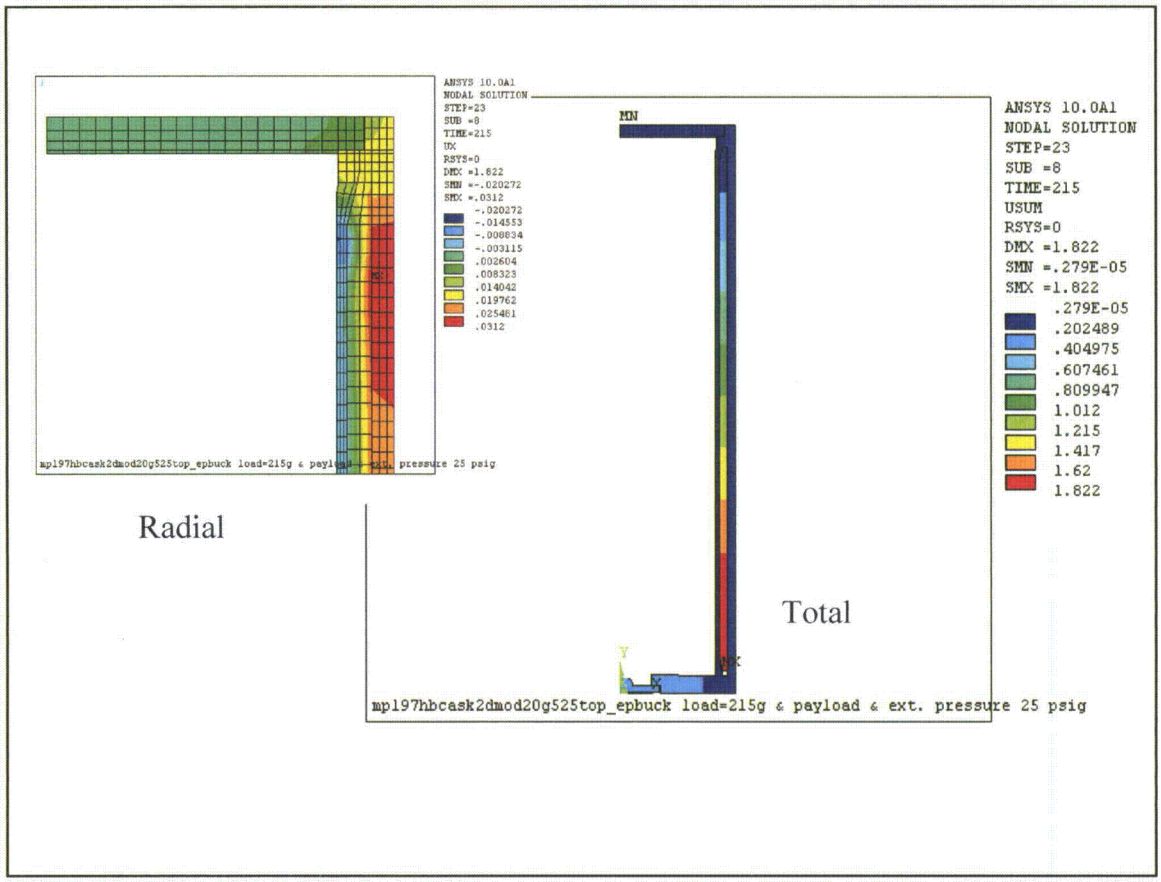


Figure A.2.13.3- 7 Displacement Plot at 215g (Lid End Drop with 25 psig External Pressure)

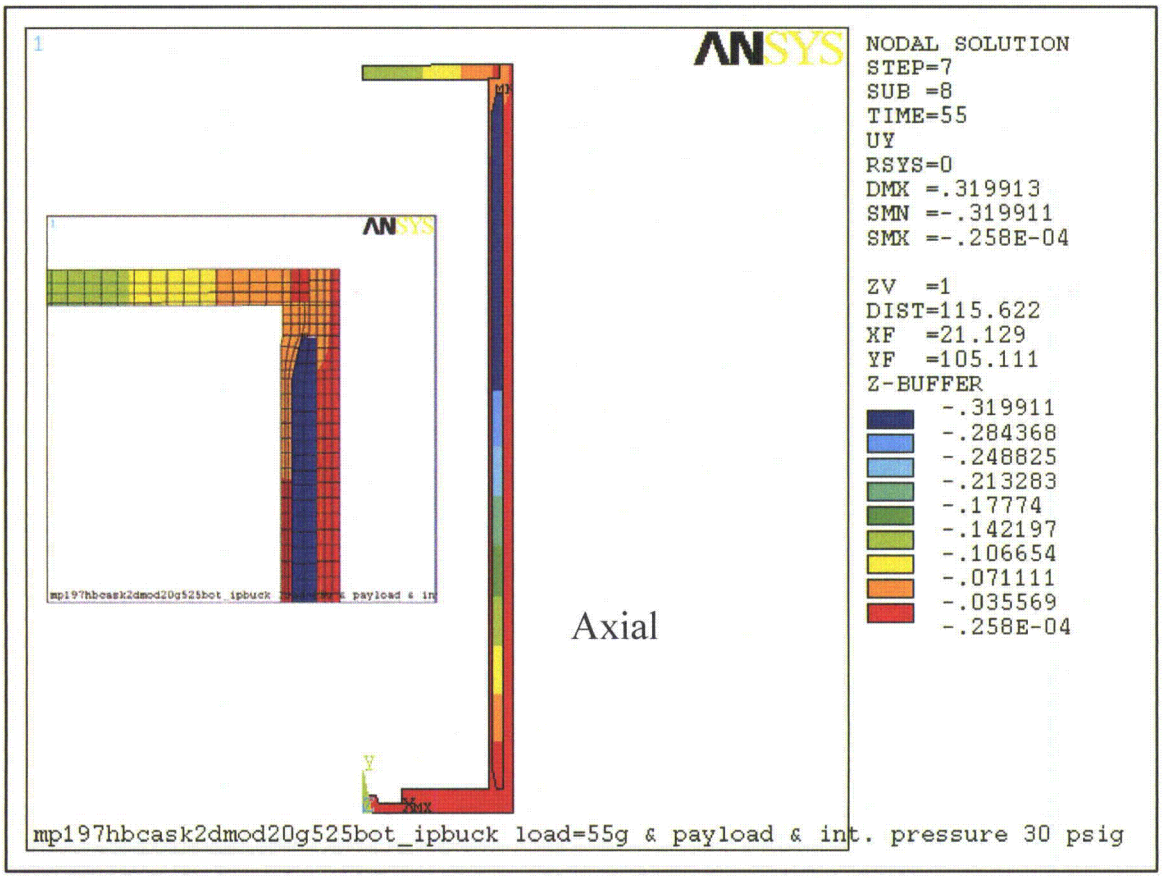


Figure A.2.13.3- 8 Lead Slump at 55g (Lid End Drop with 30 psig Internal Pressure)