(Non-Proprietary Version)

ROBATEL technologies

RT-100 Type B Cask

Safety Analysis Report

Docket Number 71-9365

Revision 6

May 15, 2015

This Part 71 Application for Approval of RT-100 Type B Cask Package for Radioactive Material represents Robatel Technologies, LLC approach to its business as applied to the specifications of this submittal. This Application requests that the Nuclear Regulatory Commission respects the proprietary information and withholds it from public disclosure subject to the provisions of 10 CFR 2.390. All detailed drawings are considered proprietary information.

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1. GENERAL INFORMATION

ROBATEL Technologies, LLC (RT) submitted its Application and Safety Analysis Report (SAR), Revision 5, to the Nuclear Regulatory Commission (NRC) on 30 January 2015 [Ref. 3] for the Model RT-100 Type B(U) Cask Package (RT-100). RT received a Request for Additional Information (RAI) from the NRC on 24 April 2015 [Ref. 4].

After review of the RAI, RT submits this Revision 6 of our Application and SAR in accordance with its NRC-approved RT Quality Assurance Program [Ref. 1]. Revision 6 replaces the previous submittal (Revision 5) in its entirety.

Chapter 1 of the SAR provides General Information that feeds information to later sections in this application according to Figure 1-1 on the following page. The RT-100 meets the following general requirements for all packages:

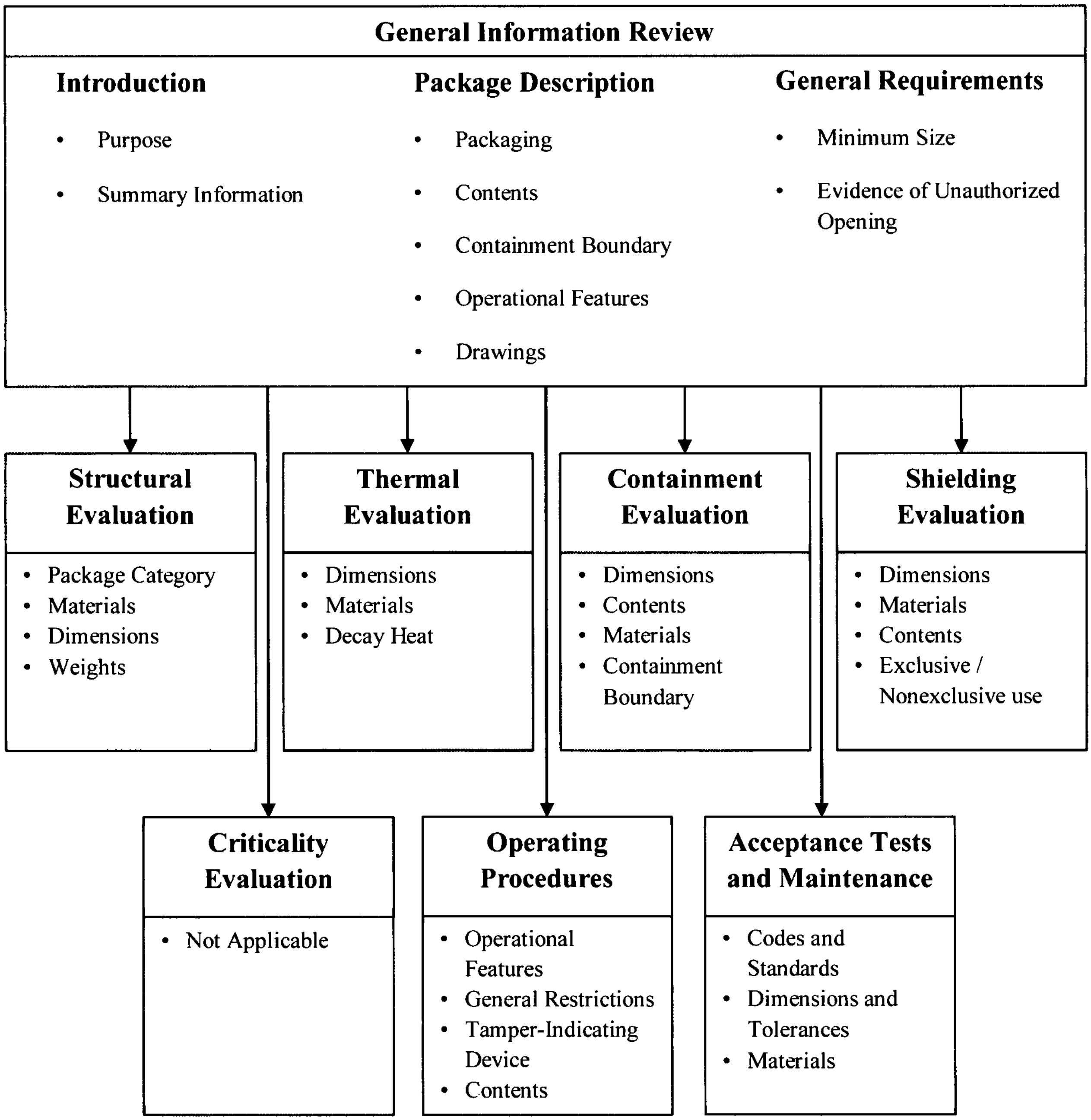
- The smallest overall dimension of the RT-100 is not less than 10 cm (4 in.).
- The outside of the RT-100 incorporates a feature that, while intact, is evidence that the package has not been opened by unauthorized persons.

1.1 Introduction

The purpose of this application is for the approval of a new type B(U) cask design. The "RT-100" is the proposed cask model number. The RT-100 is proposed to package and transport contaminated spent resins and spent filters.

This application does not request the packaging and/or transport of fissile material in quantities exceeding those exempted from consideration in accordance with 10 CFR 71.15 [Ref. 2] and thus, the Criticality Safety Index (CSI) is non-applicable.

Figure 1-1 Information Flow for General Information



1.2 Package Description

Section 1.2 provides a summary of all design aspects of the RT-100. A general arrangement of the RT-100 cask is included in Appendix 1.4. The general arrangement depicts the package dimensions and the materials of construction. Figure 1.2.1-1 shows the major components of the RT-100 as an exploded artist view with the various components labeled.

1.2.1 Packaging

Section 1.2.1 provides details regarding overall dimensions, weight, containment, shielding, criticality, structural features, heat transfer features and package markings.

1.2.1.1 Overall Dimensions

The package consists of a stainless-steel and lead cylindrical shipping cask with a pair of cylindrical foam-filled impact limiters installed on each end. The package configuration is shown in Figure 1.2.1-1.

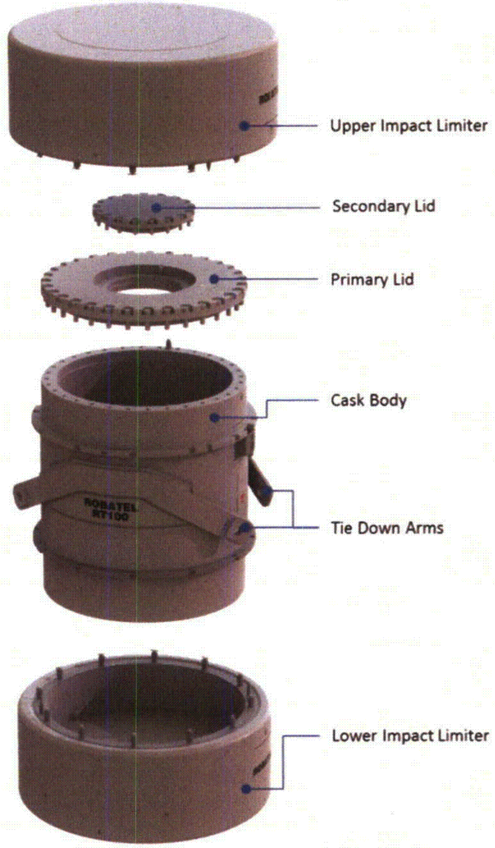


Figure 1.2.1-1 RT-100 Cask Package Artist Concept

The internal cavity dimensions are 1730 mm in diameter and 1956 mm high. The cylindrical cask body is comprised of a 35 mm thick outer stainless-steel shell and a 30 mm thick inner stainless-steel plate. The annular space between the shells is filled with 90 mm thick lead.

The base of the cask consists of a 30 mm thick stainless steel outer bottom plate, a 75 mm thick gamma shield of poured lead, and a 50 mm thick stainless steel inner bottom forging.

The primary lid consists of a 210 mm thick stainless steel forging. The primary lid is fastened to the cask body with thirty-two (32) M48 hex head bolts.

The secondary lid is made of 100 mm thick stainless steel plate, a 60 mm thick lead gamma shield and a 10 mm thick stainless steel plate. The secondary lid is attached to the primary lid with eighteen (18) M36 hex head bolts.

1.2.1.2 Weight

The maximum gross weight of the RT-100 including impact limiters is 41,500 kg (including the maximum payload weight of 6,804 kg). The maximum (empty) weight of the RT-100 including impact limiters is 34,696 kg.

1.2.1.3 Containment Features

The containment vessel of the RT-100 cask consists of the inner shell, the bottom forging, the top flange, the primary lid, the primary lid inner O-ring, the stainless steel vent port cover plate and its inner O-ring, the secondary lid and the secondary lid inner O-ring. The containment system prevents leakage of radioactive material from the cask cavity and allows pre-shipment leakage testing of the assembled cask configuration.

1.2.1.4 Neutron and Gamma Shielding Features

The RT-100 is not designed to carry fissile material or neutron sources (except typical small quantities consistent with contaminated resins and filters as discussed in Chapter 5) and thus, provision of neutron shielding is not required for the RT-100.

In regards to gamma shielding, the RT-100 cask walls provide a shield thickness of 90 mm of lead and 70 mm of stainless steel including the thermal shield plate of 5 mm thickness (65 mm used for HAC analysis). The cask bottom end provides a shield thickness of 75 mm of lead and 80 mm of stainless steel. The top end provides a shield thickness of 210 mm of stainless steel for the primary lid and a shield thickness of 60 mm of lead and 110 mm of stainless steel for the secondary lid. Contents are limited such that the radiological shielding provided assures compliance with U.S. Department of Transportation (DOT) regulatory requirements.

1.2.1.5 Shielding Features for Personnel Barriers

The RT-100 does not require the use of personnel barriers to meet 10 CFR 71 dose rate limits.

1.2.1.6 Criticality Control Features

The RT-100 contents are resins and filters from commercial nuclear power plants that contain only trace quantities of fissile radionuclides. As such, the contents meet the requirements of 10 CFR 71.15 [Ref. 2] and are exempt from classification as fissile material. As a result, the RT-100 does not require any criticality control features.

1.2.1.7 Structural Features – Lifting and Tie-Down Devices

The RT-100 cask employs lifting devices that are a structural part of the package. Two lifting pockets are welded to the cylindrical cask body as shown in Drawing RT100 PE 1001-02, Rev. H (Chapter 1, Appendix 1.4, Attachment 1.4-3). The pockets engage the arms of a separate lifting yoke used to lift the package. When not in use for package lifting, the pockets are rendered inoperable so they cannot be inadvertently used as cask tie-downs. Removable lifting lugs are

utilized for removal and handling of the primary and secondary lids, as well as the impact limiters. Refer to Chapter 2, Section 2.5.1 for a detailed analysis of the structural integrity of the lifting devices.

Two tie-down arms are welded to the external cask shell and are considered a structural part of the package. When not in use for package tie-down, the arms' holes are rendered inoperable preventing the tie-down arms from being used to lift the packaging. Refer to Chapter 2, Section 2.5.2 for a detailed analysis of the structural integrity of the tie-down arms.

1.2.1.8 Structural Features – Impact Limiters

The impact limiters have an outside diameter of 2587 mm. The lower impact limiter extends 494 mm beyond the base of the cask. The upper impact limiter extends 498 mm beyond the cask primary lid. The impact limiter external shells are stainless-steel, allowing them to withstand large plastic deformation without fracturing. The volume inside the shell is filled with crushable shock-absorbing and thermal-insulating polyurethane foam. The polyurethane is preformed and inserted into the shell to the void space. The use of preformed foam ensures homogeneous density. Several different foam densities are used to customize the shock absorbing performance of the impact limiters during hypothetical accident conditions. The rationale for use of preformed foam blocks and the use of different foam densities is presented in detail in Chapter 2, Section 2.2.

The impact limiters are attached to the cask via two stainless-steel bolt ring flanges located on the exterior cask body. The flanges are welded along the cask circumference and considered a structural part of the package. Each impact limiter is equipped with twelve (12) M36 studs and attached to the bolt ring using twelve (12) M36 stainless steel hex head nuts. The purpose of the bolt rings and bolts are to ensure the impact limiters remain attached to the cask body for all Normal Conditions of Transport (NCT) and Hypothetical Accident Conditions (HAC) events. Additionally, use of bolt rings facilitates removal of the impact limiters during loading and unloading operations.

1.2.1.9 Structural Features – Internal Supporting or Positioning Features

The RT-100 cask interior has no supporting or positioning features. The waste contents shall be pre-packaged in liners and placed into the cask cavity. Waste liners may require appropriate shoring to prevent movement during transit. It is the responsibility of the shipper to provide shoring that meets DOT requirements.

1.2.1.10 Structural Features – Outer Shell or Outer Packaging

The external surface of the cylindrical cask body is comprised of a 35 mm thick stainless-steel outer shell.

1.2.1.11 Structural Features – Packaging Closure Device

The chief packaging closure device is the primary lid that consists of a 210 mm thick stainless steel forging as described in Section 1.2.1.1. The primary lid is fastened to the cask body with thirty-two (32) M48 hex head bolts.

The secondary lid also represents a closure device for the cask and is made of 100 mm thick stainless steel plate with lead shielding and another stainless steel plate as described in Section 1.2.1.1. The secondary lid is attached to the primary lid with eighteen (18) M36 hex head bolts.

1.2.1.12 Structural Features – Heat Transfer Features

The RT-100 relies on the insulating properties of the impact limiter polyurethane foam and the cask body ceramic fiber thermal shield to minimize heat input during the hypothetical fire accident event. See Chapter 3, Section 3.4 for details.

There are no special features designed to dissipate heat from the cask.

1.2.1.13 Structural Features – Packaging Markings

The side of the cask body is marked with the Model Number of the cask "RT-100", the Certificate of Compliance No., Empty Weight, Type B(U)-96, UN 2916 and other required data.

1.2.1.14 Additional Information

- RT-100 cask has one configuration as depicted in the engineering drawings provided in Appendix 1.4, Attachments 1.4-1 thru 1.4-8.
- The RT-100 has no receptacles.
- Pressure test ports are provided between the twin O-rings for the primary lid, between the O-rings for the secondary lid, and between the O-rings for the vent port cover plate. These ports facilitate leak testing of the package in accordance with ANSI N14.5-1997 [Ref. 4].
- The vent port is provided for venting pressures within the containment cavity which may be generated during transport and prior to lid removal. Each port is sealed with an EPDM O-ring. Specification information for all O-rings is contained in Chapter 4, Section 4.1.3.
- The RT-100 does not rely on any coolants to perform its function of providing safe transportation of its radioactive contents.
- There are no external/internal protrusions other than the tie-down arms previously described.

1.2.2 Contents

The authorized contents of the RT-100 are generally described in Section 1.2.2. The radioactive contents are described to the extent required to demonstrate compliance with 10 CFR 71

requirements relating to the structural, thermal and shielding performance of the cask.

1.2.2.1 Identification and Maximum Quantity of Radioactive Material

The contents of the RT-100 cask are limited to contaminated resins and filters containing byproduct or otherwise radioactive nuclear material.

The maximum quantity of material is defined as a Type B quantity of radioactive materials not to exceed 3000 A_2. The activity of beta, gamma and neutron emitting radionuclides will not exceed the limits established in the shielding evaluation provided in Chapter 5 and using the procedure presented in Chapter 7.

1.2.2.2 Identification and Maximum Quantity of Fissile Material

The RT-100 will not transport fissile material exceeding the quantities exempt in 10 CFR 71.15 [Ref. 2]. Thus, Section 1.2.2.2 is non-applicable.

1.2.2.3 Physical and Chemical Form – Density, Moisture Content and Moderators

The type/form of material is defined as byproduct, source, or special nuclear material in the form of resins, filters, and mixtures of resins/filters. These materials are contained within secondary container(s). The chemical form of the contents is resins and filter media containing radioactive materials. The radioactive content of the resins and filters is considered to be in the form of dispersible solids. There are no contents in powdered form. The contents may include the metal housings associated with the media.

1.2.2.3.1 Ion-Exchange Resins

Single or mixed bed ion exchange resins are used in deep bed filter demineralizers for reduction of particulate matter and dissolved contaminants in utility power plant condensates. Radioactive waste systems in nuclear power plants include ion exchange systems for the removal of trace quantities of radioactive nuclides from water that will be released to the environment. The primary resin system used is the mixed bed.

Conventional ion exchange resins consist of a cross-linked polymer matrix with a relatively uniform distribution of ion-active sites throughout the structure. Ion exchange resin materials are sold as spheres or sometimes granules with a specific size and uniformity to meet the needs of a particular application. Ion exchange resins can contain up to 66% water when delivered from the manufacturer. This is essentially the same moisture content within the resin when delivered for disposal. The majority are prepared in spherical (bead) form, either as conventional resin with a polydispersed particle size distribution from about 0.3 mm to 1.2 mm (50-16 mesh) or as uniform particle sized (UPS) resin with all beads in a narrow particle size range. In the water swollen state, ion exchange resins typically show a specific gravity of 1.1-1.5. The bulk density as installed in a column includes a normal 35-40 percent voids volume for a spherical

conventional resin product. Bulk densities in the range of 560-960 g/l (35-60 lb/ft^3) are typical for wet resinous products [Ref. 8].

The contents are limited by the maximum overall weight limit of 6,804 kg as described in Section 1.2.1.2. The radioactive inventory of the contents are limited as a function of the activity concentration as described in Chapter 5.

1.2.2.3.2 Filters

Filters packaged in the secondary liner are designed for use in a nuclear power plant's primary water chemistry; therefore, the housings are a non-corrosive and non-reactive material. Filter housings may be stainless steel or a thermoplastic such as polyethylene or polypropylene. They are designed to filter radioactive material from the water, and thus are acceptable for use in a radiation environment. The filter housings do not interact with the secondary container and therefore do not interact with the RT-100 metal cavity.

1.2.2.3.3 Secondary Containers

Secondary containers may be constructed of carbon steel or stainless steel, or a thermoplastic such as polyethylene or polypropylene. The secondary containers are used to package resins or filters generated by nuclear power plants. There is a long history of transportation of these resins and filters via typical polyethylene or metal liners in metal casks by the nuclear power industry and other low-level waste generators. Secondary containers are required to be passively vented within the cask cavity during shipment. The RT-100 stainless steel inner cavity does not interact with polyethylene or metal liners typically used in the nuclear industry for the shipment of resins and filters. Secondary containers may be positioned or braced within the cavity using shoring. This shoring may be constructed of carbon steel or stainless steel, wood, or a thermoplastic material or any combination thereof.

1.2.2.4 Location and Configuration

The contents shall be packaged in secondary containers. Except for close fitting contents, shoring is placed between the secondary containers and the cask cavity liner to prevent movement during accident conditions. Providing appropriate shoring is the responsibility of the shipper.

1.2.2.5 Use of Non-Fissile Materials as Neutron Absorbers/Moderators

The RT-100 does not contain non-fissile materials as neutron absorbers/moderators.

1.2.2.6 Chemical/Galvanic/Gas Generation

Chemical Reaction and Galvanic Reactions

The contents do not include materials that may cause any significant chemical, galvanic, or other reaction.

Gas Generation

Secondary packages containing water and/or organic substances may generate combustible gases via radioanalytical reactions. A maximum molar quantity of 5% hydrogen by volume at standard temperature and pressure is allowed. The time duration is calculated as twice the expected shipment time.

Determination of hydrogen generation is made using the methods in NUREG/CR-6673 [Ref. 6], *"Hydrogen Generation in TRU Waste Transportation Packages"*, and supplemented with data from EPRI NP-5977 [Ref. 7], *"Radwaste Radiolytic Gas Generation Literature Review"*. NUREG/CR-6673 provides equations that allow prediction of the hydrogen concentration as a function of time for simple nested enclosures and for packages containing multiple contents packaged within multiple nested confinement layers. The inputs to these equations include the bounding effective $G(H_2)$-value for the contents, the $G(H_2)$-values for the packaging material(s), the void volume in the containment vessel and in the confinement layers (when applicable), the temperature when the package was sealed, the temperature of the package during transport, and the contents decay heat. EPRI NP-5799 provides G-Values for a wide range of ion exchange resins [Ref. 7].

For any package delivered to a carrier for transport, the secondary container is prepared for shipment in the same manner in which the determination for gas generation is made. Shipment period begins when the package is prepared (sealed) and is completed within a time period that is one half the time used in the hydrogen generation calculation. It is the shipper's responsibility to ensure that hydrogen generation in the cavity will be below 5% by volume, representing the lower flammability limit for hydrogen. The maximum allowable shipping time is not restricted for any other reason. Detailed discussion of the hydrogen generation calculations are provided in Chapter 4, Section 4.4, and Chapter 7, Section 7.5.

Secondary packages with radioactive contents less than Low Specific Activity (LSA) and shipped within 10 days of preparation (or within 10 days of venting the secondary container) do not require a determination of hydrogen gas generation or a restriction on shipping time.

1.2.2.7 Maximum Weight of Contents and Payload

All contents shall be packaged in a secondary container (liner). The maximum gross weight of payload is 6,804 kg including the secondary container (liner).

1.2.2.8 Maximum Decay Heat

The maximum decay heat of the RT-100 contents is 200 watts.

1.2.2.9 Loading Restrictions

Contents that are prohibited include explosives, non-radioactive pyrophoric materials, and corrosives (pH less than 2 or greater than 12.5). Pyrophoric radionuclides may be present only in residual amounts less than 1% by weight. Materials that may auto-ignite or undergo phase transformation at temperatures less than 140 °C, with the exception of water, are not included in the contents. As required by 10 CFR 71.43(d) [Ref. 2], the contents do not include materials that may cause any significant chemical, galvanic, or other reactions.

1.2.2.10 Contents for the Certificate of Compliance

The type and form of material is defined as byproduct, source, or special nuclear material in the form of dewatered or grossly dewatered resins, spent filters, or mixtures of resins/filters, contained within secondary container(s). Secondary containers are required to be passively vented within the cask cavity during shipment. The maximum bulk density of the contents may not exceed 1.0 g/cm^3. The maximum quantity of payload material including contents, secondary containers, and shoring is limited to 6,804 kg. The maximum quantity of material is defined as a Type B quantity of radioactive materials not to exceed 3000 A_2. The activity of alpha, beta, gamma and neutron emitting radionuclides does not exceed the limits established in the shielding evaluation provided in Chapter 5 and using the loading table provided in Appendix 7.6, Section 7.6.1. The contents may include fissile materials provided at least one of the paragraphs (a) through (f) of 10 CFR 71.15 [Ref. 2] is met.

1.2.3 Special Requirements for Plutonium

The RT-100 will not contain plutonium in solid form. Therefore, the requirements of 10 CFR 71.63 [Ref. 2] specifying that more than 0.74 TBq (20 Ci) of plutonium must be in solid form do not apply.

1.2.4 Operational Features

The RT-100 has no complex operational requirements. The various valves, connections, openings, seals and containment boundaries are depicted in the drawings provided in Appendix 1.4, Attachments 1.4-1 through 1.4-8. There are no piping systems associated with the RT-100 cask.

1.3 Engineering Drawings and Additional Information

Appendix 1.4 contains the engineering drawings (Attachments 1.4-1 thru 1.4-8) and additional information associated with the RT-100.

1.3.1 Engineering Drawings

The RT-100 drawings are enclosed in Appendix 1.4, Attachments 1.4-1 thru 1.4-8, and contain the following information:

- Safety features (primary and secondary lids, seals, bolts, containment boundary, and shielding)
- Materials list, dimensions, vent and leak test ports and weld inspection requirements
- Weld joint requirements
- Details of gasket joints

Appendix 1.4 does not include detailed construction drawings.

1.3.2 Conformance to Approved Design

The RT-100 cask will be fabricated in accordance with the drawings referenced in the CoC.

1.3.3 Referenced Pages

All referenced pages are generally available to the public.

1.3.4 Special Fabrication Procedures

Fabrication of the RT-100 involves standard cask fabrication techniques.

1.3.5 Package Category

The RT-100 is categorized as a Type B(U)-96 Package.

1.3.6 Supplemental Information

This application contains no supplemental information.

1.4 Appendix

Appendix 1.4 contains Proprietary Information that Robatel requests be withheld from public disclosure under 10 CFR 2.390. This request is in accordance with the Robatel Affidavit and as requested in 10 CFR 2.390.

Attachment 1.4-1 RT100 NM 1000 Rev. F — Bill of Material

Attachment 1.4-2 RT100 PE 1001-1 Rev. H — Robatel Transport Package RT-100 General Assembly Sheet 1/2

Attachment 1.4-3 RT100 PE 1001-2 Rev. H — Robatel Transport Package RT-100 General Assembly Sheet 2/2

Attachment 1.4-4 RT100 PRS 1011 Rev. E — Robatel Transport Package RT-100 Cask Sub Assembly Weld Map Cask Body

Attachment 1.4-5 RT100 PRS 1013 Rev. C — Robatel Transport Package RT-100 Cask Sub Assembly Weld Map Secondary Lid

Attachment 1.4-6 RT100 PRS 1031 Rev. D — Robatel Transport Package RT-100 Cask Sub Assembly Weld Map Lower Impact Limiter

Attachment 1.4-7 RT100 PRS 1032 Rev. D — Robatel Transport Package RT-100 Cask Sub Assembly Weld Map Upper Impact Limiter

Attachment 1.4-8 102885 MD 1031-06 Rev. F — Robatel Transport Package RT-100 Sub Assembly Fabrication Drawing Impact Limiter Foam

Proprietary Content Withheld Under 10 CFR 2.390

1.5 References

1. Robatel Technologies, LLC, Quality Assurance Program for Packaging and Transportation of Radioactive Material, 10 CFR 71 Subpart H, Dated January 31, 2012 and NRC Approved on March 21, 2012
2. U.S. Nuclear Regulatory Commission, 10 CFR Part 71--PACKAGING AND TRANSPORTATION OF RADIOACTIVE MATERIAL

71.15	71.43(d)	71.63

3. Robatel Technologies, LLC Application and Safety Analysis Report, Revision 5, for the Model RT-100 Cask Package, dated January 30,2015.
4. USNRC Request for Additional Information, dated April 24, 2015.
5. ANSI N14.5-1997, "American National Standard for Radioactive Materials – Leakage Tests on Packages for Shipment," American National Standards Institute, Inc., 11 West 42nd Street, New York, NY, www.ansi.org.
6. NUREG/CR-6673, "Hydrogen Generation in TRU Waste Transportation Packages," Anderson, B., Sheaffer, M., & Fischer, L., Lawrence Livermore National Laboratory, Livermore, CA, May 2000.
7. EPRI NP-5977, “Radwaste Radiolytic Gas Generation Literature Review”, Electric Power Research Institute, September 1988.
8. Resin and Filter Handbook – Primers and Product Information

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2. STRUCTURAL EVALUATION

Chapter 2 describes the structural evaluation for the RT-100 under the RT Quality Assurance Program [Ref. 1] and summarizes the results to demonstrate compliance with the structural requirements of 10 CFR Part 71 [Ref. 2]. These evaluations follow nuclear industry standards [Refs. 3 – 20]. Chapter 1 General Information and Chapter 3 Thermal Evaluation provide input to the Chapter 2 Structural Evaluation; furthermore, these three chapters feed information to later Chapters of the SAR as demonstrated in Figure 2-1 on the following page.

The RT-100 structural performance under 10 CFR Part 71 [Ref. 2] Normal Conditions of Transport (NCT) and Hypothetical Accident Conditions (HAC) significantly affects the package ability to meet the thermal, containment, shielding and subcriticality requirements. Consequently, results from the structural evaluation are used in the thermal, containment, and shielding evaluations (Note: criticality issues are not applicable to the RT-100).

The foremost structural requirement of the RT-100 is to withstand NCT and HAC loadings with sufficient structural integrity to maintain shielded containment. Evaluations in the following sections demonstrate the RT-100 package design satisfies these requirements. Before presenting these detailed evaluations, a general description of the RT-100 cask design is provided and includes complete specifications for the containment boundary.

2.1 Description of Structural Design

Major design features that govern the structural performance of the RT-100 under NCT and HAC conditions are the impact limiters (upper and lower) and the cask body including the impact limiter attachment rings, bolting ring, primary and secondary lids, lifting pockets and tie- down arms. These features are sufficiently designed so that the structural response of the RT-100 exceeds all 10 CFR 71 [Ref. 2] requirements.

Appendix 1.4 (Attachment 1.4-2 thru 1.4-8) shows the general assembly drawings of the RT-100 Cask Package. The major components are identified and include the impact limiters and cask body. As subsequently discussed in Section 2.1.1.1, the package containment boundary is defined by the inner surfaces of the cask body, and the primary and secondary lids. Shielding is provided by the following features:

- Cask bottom and sidewall that contain 75 and 90 mm lead layers, respectively
- 210 mm thick stainless steel primary lid
- 170 mm (nominally) stainless steel secondary lid with embedded 60 mm thick lead layer

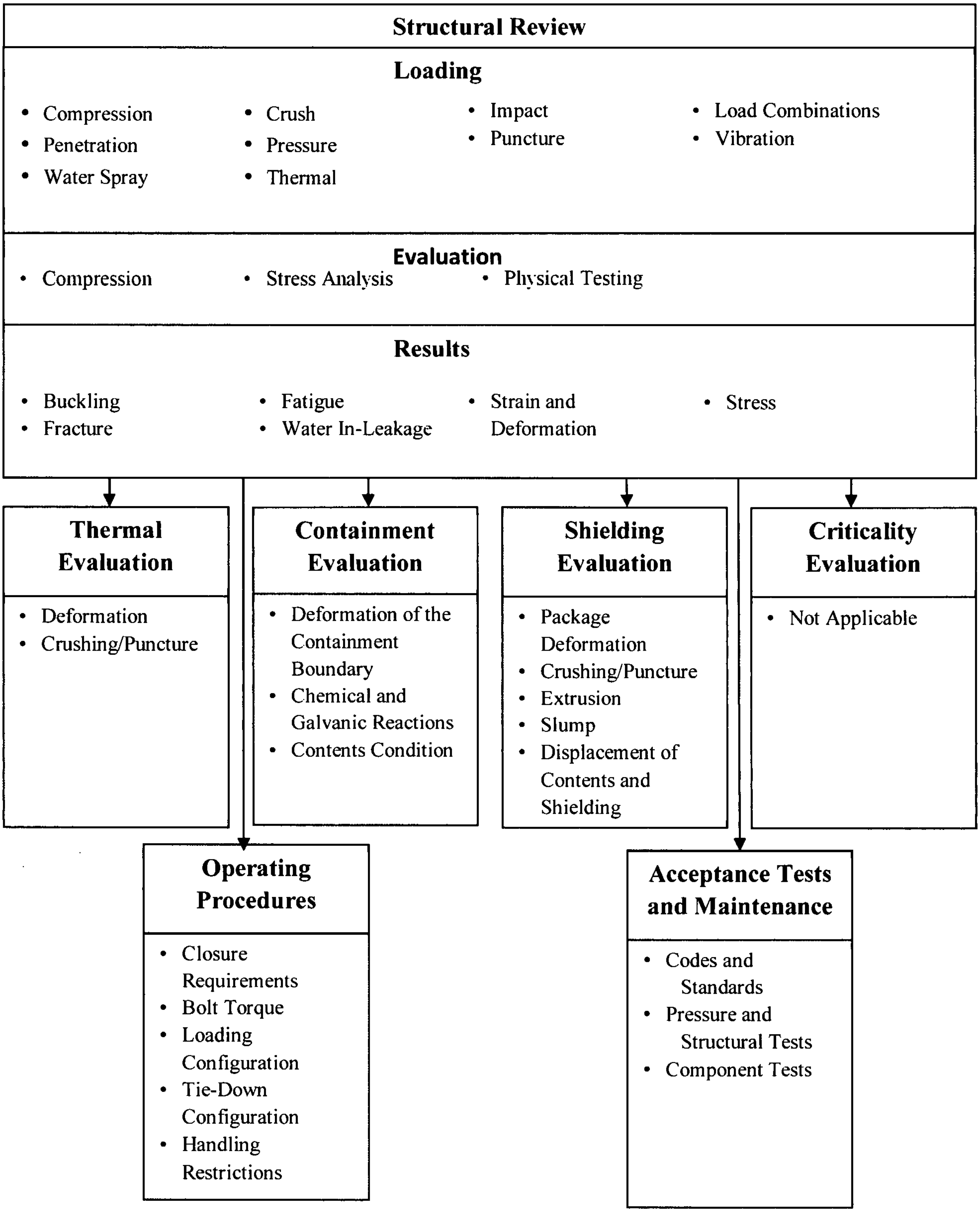


Figure 2-1 Information Flow for the Structural Review

2.1.1 Discussion

The RT-100 cask body is a cylindrical container with an outside diameter of 2060 mm and an overall height of 2321 mm (including lids). The sidewalls are nominally 165 mm thick, consist of a 90 mm thick lead layer encased by 30 mm thick internal and 35 mm thick external (ASTM A240, Type 304) stainless steel shells, have a 5 mm thick ceramic insulation layer, and have an outer 5 mm thick protective shell (ASTM A240, Type 304L stainless steel). The cask sidewall design varies from the above description in the following areas:

- Regions of the cask body encompassed by the impact limiters
- Impact limiter attachment rings
- Lifting pocket locations
- Tie-down arm attachment pads.

The specific sidewall configuration at each of these locations is further described and fully considered in all subsequent evaluations.

The bottom end of the cask body consists of a 75 mm thick lead layer encased by a 50 mm thick (ASTM A240, Type 304L) stainless steel bottom forging on top, and a 30 mm thick external stainless steel bottom plate underneath. The bottom forging is connected to the inner shell with full penetration welds. The bottom plate is connected to the outer shell with a full penetration weld.

The top end of the cask body consists of an upper forging (ASTM A240, Type 304L), and two lids (primary and secondary, both ASTM A240, Type304L). The upper forging is connected to the inner shell with full penetration welds. The upper forging is connected to the cask outer shell with full penetration welds. Thirty-two (32) M48×2d threaded holes for securing the primary lid are equally spaced along the upper forging top surface. The upper forging top surface also provides a seating surface for the primary lid seals. The primary lid is nominally 210 mm thick.

The primary lid has thirty-two (32) clearance holes near its outer periphery for the M48 bolts (ASTM A354 Gr. BD or equivalent), which secure it to the bolting ring. These clearance holes are sufficiently counter-bored to preclude direct impact to the M48 bolts during a drop. Additionally, the primary lid has a central 737 mm diameter through-hole with a 2016 mm OD × 82 mm deep counter-bore. The counter-bore surface has eighteen (18) M36×2d equally spaced threaded holes for securing the secondary lid and also provides a seating surface for the secondary lid seals. The secondary lid is nominally 170 mm thick with an embedded 60 mm thick lead layer. The secondary lid has eighteen (18) clearance holes near its outer periphery for the M36 bolts (ASTM A354 Gr. BD or equivalent) used to attach it to the primary lid. The primary and secondary lids have one vent port each which allows for leakage monitoring.

The impact limiters are cylindrically-shaped components that surround the top and bottom ends of the cask as shown in Chapter 1, Figure 1.2.1-1. Each impact limiter has twelve (12) M36 studs. The impact limiters are attached to the cask with these studs that pass through clearance holes in the top and bottom impact limiter attachment rings, and accept M36 stainless steel nuts. The

impact limiters are comprised of segmented polyurethane foam blocks encased in relatively thin stainless steel outer coverings. The outer coverings are 4 mm thick except near the cask surface where the thickness is 10 mm. During NCT and HAC tests, the impact limiters are designed to protect the cask by absorbing energy and for providing thermal insulation.

2.1.1.1 Containment Boundary

As shown in Chapter 4, Figure 4.1.2-1 ("Illustration of Containment Boundary"), the containment boundary of the RT-100 cask is defined by the following specific features of the cask body and the primary and secondary lid.

- Bottom forging at the bottom end of the cask
- Inner shell that forms the wall of the cask with a full penetration weld
- Full penetration weld between the inner bottom forging and the inner shell bottom
- Top forging at the top of the cask
- Full penetration weld between the upper forging and inner shell top
- Primary lid and inner O-ring
- Vent port cover plate and inner O-ring
- Secondary lid and inner O-ring

2.1.2 Design Criteria

The RT-100 design satisfies the NCT requirements of 10 CFR 71.71 [Ref. 2], and HAC requirements of 10 CFR 71.73 [Ref. 2]. Furthermore, the design complies with "General Standards for All Packages" as specified in 10 CFR 71.43 [Ref. 2], and the "Lifting and Tie-Down Standards" specified in 10 CFR 71.45 [Ref. 2]. These criteria are demonstrated in Sections 2.5.1 and 2.5.2.

The design criteria used in the qualification of the RT-100 were selected based on guidance provided in Regulatory Guide 7.6 [Ref. 4]. Regulatory Guide 7.6 provides design criteria based on the ASME B&PV Code, Section III [Ref.7], and is intended for Type B packages used to transport irradiated fuel assemblies. Therefore, allowable stresses values for NCT Service Level A Limits and HAC Service Level D Limits are conservatively adopted from Regulatory Guide 7.6 [Ref. 4] for the qualification of the RT-100 cask body.

Allowable stresses are derived from the Stress Intensity values appropriate to ASME B&PV Code, Section III, Subsection ND [Ref. 7]. Stress Intensity values based on Subsection ND are presented in Table 2.2.1-1.

The load combinations used in performing the structural evaluations of the RT-100 cask are in accordance with Regulatory Guide 7.8 [Ref. 3]. Load combinations for the RT-100 cask body analysis are summarized in Table 2.1.2-1.

Table 2.1.2-1 Load Combinations for RT-100 Cask Body Analyses

LOAD		NORMAL		ACCIDENT			
Reg. Guide 7.8 Load Combinations		A		D			
		1	2	1	2	3	4
Dead Weight	With maximum contents	X	X	X	X	X	X
Thermal Stresses	Hot	X		X		X	
	Cold		X		X		X
Internal Pressure	Normal	X	X	X	X		
	Accident (fire)					X	X
Drop/Impact	0.3 Meters	X	X				
Drop/Impact	9 Meters			X	X		

2.1.2.1 Cask Body Criteria (except Bolts and O-Rings)

The criteria for the cask shells and lids are developed per Regulatory Guide 7.6 Regulatory Position 2 [Ref. 4]. (The tie-down arms are also fabricated from stainless steel but their criteria are developed separately in Section 2.5.2). Table 2.1.2-2 provides a summary of the allowable stress limits defined in Regulatory Guide 7.6.

Table 2.1.2-2 Structural Design Criteria for RT-100

Reg. Guide 7.6 Service Level	Stress Criteria	Notes
Normal conditions: Service Level A	$P_m \leq S_m$	(1)(2)
	$P_m + P_b \leq 1.5\ S_m$	(2)
	$P_m + P_b + Q \leq 3\ S_m$	(3)
Accident conditions: Service Level D	$P_m \leq 2.4\ S_m$ or $0.7\ S_u$ (whichever is less)	(4)
	$P_m + P_b \leq 3.6\ S_m$ or $1.0\ S_u$ (whichever is less)	(4)
	Total Stress $< 2\ S_u$	(5)

1. Regulatory Guide 7.6 [Ref. 4], Regulatory Position 1
2. Regulatory Guide 7.6, Regulatory Position 2
3. Regulatory Guide 7.6, Regulatory Position 4
4. Regulatory Guide 7.6, Regulatory Position 6
5. Regulatory Guide 7.6, Regulatory Position 7

2.1.2.2 Bolts

The allowable stresses under NCT (per NUREG/CR-6007 [Ref. 10]) are:

$$f_t < S_m$$

$$f_t^{max} < 3S_m \text{ if } S_u < 689 \text{ MPa}$$
$$< 2.7S_m \text{ if } S_u > 689 \text{ MPa}$$

$$P_m + P_b + \text{residual torsion} < S_m$$

where

$$f_t = \text{average tensile stress}$$

f_t^{max} = maximum tensile stress under combined tension and bending, and all other terms are as previously defined.

The allowable stresses under NCT (per NUREG/CR-6007 [Ref. 10]) are:

$$f_t < F_{tb}$$

$$f_v < F_{vb}$$

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

where

f_v = average shear stress

F_{tb} = allowable average tensile stress

= Min (0.7Su, Sy) at temperature

F_{vb} = allowable average shear stress

= Min (0.42Su, 0.6Sy) at temperature and all other terms are as previously defined.

2.1.2.3 Lead

The structural integrity of the RT-100 cask does not depend on lead strength and thus, no lead strength criteria are specified. Mechanical and thermal properties which are important to the RT-100 cask structural performance are discussed in Sections 2.2, 2.14, and 3.2

2.1.2.4 Foam

Criteria of the polyurethane foam used in the impact limiters are provided in Appendix 2.12 Impact Limiter Evaluation.

2.1.3 Weights and Centers of Gravity

The nominal RT-100 weights and centers of gravity are shown in Table 2.1.3-1. Refer to RT100 PE 1001-1 Rev. H – Robatel Transport Package RT-100 General Assembly Sheet 1/2 (Chapter 1, Appendix 1.4, Attachment 1.4-2) for identification of assemblies and centers of gravity data. These weights are utilized in the structural evaluation presented in this chapter.

With the exception of the impact limiter, all analyses are performed with no less than a minimum gross weight of 41,500 kg. The impact limiter calculation is performed using 41,000 kg. The reason for this is that the max crush is obtained by using the minimum density of the foam. The calculation package RTL-001-CALC-ST-0401 Rev. 6 [Ref. 40] calculates the maximum g-load using both 41,500 kg and 41,000 kg. It is shown that max g-load is obtained using a gross weight of 41,000 kg. Thus, the impact limiter calculation is performed using a gross weight of 41,000 kg.

Table 2.1.3-1 Assembly Weights and Center of Gravity Locations

Assembly[3]	Nominal Weight (kg)	Center of Gravity[3] (mm)
Lower Impact Limiter	2,450	516
Cask Body	24,500	1,446
Primary Lid w/ bolts	3,670	2,716
Secondary Lid w/ bolts	870	2,737
Upper Impact Limiter	2,550	2,812
Total Assembly Empty	34,040	1,650
Payload	6,805[1]	1,434 min.[3] 1,826 max.[3]
Total Assembly with payload	40,845[2]	1,620 min.[3] 1,676 max.[3]

Notes: 1. Maximum.
2. A minimum weight of 41,000 kg was used in all structural evaluations.
3. Value determined using payload center of gravity at 10% of cask interior height below or above the cask interior geometric centerline.

As shown in Table 2.1.3-1, the center of gravity of the empty RT-100 cask is approximately 1650 mm above the bottom of the cask. This location is just 20 mm lower than the 1630 mm elevation of the center of the inner cavity. Further, the maximum payload weight is less than 17% (= 6,805/40,845 ×100%) of the loaded cask weight. Thus, payload weight and/or center of gravity variations will not result in large changes to the loaded RT-100 cask center of gravity. Indeed, locating the payload center of gravity within 10% of the cavity internal height above or below the cavity centerline elevation moves the loaded RT-100 cask center of gravity by no more than +/- 28 mm. Such minor variations are insignificant during either NCT or HAC.

2.1.4 Identification of Codes and Standards for Package Design

Since the package is used to transport contents with 3,000 A_2 (as defined in 10 CFR 71.4 [Ref. 2]), the RT-100 cask is a Type B Category II package per Regulatory Guide 7.11 [Ref. 5]. The codes and standards used in the design of the RT-100 cask are selected based on guidance provided in Regulatory Guide 7.6 [Ref. 4 and NUREG/CR-3854 [Ref. 6] for packages transporting Category II contents.

Per NUREG/CR-3854 [Ref. 6], the package containment system is fabricated in accordance with the ASME Code, Section III, Subsection ND [Ref. 7], and the tie-downs are fabricated in accordance with Subsection NF [Ref. 8]. These codes are applicable to the RT-100 cask design as they were developed for components of similar material as well as, for similar loading operations and potential package failures.

Several regulatory guides and NUREGs are used to design and evaluate the RT-100 package. Regulatory Guide 7.8 [Ref. 3] is used in identifying the load combinations to be used in package design evaluation. Regulatory Guide 7.6 [Ref. 4] is used to determine the design criteria. NUREG/CR-4554 [Ref. 9] is used in evaluating buckling of the containment vessel.

NUREG/CR-6007 [Ref. 10] is followed for the bolt evaluations.

2.2 Materials

Material properties used in the RT-100 cask structural analyses are shown in Tables 2.2.1-1, 2.2.1-2, and 2.2.1-3. Material properties for the structural analyses of the polyurethane foam used in the impact limiter evaluations are provided in Appendix 2.12. Properties of both cask materials and foam used in the thermal analyses are provided in Section 3.2.1.

2.2.1 Material Properties and Specifications

Structural components of the cask body are specified to be ASME A240 Type 304/304L steel, with the exception of the tie-down straps, which are ASME A240 UNS No. S31803 (Type 318) stainless steel. The primary and secondary lids are ASME A240 Type 304/304L steel, and the M36 and M48 bolts used to secure the lids are fabricated to meet the critical characteristics given in Chapter 8. These materials meet the requirements of ASME Section III, Subsection ND [Ref. 7]. Strength properties for these materials are presented in Table 2.2.1-1 using material information taken from ASME Section II-D [Ref. 31]. Table 2.2.1-2 provides density and Poisson's ratio values also from ASME Section II-D.

The shielding is specified to be ASTM B-29 lead. The lead properties are provided in NUREG/CR-0481[Ref. 11] and are presented in Table 2.2.1-2.

EPDM (material designation per ASTM D1418) is used for all O-rings as part of the containment boundary. They serve as one of the boundaries for the cask. These O-rings have a usable temperature range going from -50°C up to 150°C; this temperature range meets or exceeds both NCT and HAC requirements.

RT verifies that all the materials of structural components have sufficient fracture toughness to preclude brittle fracture under NCT and HAC. Regulatory Guides 7.11 [Ref. 5] and 7.12 [Ref. 16] are used to provide criteria for fracture toughness. RT shall procure all materials under the RT Quality Assurance Program [Ref. 1] with the specifications for each material. Regulatory Guides 7.11 and 7.12 do not apply to the RT-100; use of Stainless Steel ASTM A-240 type 304, ASTM A-240 type 304L, and ASTM A-240 UNS S31803 precludes brittle fracture under both NCT and HAC.

RT verifies that all material properties are appropriate for the load conditions specified in Regulatory Guide 7.6 [Ref. 4] and temperatures at which allowable stress limits are defined are consistent with minimum and maximum service temperatures. Allowable stresses based on Regulatory Guide 7.6 [Ref. 4] at the bounding NCT temperature of 100°C are provided in Table 2.2.1-3. Allowable stress intensities at other temperatures considered to be the bounding condition for a specific case are defined as needed in the section where that analysis is presented.

RT verifies that all the force-deformation properties for impact limiters are based on appropriate test conditions and temperature. Test parameters for qualifying the foam material are identified in Chapter 2, Appendix 2.13.

Table 2.2.1-1 Cask Temperature-Dependent Material Properties

Material	Temperature (°C)	Yield Strength (S_y) (MPa)	Tensile Strength (S_u) (MPa)	Design Stress Intensity (S_m) (MPa)	Young's Modulus (GPa)	Coefficient of Thermal Expansion (10^{-6}/°C)
ASME SA-240 Type 304/304L (Dual Certified)	-30	207	517	138	198	—
	20	207	517	138	195	15.3
	65	184	496	138	192	15.8
	100	170	485	138	189	16.2
	150	154	456	138	186	16.6
	200	144	442	129	183	17.0
	250	135	437	122	179	17.4
ASME SA-240 Type 304L	-30	172	483	115	198	—
	20	172	483	115	195	15.3
	65	157	463	115	192	15.8
	100	146	452	115	189	16.2
	150	132	421	115	186	16.6
	200	121	406	110	183	17.0
	250	114	398	103	179	17.4
ASME SA-240 Type 316L	-30	172	483	115	198	—
	20	172	483	115	195	15.3
	65	157	471	106	192	15.8
	100	145	467	96.3	189	16.2
	150	131	441	87.4	186	16.6
	200	121	429	81.2	183	17.0
	250	114	426	76.0	179	17.4
ASME SA-240 UNS No. S31803	-30	448	621	207 = S_u/3	211	—
	20	448	621	207	205	15.3
	65	418	620	207	200	15.8
	100	395	619	206	194	16.2
	150	370	598	199	190	16.6
	200	354	577	193	186	17.0
	250	344	564	188	183	17.4
ASME SA-354 Grade BD (Bolting material)	-30	896	1030	343 = S_u/3	199	—
	20	896	1030	343	202	11.5
	65	855	1030	343	199	11.8
	100	816	1030	343	197	12.1
	150	792	1030	343	194	12.4
	200	768	1030	343	191	12.7
	250	737	1030	343	188	13.0
ASME SA-479, ER308	-30 to 40	205	515	—	—	—
ASTM B-29 Lead	-29	—	—	—	16.75	28.2
	20	—	—	—	15.67	28.9
	50	—	—	—	14.94	29.4
	100	—	—	—	13.73	30.2
	150	—	—	—	12.74	31.2
	200	—	—	—	11.80	32.6
	250	—	—	—	10.70	34.1

Table 2.2.1-2 Cask Temperature-Independent Material Properties ASME [Ref. 31]

Material	Density (kg/m^3)	Poisson's Ratio
ASME SA-240 Type 304/304L (Dual Certified)	8030	0.31
ASME SA-240 UNS No. S31803	8030	0.31
ASME SA-354 Grade BD (Bolting material)	7750	0.30
ASTM B-29 Lead	11300	0.40

Table 2.2.1-3 Allowable Stresses for Cask Body Materials

Design Criteria		Material				
		ASME SA-240 Type 304/304L (Dual Certified)	ASME SA-240 Type 304L	ASME SA-240 Type 316L	ASME SA-240 UNS No. S31803	ASME SA-354 Grade BD
		MPa	MPa	MPa	MPa	MPa
Yield Stress, S_y		170	146	145	395	816
Tensile Strength, S_u		485	452	467	619	1030
Design Stress Intensity, S_m		138	115	96.3	206	299
Normal Conditions	P_m	138	115	96.3	206	299
	$P_m + P_b$	207	173	144	309	449
	$P_m + P_b + Q$	414	345	289	618	897
Hypothetical Accident Conditions	P_m	331	276	231	433	718
	$P_m + P_b$	485	414	347	619	1030
	Total Stress	970	904	934	1238	2060

2.2.2 Chemical, Galvanic, or Other Reactions

The materials used in the fabrication and operation of the RT-100, including coatings, lubricants, and cleaning agents, are evaluated to determine whether chemical, galvanic, or other reactions among the materials, contents, and environments can occur. All phases of operation, loading, unloading, handling, storage, and transportation, are considered (in conjunction with the procedures described in Chapter 7) for the environments that may be encountered under normal, off-normal, or accident conditions. Based on the evaluation, there are no potential reactions that could adversely affect the overall integrity of the cask or the structural integrity and retrievability of the contents from the cask. The evaluation conforms to the guidelines of NRC Bulletin 96-04, "Chemical, Galvanic, or Other Reactions in spent Fuel Storage and Transportation Casks," dated July 5, 1996 [Ref. 52], and demonstrates that the RT-100 cask meets the requirements of 10 CFR 71.43(d) [Ref. 2].

2.2.2.1 Component Material Categories

The component materials evaluated are categorized based on similarity of physical and chemical properties and/or on similarity of component functions. The categories of materials that are considered are as follows:

- Stainless/nickel alloy steels
- Nonferrous metals
- Shielding materials
- Criticality control materials
- Energy absorbing materials
- Cellular foams and insulations
- Lubricants and greases
- O-rings
- Secondary Containers and Shoring
- Filters

These categories are evaluated based on the environment to which they could be exposed during operation or use of the RT-100.

The RT-100 component materials are not reactive among themselves, with the cask's contents, nor with the cask's operating environments during any phase of normal, or accident condition loading, unloading, handling, storage or transportation operations. No reactions occur, and no gases or other corrosion byproducts are generated.

2.2.2.1.1 Stainless/Nickel Alloy Steels

No reaction of the cask components (stainless or nickel alloy) is expected in any environment. During the fabrication process of the RT-100 ridges and crevices on the external surfaces are reduced through the finishing process and the external surface is passivated to prevent corrosion.

Galvanic corrosion between the stainless steels and nickel alloy steels does not occur due to the lack of effective electrochemical potential difference between these metals. No coatings are applied to the stainless steel or nickel alloy steels.

There is no potential for a reaction between stainless steel and any silicone products, fluorocarbon elastomers, dry film lubricants, blended polytetrafluoroethylene (PTFE), or ethylene glycol.

Based on the foregoing discussion, there are no potential reactions expected with the stainless steel cask components.

2.2.2.1.2 Nonferrous Metals

There are no nonferrous metals used in the RT-100. Therefore, no electrochemical driving potential exists.

2.2.2.1.3 Shielding Materials

The primary shielding materials used in the RT-100 is lead which is completely enclosed and sealed in stainless steel. Therefore, there are no potential reactions associated with the cask shielding materials.

2.2.2.1.4 Criticality Control Material

The RT-100 does not contain materials for criticality control. Therefore, no potential reactions associated with these materials exist.

2.2.2.1.5 Energy Absorbing Material

The RT-100 utilizes polyurethane foam for energy absorption in the impact limiters. The foam is completely enclosed (sealed) in stainless steel and there are no potential reactions between the foam and the stainless steel shells. The foam is cured, cut, and machined prior to installation. During fabrication the machined foam blocks are inserted into the impact limiter stainless steel shell. During the welding process backing strips, high temperature heat tape, and rock wool are used to protect the foam. Therefore, no potential reactions associated with the energy absorbing material exists.

2.2.2.1.6 Cellular Foam and Insulation

The RT-100 does not utilize cellular foam or insulation. Therefore, no potential reactions associated with the cellular foam or insulation exists.

2.2.2.1.7 Lubricant and Grease

The dry film lubricants used with the RT-100 meet the performance and general compositional requirements of the nuclear power industry. These lubricants are used primarily on threaded/mechanical connection surfaces. These lubricants are insoluble in most solutions. There are no potential reactions associated with these lubricants or grease.

2.2.2.1.8 O-Rings

The RT-100 utilizes seals formed from EPDM. EPDM is a synthetic rubber elastomer. Elastomer O-rings are used for transport cask applications because of their excellent short-term sealing capabilities, ease of handling, and more economical cost. Seal and gasket materials have stable, non-reactive compositions. There are no potential reactions associated with the RT-100 seal materials.

2.2.2.1.9 Secondary Containers and Shoring

Secondary containers and shoring features may be constructed of carbon steel, stainless steel, wood, or a thermoplastic such as polyethylene or polypropylene.

2.2.2.1.10 Filters

Filters shipped for disposal may be constructed from stainless steel or thermoplastic such as polyethylene or polypropylene.

2.2.2.2 General Effects of Identified Reactions

No significant potential galvanic or other reactions have been identified for the RT-100. Therefore, no adverse conditions can result during any phase of cask operations for NCT or HAC.

2.2.2.3 Adequacy of the Cask Operating Procedures

Based on the results of this evaluation, it is concluded that the RT-100 operating controls and procedures presented in Chapter 7 are adequate to minimize occurrence of hazardous conditions.

2.2.2.4 Effects of Reaction Products

No significant potential chemical, galvanic, or other reactions are identified for the RT-100. Therefore, the overall integrity of the cask and the structural integrity and retrievability of the contents are not adversely affected for any cask operations throughout the design basis life of the cask. Based on the evaluation, no significant reactions are identified and thus, there is no change in cask properties, no binding of mechanical surface, and no degradation of any safety components either directly or indirectly.

2.2.3 Effects of Radiation on Materials

Gamma radiation has no significant effect on metal and therefore, the radiation produced by the contained radioactivity does not cause any measurable damage to the cask metallic components (stainless steel, carbon steel and lead).

For seals, the absorbed dose in a year is expected to be below 350 rad which is significantly below the polymer damage threshold of 1×10^5 rad. Additional support information about EPDM resistance to radiation up to 5×10^8 rads while retaining reasonable flexibility and strength, hardness and very good compression set resistance is provided by an IEEE paper [Ref. 54].

For the ceramic thermal shield, the absorbed dose is expected to be below 350 rad. However, ceramic materials are insensitive to gamma radiation damage and thus, the ceramic thermal shield is expected to be unaffected by radiation.

2.3 Fabrication and Examination

The following subsections provide a summary description of fabrication and examination of the RT-100. A more detailed description is provided in subsequent sections of the SAR.

2.3.1 Fabrication

The RT-100 packaging is designed as a category II container, as mentioned in Section 2.1.4. Fabrication and procurement of the containment components is based on ASME B&PV code, section III, Subsection ND [Ref. 7]. The other components (non-containment) are fabricated based on ASME B&PV code, Section III, subsection NF [Ref.8]. See Sections 2.1.2 and 2.1.4 for additional information.

2.3.2 Examination

Examination of the RT-100 during and after fabrication is conducted in accordance with the requirements of the ASME B&PV code, Section III, Subsection ND-5000 [Ref. 7]. The non-containment components examination is conducted in accordance with the requirements of ASME B&PV Code, Section III, Subsection ND-5000 or NF5000 [Ref. 8]. See Chapter 8, Sections 8.1 and 8.2 for additional information.

2.4 General Requirements for All Packages

The RT-100 meets or exceeds all the requirements in 10 CFR 71.43 [Ref 2]. Also, the RT-100 meets the general package requirements Regulatory Guide 7.9 [Ref. 49] as listed below:

- Smallest overall dimension is greater than 10 cm (4 in).
- Outside of the cask incorporates a feature, such as a seal, that is not readily breakable and that, while intact, would be evidence that the package has not been opened by unauthorized persons.
- Cask includes a containment system closed by a positive fastening device that cannot be opened unintentionally or by a pressure that may arise within the package.

The following sections describe compliance of the RT-100 with these requirements.

2.4.1 Minimum Package Size

This section is not applicable since the RT-100 has dimensions larger than 10 cm (4 inches). The smallest overall dimension of the cask body is the outer diameter, which is over 200 cm.

2.4.2 Tamper-Indicating Feature

The RT-100 upper impact limiter covers the upper end of the cask including the primary and secondary lids, which prevents access to the cask lids. Therefore, tamper-indicating devices are attached to the impact limiter aligning pin. Impact limiters are installed on the cask body following the lid closure operation. Once the impact limiters are installed on the cask body, the attachment nuts are threaded on the attaching studs and hand-tightened (drop testing has shown that torquing of the attachment bolts is not necessary). A tamper-indicating seal is installed on the aligning pin of the upper impact limiter to ensure that removal of the impact limiter by unauthorized individuals can be detected.

2.4.3 Positive Closure

The RT-100 design includes a containment system that is bounded by the inner shell, primary lid, secondary lid, and vent port cover plate. Each lid and the cover plate are secured to the cask body by multiple bolts. These bolts are tightened during the loading process to a set torque value that cannot be inadvertently loosened. Additionally, the stress analysis of the bolts presented in Section 2.6.7 demonstrates that the bolts can maintain positive closure during operation.

2.5 Lifting and Tie-Down Standards for All Packages

The RT-100 lifting and tie-down components are evaluated structurally in the following sections. The lifting and tie-down requirements are as specified in 10 CFR 71.45 [Ref. 2].

2.5.1 Lifting Devices

The primary lifting device for the RT-100 is the set of two lifting pockets that are welded to the outer shell of the cask. After removal of the impact limiters, the lifting pockets are designed to allow the loaded cask to be lifted using a lifting yoke. The primary and secondary lids and the upper/lower impact limiters are fitted with threaded bolt holes; these bolt holes provide for attachment of lifting rings that are used in lifting each component.

2.5.1.1 Lifting Design Criteria

Lifting attachments that are a structural part of the RT-100 cask are designed with a minimum safety factor of three against yielding when used to lift the package. The lifting devices are also designed so that any failure of the lifting device under excessive load would not impair the ability of the RT-100 to meet other requirements of 10 CFR 71.45 [Ref. 2]. The design weights used in the lifting evaluation are as follows:

- Fully loaded RT-100 with maximum contents and the lower impact limiter is 41,500 kg
- Primary lid with secondary lid in place is 4,505 kg
- Secondary lid is 857 kg
- Upper impact limiter is 2,541 kg
- Lower impact limiter is 2,448 kg

2.5.1.2 Lifting Device Descriptions

In this section, the following RT-100 components are evaluated for lifting:

- Lifting Pockets
- Primary Lid
- Secondary Lid
- Lower Impact Limiter
- Upper Impact Limiter

The lifting pockets are utilized to lift the assembled cask; the bounding configuration is the cask loaded with the maximum payload weight and the lower impact limiter attached. Additionally, the primary and secondary lids and the upper and lower impact limiters are evaluated for lifts using removable lifting rings.

2.5.1.3 Lifting Device Evaluations

In the following sections, each device used for lifting is evaluated for stress. The details of each evaluation are presented including the worst-case stress results and safety factors. Additional details supporting these calculations are provided in Calculation Package RTL-001-CALC-ST-0201, Rev. 5 [Ref. 33].

2.5.1.3.1 Cask Body Lifting Evaluation

The cask is lifted by using the two lifting pockets that are welded to the cask exterior sidewall on opposite sides of the cask body. The assembled and loaded cask is lifted with the upper impact limiter removed to accommodate the connection between the lift yoke and the lifting pockets. The cask lifting load is the total weight of the fully assembled cask, including the payload, but with the upper impact limiter load removed. The upper impact limiter is lifted separately. The lifting pockets are evaluated for the tear-out stress, bearing stress, and weld stress due to the required lifting activities. The lifting pockets are also evaluated for pure shear stress as described in ASME Section III Subsection NF [Ref. 8].

A Dynamic Load Factor (DLF) of 1.35 is applied to the lift forces that act on the cask components during movement. ANSI N14.6 [Ref. 56] requires additional safety features for handling of critical loads. One option identified is to apply increased stress design factors on the load-bearing members; however, the standard does not recommend a value for the stress design factor. The German Nuclear Safety Standards Commission provides standard KTA-3905 for lifting loads in nuclear power plants. [Ref. 57] This standard requires a live load factor of 1.35 for dead weight lifts. This calculation uses the KTA-3905 live load factor value as the dynamic load factor. The dynamic load factor is applied to all load bearing members.

2.5.1.3.1.1 Lifting Pocket Design Features

The lifting pockets are manufactured from blocks of ASTM A240 Dual Certified Type 304/304L stainless steel that are welded to opposite sides of the outer shell of the cask body, also manufactured from ASTM A240 Type 304/304L stainless steel. The weld material is SA-279 Grade ER308 UNS S30880. The welds extend down both sides and along the bottom of the lifting pockets, forming a "U" shape. The lifting pockets have a cutout that allows the lifting yoke to pass downward and through the lifting pocket. The connection is completed with a rectangular shaped retaining pin that is inserted through cutouts in both the lifting pocket and the lifting yoke. Figure 2.5.1-1 provides the configuration and dimensions of the lifting pockets and shows the cutouts for the lifting yoke and retaining pin. The design loads and material strengths of the lifting pocket base metal and weld materials are as follows:

Total Lifted Cask Weight	$W = 41{,}500 - 2{,}541\ \text{kg} = 38{,}959 \rightarrow$ use 39,500 kg
Dynamic Load Factor	$DLF = 1.35$
Number of Lifting Pockets	$n_p = 2$
Gravitational Acceleration	$g = 9.81\ \text{m/s}^2$
Vertical Shear Load	$PV = \frac{W \times DLF \times g}{n_p} = \frac{39500 \times 1.35 \times 9.81}{2} \times \frac{1\ \text{kN}}{1000\ \text{N}}$
	$= 261.6$ kN pocket
Lifting Pocket Yield Strength	$Sy = 199$ MPa
Lifting Pocket Tensile Strength	$Su = 511$ MPa
Factor of Safety on Yield Strength	$Fsy = 3$
Factor of Safety on Tensile Strength	$F_{su} = 5$

The critical dimensions for the weld evaluation are as follows. These dimensions ignore the dimensions of the welds.

Lifting Pocket Length	$L_p = 191\ \text{mm} = 0.191\ \text{m}$
Lifting Pocket Edge Distance	$d_p = 55\ \text{mm} = 0.055\ \text{m}$
Lifting Pocket Eye Length	$L_e = 84\ \text{mm} = 0.084\ \text{m}$
Retaining Pin Dimensions	$W_p = 60\ \text{mm} = 0.060\ \text{m}$
	$H_p = 80\ \text{mm} = 0.080\ \text{m}$

The "eye" refers to the rectangular cutout in the lifting pocket for the retaining pin and the eye length is the vertical height of the eye. The lifting pocket length is the distance from the horizontal centerline of the retaining pin eye to the top of the lifting pocket. The lifting pocket edge distance refers to the vertical height of the recessed cap on the lifting pocket.

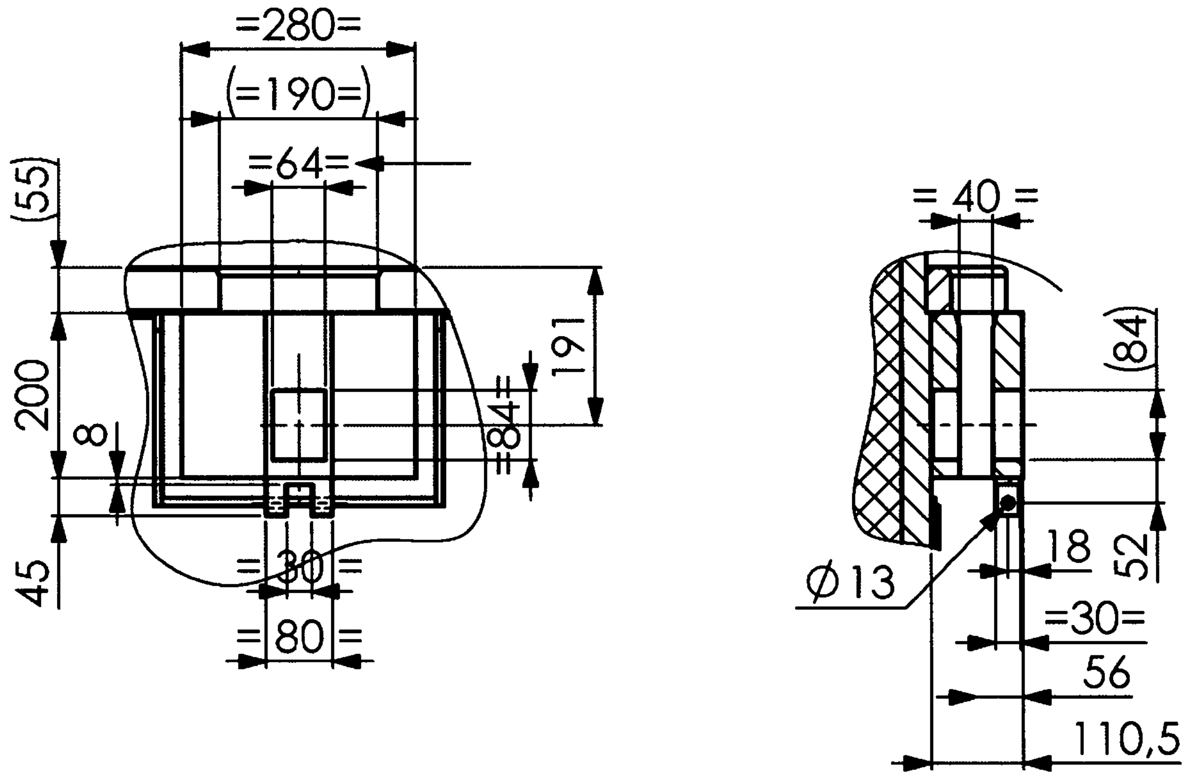


Figure 2.5.1-1 RT-100 Lifting Pocket Dimensions

2.5.1.3.1.2 Lifting Pocket Tear-out Stresses

The lifting pockets are used for lifting the assembled and loaded cask body, without the upper impact limiter, and are rendered inoperable by removing the lifting attachment from the lifting pocket during transport. The lifting pockets are considered to be a structural part of the package with respect to lifting and shall be designed for the factor of safety against yielding and ultimate stresses. A lifting yoke is used to lift the assembled cask body and to ensure that the lifting straps or cables remain parallel to the body of the cask during lifting operations. The tear-out stresses for the lifting pocket retaining pin hole are as follows:

Lifting Eye Tear-out distance $d_{to} = L_p - d_p - \frac{L_e}{2} = 0.191 - 0.055 - \frac{0.084}{2}$
$= 0.094$ m

Lifting Pocket Thickness $t_p = 110.5 - 40 = 70.5$ mm $= 0.071$ m

Lifting eye Tear-out Area $A_{to} = d_{to} \times t_p = 0.094\ x\ 0.071$
$= 0.00663$ m^2

The tear-out stresses for the lifting pocket are calculated:

Nominal Tear-out Stress $\tau_{to} = \frac{P_V}{2 \times A_{to}} = \frac{261.6}{2 \times 0.00663} = 19734 \frac{kN}{m^2} = 19.7\, MPa$

Allowable Yield Stress

$$\sigma_y = 0.6 \times S_{yL} = 119\text{ MPa}$$

Allowable Ultimate Stress

$$\sigma_u = 0.6 \times S_{uL} = 307\text{MPa}$$

Factor of Safety on Yield Strength

$$FS = \frac{\sigma_y}{\tau_{to}} = \frac{119}{19.7} = 6.05 > 3.0$$

Factor of Safety on Tensile Strength

$$FS = \frac{\sigma_u}{\tau_{to}} = \frac{307}{19.7} = 15.54 > 5.0$$

2.5.1.3.1.3 Lifting Pocket Bearing Stresses

The bearing stress in the lifting pocket from the lift yoke retaining pin is calculated as follows. The acceptance criterion for the pocket bearing stress are the yield strength of the material.

Lifting Pocket Bearing Area

$$A_b = W_p \times t_p = 0.06 \times 0.071 = 0.00423\, m^2$$

Nominal Bearing Stress

$$\tau_b = \frac{P_V}{A_b} = \frac{261.6}{0.00423} = 61834 \frac{kN}{m^2} = 61.8\, MPa$$

Factor of Safety on Yield Strength

$$FS = \frac{S_y}{\tau_b} = \frac{199}{61.8} = 3.22 > 1.0$$

2.5.1.3.1.4 Lifting Pocket Weld Stresses

The stresses in the welds (attaching the lifting pocket to the cask outer shell) are found by applying the shear load from the lifting pockets to the weld around the perimeter of the plate. Based on the safety factors for the lifting pocket, yielding controls the weld evaluation. The stresses and allowables are determined as described in "Design of Welded Structures" [Ref. 25] and Calculation Package RTL-001-CALC-ST-0201, Rev. 5 [Ref. 33]

Conservatively, the upper section of the pocket is considered to take the full lifting load. The lifting pocket is seal welded to and bears upon the cask bolting ring. The lifting load is therefore shared between the lifting pocket weld and the bolting ring. Conservatively, the full load is considered to be taken by the lifting pocket weld only.

The stresses in the welds attaching the lifting pocket to the cask outer shell are found by applying the shear load from the lifting pockets to the weld around the perimeter of the lifting pocket. Based on the safety factors for the lifting pocket, yielding controls the weld evaluation. The welds on the lifting pockets are evaluated as a line force on the weld as described in "Design of Welded Structures" [Ref. 25] (Refer to pages 7.4-6 and 7, Tables 4 and 5). Since the cask is lifted using a yoke that maintains the force in a vertical direction, there are no bending or twisting loads, so the section Modulus and the polar moment of inertia are zero and can be ignored. The weld geometry is provided in Figure 2.5.1-2

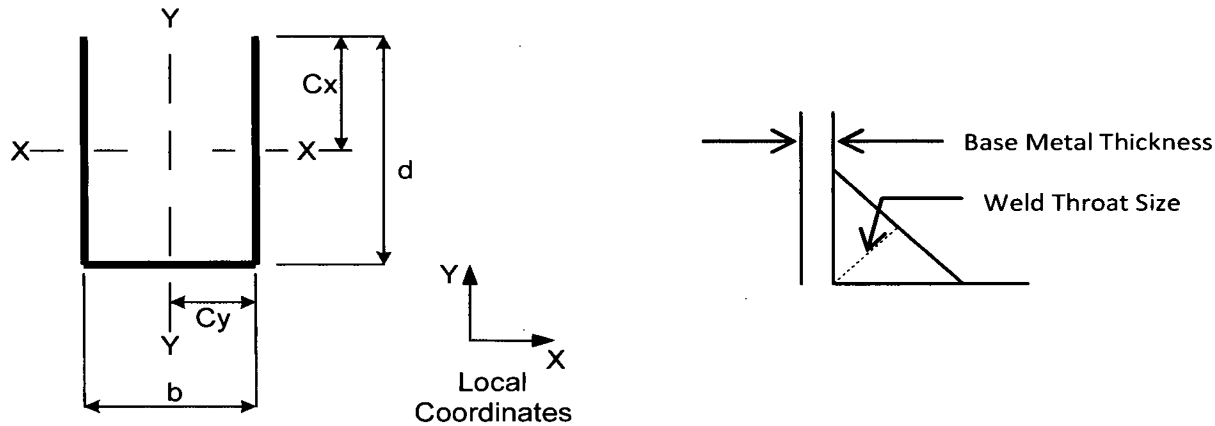


Figure 2.5.1-2 Weld Geometry

Weld properties are as follows:

Length of horizontal weld	$b = 0.28$ m
Length of vertical weld	$d = 0.20$ m
Weld Length	$A_w = b + 2d = 0.68$ m
Weld Throat Size	$T_w = 0.015$ m
Base Metal (Cask Wall) Thickness	$T_c = 0.035$ m

The force acting on the weld is:

$$f_{vy} = \frac{F_y}{A_w} = \frac{261.6}{0.68} = 384.71\ \frac{kN}{m}$$

Yield Weld Allowable

$$\tau_{wya} = 0.6 \times S_{wy} \times T_w \times 1000$$
$$= 0.6 \times 205 \times 0.015 \times 1000 = 1845\ kN/m$$

Tensile Weld Allowable

$$\tau_{wya} = 0.6 \times S_{wu} \times T_w \times 1000$$
$$= 0.6 \times 515 \times 0.015 \times 1000 = 4635\ kN/m$$

Yield Cask Allowable

$$\tau_{cya} = \frac{0.6 \times S_{cy} \times T_c \times 1000}{0.7071} = \frac{0.6 \times 199 \times 0.035 \times 1000}{0.7071}$$

$$= 5910\ kN/m$$

Tensile Cask Allowable

$$\tau_{cua} = \frac{0.6 \times S_{cu} \times T_c \times 1000}{0.7071} = \frac{0.6 \times 511 \times 0.036 \times 1000}{0.7071}$$

$$= 15176 \text{ kN/m}$$

Weld Yield FS

$$= \frac{\tau_{wya}}{f_w} = \frac{1845}{384.71} = 4.80 > 3.0$$

Weld Tensile FS

$$= \frac{\tau_{wua}}{f_w} = \frac{4635}{384.71} = 12.05 > 5.0$$

Cask Yield FS

$$= \frac{\tau_{cya}}{f_w} = \frac{5910}{384.71} = 15.36 > 3.0$$

Cask Ultimate FS

$$= \frac{\tau_{cua}}{f_w} = \frac{15176}{384.71} = 39.45 > 5.0$$

2.5.1.3.1.5 Lifting Pocket Average Pure Shear

The lifting pocket average pure shear is evaluated in accordance with ASME Section III Subsection NF [Ref. 8] Subparagraph 3223.2 and is limited to 0.6 S_m. The factor of safety is determined by comparing the pure shear to the lifting pocket tear out stress. For the lifting pocket weld evaluation, the average pure shear is evaluated as follows.

Cask Membrane Strength

$$S_m = 115\text{MPa}$$

Cask Allowable Pure Shear

$$S_{ap} = 0.6 \times S_m = 0.6 \times 115 = 69.0\text{MPa}$$

FS for Cask Pure Shear

$$= \frac{S_{ap}}{\tau_{to}} = \frac{69.0}{19.7} = 3.50 > 1.0 \; \textit{cask pure shear is OK}$$

2.5.1.3.1.6 Summary of Results

Table 2.5.1-1 provides a summary of the Factors of Safety for each of the lifting conditions that are evaluated for the assembled RT-100. The table shows that all of the lifting conditions meet the required factor of safety greater than 3.0 against yield and the factor of safety greater than 5.0 against ultimate stress for the tear out and weld stress and a greater than 1.0 for the bearing stresses and average pure shear.

Table 2.5.1-1 Summary of Results for Lifting Assembled Cask

Lifting Condition Evaluated	Factor of Safety	
	Yield (> 3)	Ultimate (>5)
Lifting Pocket Tear-out Stresses	6.05	15.54
Lifting Pocket Weld Stresses: Weld	4.80	12.05
Lifting Pocket Weld Stresses: Cask	15.36	39.45
	Factor of Safety (>1)	
Lifting Pocket Bearing Stresses	3.22	N/A
Lifting Pocket Average Pure Shear	3.50	

2.5.1.3.2 Primary Lid Lifting Evaluation

The primary lid is evaluated for the working load limit in the lifting rings and for the tear-out stresses in the lid from the lifting activities. The lifting rings for the primary lid can only be used when the cask lid is separated from the cask body. The secondary cask lid is also removable, so the primary lid may be lifted with the secondary lid attached or separated from the primary lid. Conservatively, the combined primary and secondary lid is used for the lifting evaluation. The primary lid design information is:

Primary Lid Weight	W_{PL}	= 3648 kg, assume 3700 kg
Secondary Lid Weight	W_{SL}	= 857 kg, assume 900 kg
Total Lid Lifting Weight	W_L	= 3700 + 900 = 4600 kg
Number of Lifting Rings	n_r	= 3
Dynamic Load Factor	DLF	= 1.35

2.5.1.3.2.1 Primary Lid Lifting Ring Working Loads

The lifting rings on the primary lid are only used for lifting when the lid is detached from the cask body, and are rendered inoperable by removing the rings from the lid when the cask is assembled. The rings are therefore not considered to be a structural part of the package and do not need to be designed for the factor of safety against yielding.

Lifting Ring Load $$P_r = \frac{W_L \times DLF}{n_r} = \frac{4600 \times 1.35}{3} = 2070 \text{ kg}$$

Ring Working Load Limit $$P_{r,max} = 3000 \text{ kg}$$

Factor of Safety $$FS = \frac{P_{r,max}}{P_r} = \frac{3000}{2070} = 1.45 > 1.0$$

2.5.1.3.2.2 Primary Lid Thread Engagement

The minimum required thread engagement length is determined in accordance with "Machinery's Handbook [Ref. 27]. The primary lid is manufactured from ASTM A240 Type 304L SS material. This material is weaker than the M20 lifting ring material (ASTM A-354 Gr. BD), so failure will occur at the root of the primary lid material threads. The minimum required thread engagement length that prevents primary lid material failure is:

Minimum Engagement Length $$L_e = \frac{S_{bt} \times 2 \times A_b}{S_{ct} \times \pi \times n \times D_{s,min} \times \left[\frac{1}{2 \times n} + 0.57735 \times (D_{s,min} - E_{n,max})\right]}$$

Where

S_{bt} =Bolt External Thread Tensile Strength, MPa

A_b =Stress Area of Bolt External Threads, mm²

S_{ct} =Cask Internal Thread Tensile Strength, MPa n = Number of threads per millimeter

$D_{s,min}$ = Minimum Major Bolt Diameter, mm

$E_{n,max}$ = Maximum Pitch Diameter of Internal Thread, mm

Solving the equation for Minimum Engagement Length, L_e:

Minimum Engagement Length

$$L_e = \frac{150{,}000 \times 2 \times 0.38}{69{,}000 \times \pi \times 10.16 \times 0.773 \times \left[\frac{1}{2 \times 10.16} + 0.57735 \times (0.773 - 0.699)\right]}$$

$$= 0.73 \text{ in} = 18.5 \text{ mm}$$

Where

S_{bt} = 1030 MPa = 150,000 psi

A_b = 245.0 mm² = 0.38 in²

S_{Lt} = 470 MPa = 69,000 psi

p = Thread Pitch = 2.5 mm = 0.098 in

$n = \frac{1}{p} = \frac{1}{0.098} = 10.16$ Threads/inch

$D_{s,min}$ = 19.623 mm = 0.773 in

$E_{n,max}$ = 17.744 mm = 0.699 in

The available thread engagement, L_{ep}, is 32 mm. Therefore, the factor of safety is:

$$FS = \frac{L_{ep}}{L_e} = \frac{32.0}{18.5} = 1.73 > 1.0$$

The lifting ring configuration is acceptable for the applied loads. In the unlikely event that failure does occur in the lid threads, no adverse effects on the RT-100 will occur since the threads are outside the cask containment boundary.

2.5.1.3.3 Secondary Lid Lifting Evaluation

The secondary lid is lifted using a set of three lifting rings that attach to threaded holes in the top surface of the lid. Although the maximum evaluated weight of the secondary lid lift includes only the secondary lid, the hardware is the same as that used for the primary lid. The combined primary and secondary lid are evaluated for lifting in Section 2.5.1.3.2. This section evaluates the working load limit in the lifting rings and for the minimum thread engagement in the lid during lifting activities. The secondary lid design information is:

Secondary Lid Weight	$W_{SL}=$	857 kg, assume 900 kg
Number of Lifting Rings	$n_r=$	3
Dynamic Load Factor	DLF=	1.35

2.5.1.3.3.1 Lifting Ring Working Load

The lifting rings on the secondary lid are only used for lifting when the lid is detached from the cask and are rendered inoperable by removing the rings from the lid when the cask is assembled. The rings are therefore not considered to be a structural part of the package and do not need to be designed for the factor of safety against yielding.

Lifting Ring Load

$$P_r = \frac{W_{SL \times DLF}}{n_r} = \frac{900 \times 1.35}{3} = 405 \text{ kg}$$

Ring Working Load Limit

$$P_{r,max} = 3000 \text{ kg}$$

Factor of Safety

$$FS = \frac{P_{r,max}}{P_r} = \frac{3000}{405} = 7.4 > 1.0$$

2.5.1.3.3.2 Secondary Lid Thread Engagement

The minimum required thread engagement length is determined in accordance with "Machinery's Handbook" [Ref. 27]. The secondary lid is manufactured from ASTM A240 Type 304L SS material. This material is weaker than the M20 lifting ring material (ASTM A-354 Gr. BD), so failure will occur at the root of the secondary lid material threads. The minimum required thread engagement length that prevents secondary lid material failure is:

Minimum Engagement Length $L_e = \dfrac{S_{bt} \times 2 \times A_b}{S_{ct} \times \pi \times n \times D_{s,min} \times \left[\frac{1}{2 \times n} + 0.57735 \times \left(D_{s,min} - E_{n,max}\right)\right]}$

S_{bt} =Bolt External Thread Tensile Strength, MPa

A_b =Stress Area of Bolt External Threads, mm²

S_{ct} =Cask Internal Thread Tensile Strength, MPa n = Number of threads per millimeter

$D_{s,min}$ = Minimum Major Bolt Diameter, mm

$E_{n,max}$ = Maximum Pitch Diameter of Internal Thread, mm

Solving the equation for Minimum Engagement Length, L_e:

Minimum Engagement Length

$$L_e = \frac{150{,}000 \times 2 \times 0.38}{69{,}000 \times \pi \times 10.16 \times 0.773 \times \left[\frac{1}{2 \times 10.16} + 0.57735 \times (0.773 - 0.699)\right]}$$

$$= 0.73 \text{ in} = 18.5 \text{ mm}$$

Where

S_{bt} = 1030 MPa = 150,000 psi

A_b = 245.0 mm² = 0.38 in²

S_{Lt} = 470 MPa = 69,000 psi

p = Thread Pitch = 2.5 mm = 0.098 in

n = $\frac{1}{p} = \frac{1}{0.098} = 10.16$ Threads/inch

$D_{s,min}$ = 19.623 mm = 0.773 in

$E_{n,max}$ = 17.744 mm = 0.699 in

The available thread engagement, L_{ep}, is 32 mm. Therefore, the factor of safety is:

$$FS = \frac{L_{ep}}{L_e} = \frac{32.0}{18.5} = 1.73 > 1.0$$

Therefore, the secondary lid lifting ring configuration is acceptable for the required loads.

2.5.1.3.4 Upper Impact Limiter Lifting Evaluation

The upper impact limiter is lifted using a set of three lifting rings that attach to threaded holes in the top surface of the limiter. The lifting rings are designed to remove the impact limiter from the cask body and not to lift the cask body while still attached. In the following sections, the impact limiter is evaluated for the working load limit in the lifting ring and the lifting ring thread engagement. The upper impact limiter design information is:

Secondary Lid Weight	W_{UL}=	2541 kg, assume 2700 kg
Number of Lifting Rings	n_r=	3
Dynamic Load Factor	DLF=	1.35

2.5.1.3.4.1 Lifting Ring Working Load

The lifting rings on the upper impact limiter are used only for lifting when the impact limiter is detached from the cask body; the rings are rendered inoperable by removing the rings from the impact limiter when the cask is assembled. Since the rings are not considered a structural part of the package, they do not need to be designed for the factor of safety against yielding.

Lifting Ring Load

$$P_r = \frac{W_{UL} \times DLF}{n_r} = \frac{2700 \times 1.35}{3} = 1215 \text{ kg}$$

Ring Working Load Limit

$$P_{r,max} = 3000\text{kg}$$

Factor of Safety

$$FS = \frac{P_{r,max}}{P_r} = \frac{3000}{1215} = 2.47 > 1.0$$

2.5.1.3.4.2 Impact Limiter Thread Engagement

The minimum required thread engagement length to prevent impact limiter material failure is determined in accordance with "Machinery's Handbook" [Ref. 27]. The upper impact limiter is manufactured from ASTM A240 Dual Certified Type 304/304L material. This material is weaker than the M20 lifting ring material (ASTM A-354 Gr. BD), so failure will occur at the root of the upper impact limiter material threads. The minimum required thread engagement length that prevents upper impact limiter material failure is:

Minimum Engagement Length $L_e = \dfrac{S_{bt} \times 2 \times A_b}{S_{ct} \times \pi \times n \times D_{s,min} \times \left[\dfrac{1}{2 \times n} + 0.57735 \times (D_{s,min} - E_{n,max})\right]}$

S_{bt} =Bolt External Thread Tensile Strength, MPa

A_b =Stress Area of Bolt External Threads, mm²

S_{ct} =Cask Internal Thread Tensile Strength, MPa n = Number of threads per millimeter

$D_{s,min}$ = Minimum Major Bolt Diameter, mm

$E_{n,max}$ = Maximum Pitch Diameter of Internal Thread, mm

Solving the equation for Minimum Engagement Length, L_e:

Minimum Engagement Length

$$L_e = \frac{150{,}000 \times 2 \times 0.38}{69{,}000 \times \pi \times 10.16 \times 0.773 \times \left[\frac{1}{2 \times 10.16} + 0.57735 \times (0.773 - 0.699)\right]}$$

$$= 0.73 \text{ in} = 18.5 \text{ mm}$$

Where

S_{bt} = 1030 MPa = 150,000 psi

A_b = 245.0 mm² = 0.38 in²

S_{Lt} = 470 MPa = 69,000 psi

p = Thread Pitch = 2.5 mm = 0.098 in

n $= \frac{1}{p} = \frac{1}{0.098} = 10.16$ Threads/inch

$D_{s,min}$ = 19.623 mm = 0.773 in

$E_{n,max}$ = 17.744 mm = 0.699 in

The available thread engagement, L_{ep}, is 32 mm. Therefore, the factor of safety is:

$$FS = \frac{L_{ep}}{L_e} = \frac{32.0}{18.5} = 1.73 > 1.0$$

Therefore, the upper impact limiter lifting ring configuration is acceptable for the required loads.

2.5.1.3.5 Lower Impact Limiter Lifting Evaluation

The lower impact limiter is lifted using three of the threaded bolt studs that are utilized to attach the lower limiter to the cask body. As such, it cannot be lifted while attached to the cask body. The lower impact limiter is evaluated for the bolt stresses and for minimum thread engagement in the lower impact limiter during lifting activities. The lower impact limiter design information is:

Lower Impact Limiter Weight	W_{LL}	= 2448 kg, assume 2600 kg
Number of Lifting Rings	n_r	= 3
Dynamic Load Factor	DLF	= 1.35
Gravitational Acceleration	g	= 9.81 m/s²

2.5.1.3.5.1 Attachment Bolt Stresses

The bolts on the lower impact limiter are only used for lifting when the lower impact limiter is detached from the cask body, and are rendered inoperable by securing them to the cask body as part of the assembled cask. The bolts are therefore not considered to be a structural part of the package with respect to lifting and do not need to be designed for the factor of safety against yielding. Since the arrangement of the cables or straps used to lift the lower impact limiter may vary, the total lifting load is conservatively considered simultaneously in the vertical and horizontal directions.

Bolt Tension $T = \frac{W_{LL} \times DLF \times g}{n_b} = \frac{2600 \times 1.35 \times 9.81}{3} = 11477.7\text{ N}$

Bolt Shear $V = \frac{W_{LL} \times DLF \times g}{n_b} = \frac{2600 \times 1.35 \times 9.81}{3} = 11477.7\text{ N}$

Bolt Stress Area $A_b = 0.000817\text{ m}^2$

Bolt Tensile Stress $\sigma_1 = \frac{T}{A_b} = \frac{11477.7}{0.000817 \times 1000} = 14048.6\frac{\text{kN}}{\text{m}^2} = 14.0\text{ MPa}$

Bolt Shear Stress $\tau = \frac{V}{A_b} = \frac{11477.7}{0.000817 \times 1000} = 14048.6 \frac{kN}{m^2} = 14.0 \text{ MPa}$

Maximum Principal Stress $\sigma_{p1} = \frac{1}{2} \times \left[\sigma_1 + \sqrt{\sigma_1^2 + 4 \times \tau^2}\right]$

$= \frac{1}{2} \times \left[14.0 + \sqrt{14.0^2 + 4 \times 14.0^2}\right] = 22.7 \text{ MPa}$

Minimum Principal Stress $\sigma_{p2} = \frac{1}{2} \times \left[\sigma_1 - \sqrt{\sigma_1^2 + 4 \times \tau^2}\right]$

$= \frac{1}{2} \times \left[14.0 - \sqrt{14.0^2 + 4 \times 14.0^2}\right] = -8.7 \text{ MPa}$

Maximum Shear Stress $\tau_{max} = \frac{\sigma_{p1} - \sigma_{p2}}{2} = \frac{22.7-(-8.7)}{2} = 15.7 \text{ MPa}$

Bolt Yield Stress $S_y = 896.3 \text{ MPa}$

Allowable Shear Stress $S_a = 0.6 \times S_y = 537.6 \text{ MPa}$

Factor of Safety $FS = \frac{S_a}{\tau_{max}} = \frac{537.6}{15.7} = 34.2 > 3.0$

2.5.1.3.5.2 Lower Impact Limiter Thread Engagement

The minimum required thread engagement length to prevent impact limiter material failure is determined in accordance with "Machinery's Handbook", 26th Edition [Ref. 27]. Since the constants in the equation assume U.S. customary units, the metric units used in this calculation are converted for determination of the required engagement length. The minimum required thread engagement length that prevents upper impact limiter material failure is:

Minimum Engagement Length $L_e = \frac{S_{bt} \times 2 \times A_b}{S_{ct} \times \pi \times n \times D_{s,min} \times \left[\frac{1}{2 \times n} + 0.57735 \times (D_{s,min} - E_{n,max})\right]}$

S_{bt} =Bolt External Thread Tensile Strength, MPa

A_b =Stress Area of Bolt External Threads, mm²

S_{ct} =Cask Internal Thread Tensile Strength, MPa n = Number of threads per millimeter

$D_{s,min}$ = Minimum Major Bolt Diameter, mm

$E_{n,max}$ = Maximum Pitch Diameter of Internal Thread, mm

Solving the equation for Minimum Engagement Length, L_e:

Minimum Engagement Length

$$L_e = \frac{150{,}000 \times 2 \times 1.27}{69{,}000 \times \pi \times 6.35 \times 1.396 \left[\frac{1}{2 \times 6.35} + 0.57735 \times (1.396 - 1.313)\right]}$$

$= 1.56 \text{ in} = 39.5 \text{ mm}$

Where

S_{bt} = 1030 MPa = 150,000 psi

A_b = 817.0 mm² = 1.27 in²

S_{Lt} = 470 MPa = 69,000 psi

p = Thread Pitch = 4.0 mm = 0.157 in

n = $\frac{1}{p} = \frac{1}{0.157} = 6.35$ Threads/inch

$D_{s,min}$ = 35.465 mm = 1.396 in

$E_{n,max}$ = 33.342 mm = 1.313 in

The available thread engagement, L_{ep}, is 75 mm. Therefore, the factor of safety is

$$FS = \frac{L_{ep}}{L_e} = \frac{75.0}{39.5} = 1.90 > 1.0$$

Therefore, the lower impact limiter lifting ring configuration is acceptable for the required loads.

2.5.2 Tie-down Devices

The RT-100 cask utilizes two sets of tie down arms, as shown in Chapter 7, Figure 7.4.4-1. These tie-down arms are welded to two different tie-down plates that in turn are welded to the outer shell of the cask body. Each set of arms on opposite sides of the cask are designed to cross over and securely position the cask, and to absorb the latitudinal, longitudinal and vertical forces required by 10 CFR 71.45 [Ref. 2]. The tie-down arms and plates are a structural part of the package, and must withstand the following loads without impairing the safety of the cask:

- Two (2) times the loaded weight of the cask in the vertical direction
- Ten (10) times the loaded weight of the cask in the direction of travel
- Five (5) times the loaded weight of the cask transverse to the direction of travel

These loads are considered to act simultaneously on the cask and the tie-down arms.

The lifting pockets on the cask body are the only other parts of the cask that could possibly be used to tie down the cask. As such, these pockets are rendered inoperable for tie-down during transport by ensuring that the lift yoke retaining pins are installed in place prior to transport.

2.5.2.1 Tie-down Load Calculation

The maximum forces applicable in each of the three loading directions are calculated in this section. This calculation is accomplished by using the mass of the fully loaded cask along with the gravitational acceleration and the vertical, longitudinal and lateral factors specified in 10 CFR 71.45 [Ref. 2]. The loaded weight of the cask is specified in Chapter 1, Section 1.2.1.2.

Gravitational Acceleration:	$g = 9.81\ m/s^2$
Cask Mass:	M_c = 34696 kg
Payload Mass:	M_p = 7060 kg
Total Mass:	$M = M_c + M_p$ = 34696 kg, assume 42000 kg

Total Weight:	$W = M_g = 412.02$ kN
Vertical Acceleration	$d_v = 2$
Axial Acceleration	$d_a = 10$
Transverse Acceleration	$d_L = 5$
Vertical Load	$P_y = M \times g \times d_y = 824$ kN
Axial Load	$P_a = M \times g \times d_a = 4120.2$ kN
Transverse Load	$P_L = M \times g \times d_L = 2060.1$ kN

2.5.2.2 Tie-down Force Calculation

The geometric configuration of the tie-down system is designed so that the resultant tie-down arm tensile loads are tangent to the cask surface in order to minimize the effects of out-of-plane stresses in the cask shell. Figure 2.5.2-1 and Figure 2.5.2-2 illustrate the details of the tie-down system geometry. Shear stops are utilized to convert some of the cask loads into turning moments that are restricted by the tie-down arms. As shown on drawing RT PE 1001-1Rev. F – Robatel Transport Package RT-100 General Assembly Sheet 1/2 (Chapter 1, Appendix 1.4, Attachment 1.4-2), the tie-down arms have slightly different angles in the front and rear of the casks. These differences are summarized in Table 2.5.2-1. The horizontal angles from the cask body to each arm varies from 40° and 44° on one end of the cask and 37° and 41° on the other.

Table 2.5.2-1 Tie-down Arms Horizontal Angles

Load	Arms in Tension	Angles	Average Angle
Longitudinal	L & M (Rear)	44 and 40	42
	Q & R (Front)	37 and 41	39
Lateral	M & R	40 and 41	40.5
	L & Q	44 and 37	40.5
Vertical	L, M, Q, R	44, 40, 37, 41	40.5

The analytical model for determining the reaction loads required to prevent rotation and translation of the package due to the 10 CFR 71.45 [Ref. 2] applied loads is shown in Figure 2.5.2-1 and Figure 2.5.2-2. The evaluation is bounded by analyzing the high average angle (42°) caused by longitudinal forces on the tie-down arms on the rear of the cask, and the low average angle (32°) caused by longitudinal forces on the tie-down arms on the front of the cask. The shear stop forces at the bottom of the package are represented by the orthogonal components of a single force vector, S, making an angle of γ with the global y-axis. The stresses in the members are determined by considering the component loads (10W, 5W, and 2W) individually and superimposing the results. The geometry of the arms has a slight asymmetry so that the tie downs can cross one another; this slight asymmetry is ignored and average dimensions are used for calculation purposes. A detailed force analysis is conducted using the dimensions and notations shown in the figures; other terms are defined below:

- W: weight of cask, kN
- T_x: tensile force in member 2 and 3 resulting from 5W load, kN
- T_y: tensile force in member 1 and 2 resulting from 10W load, kN

T_z: tensile force in each member resulting from 2W load, kN

$T_{1,2,3,4}$: total tensile force in subscripted member, kN

F_x: total force in the x direction resulting from 5W load, kN

F_y: total force in the y direction resulting from 10W load, kN

L: Effective length of tie-down arm, i.e. distance between tie-down tangent point and center of tie-down attachment eye, mm

The forces are derived in detail in Calculation Package RTL-001-CALC-ST-0202, Rev. 4 [Ref. 34] and are developed via summing the moments about the center of gravity. A summary of the values calculated using Figure 2.5.2-1 and Figure 2.5.2-2 are provided in Table 2.5.2-2. The maximum calculated forces using these values is provided in Table 2.5.2-3. The results show that the front arms with the lower horizontal angle are subjected to the greater forces. The evaluation of the longitudinal loads on the two front tie-down arms bounds the evaluation of all other load conditions on the cask. The tension calculations and safety margin evaluations contained in the following sections focuses on the front tie-down arms.

Unit: mm
R = impace limiter radius = 2587/2
r = cask radius = (2040+60)/2
d = cask C.G. elev. = 1648
t = avg. tie-down eye elev. = 1429
L = total length from the tangent point of the tie-down arm (to the cask body) to the tie-down eye
x' = avg. tie-down eye X axis offset
y' = avg. tie-down eye Y axis offset
z' = cask tangent elev.
a = L cosθ sinϕ
b = L cosθ cosϕ
c = L sinθ

weight	412.02	KN
R	1293.5	mm
r	1050	mm
d	1648	mm
t	1429	mm
L	605	mm
θ	0.514872	rad
φ	0.733038	rad
a	352.3409	mm
b	391.3142	mm
c	297.9163	mm
x'	427.9612	mm
y'	1093.901	mm
z'	1726.916	mm

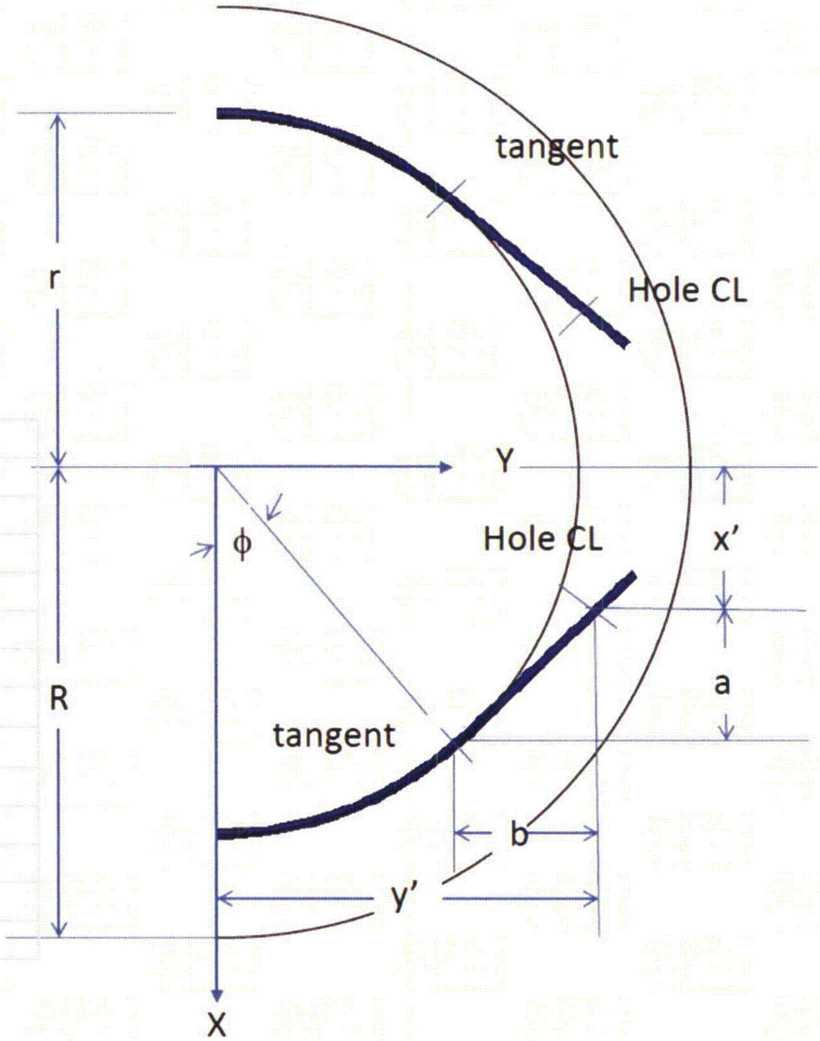


Figure 2.5.2-1 RT-100 Tie-Down Arm Geometry

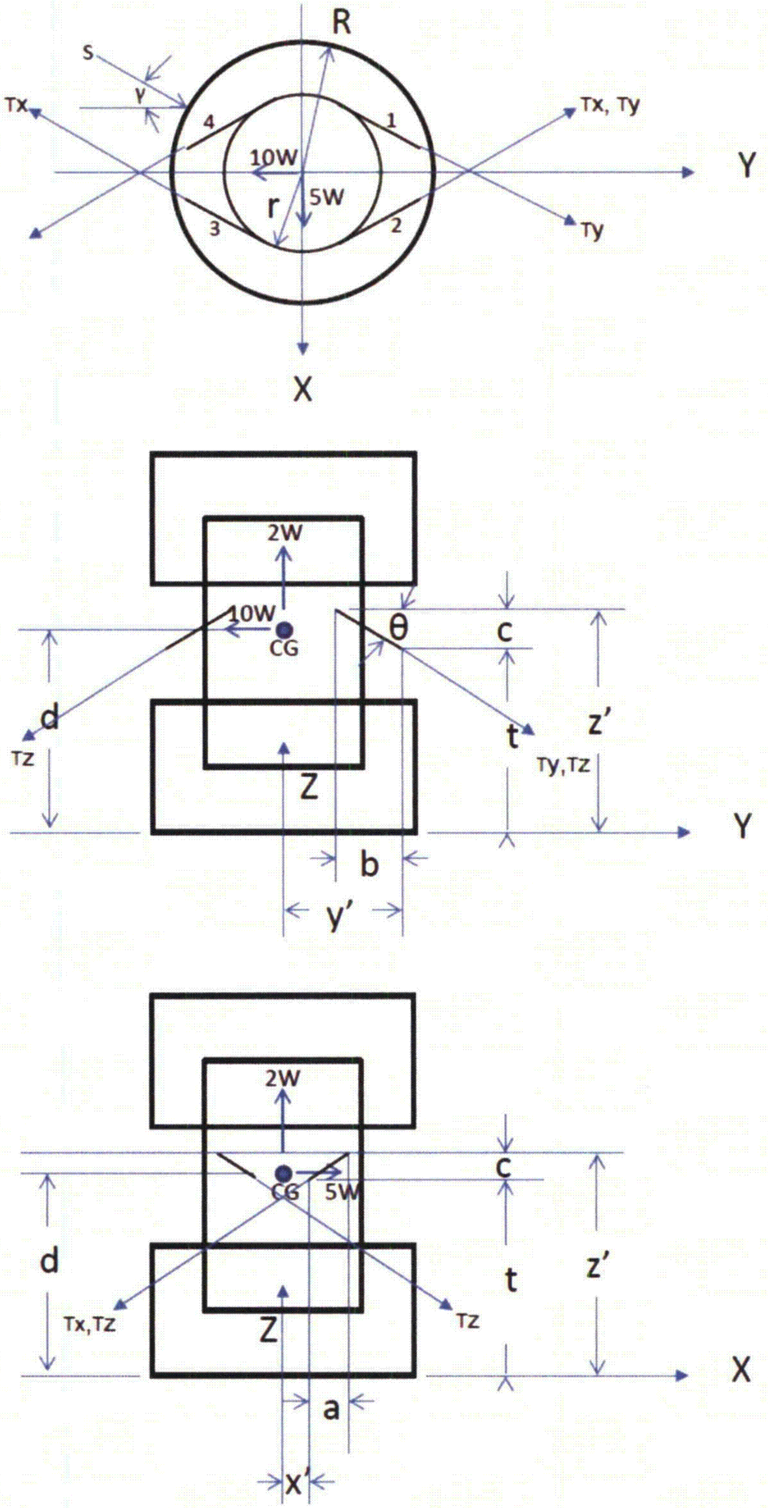


Figure 2.5.2-2 RT-100 Tie-Down Free Body Diagrams

Table 2.5.2-2 Calculated Values for Tie-Down Arms

	Rear Arms		Front Arms	
Φ	(44° & 40°)= > 0.733038	rad	(41° & 37°)= > 0.680678	rad
a	351.47	mm	365.61	mm
b	390.34	mm	451.49	mm
c	297.18	mm	328.69	mm
L	(616 + 591)/2 = 603.5	mm	(682 + 653)/2 = 667.5	mm
x'	451.13	mm	473.71	mm
y'	1113.01	mm	1131.16	mm
z'	1726.18	mm	1757.59	mm

(Note: these values calculated using parameters as defined in Figure 2.5.2-1 and Figure 2.5.2-2)

Table 2.5.2-3 Calculated Forces for Tie-Down Arms

	Rear Arms		Front Arms	
Tx	1361.26	kN	1430.82	kN
Ty	1609.56	kN	1571.40	kN
Tz	418.36	kN	418.36	kN
Tmax	3389.18	kN	3420.58	kN
Fxx	474.56	kN	492.68	kN
Fyy	2038.07	kN	1994.43	kN
Fn	2925.80	kN	2956.73	kN
Ff	146.29	kN	147.84	kN
Sx	204.57	kN	213.28	kN
Sy	953.61	kN	931.10	kN

2.5.2.3 Tie-Down Arm Evaluation

The maximum tie-down arm load of 3420.58 kN is determined as described in Section 2.5.2.2 above. This load is applied to the tie-down arm design to ensure that stresses are within allowable limits. As show in the drawings presented in (Chapter 1, Appendix 1.4, Attachments 1.4-2 through 1.4-8) the tie-down arm is reinforced in the portion containing the attachment hole. This reinforcement ensures that the loads in this area of reduced cross-section can be transmitted safely into the rest of the tie-down arm. Stresses for the tie-down arm and its connection to the exterior cask shell are calculated as follows:

<u>Arm Tension Stress at Hole</u>

Arm Cross-Sectional Area at Hole, A_{net} = 11,450 mm^2

Arm Tension Stress, $\sigma_{net} = T_{max} / A_{net}$ = 298.74 MPa

Stress Allowable, σ_{allow} = 437.2 MPa (@50°C per Table 2.2.1-1)

Factor of Safety, FS = $\sigma_{allow} / \sigma_{net}$ = 437.2 / 298.74 = <u>1.46</u> > 1.0

<u>Arm Bearing Stress at Hole</u>

Arm Bearing Area at Hole, A_{bear}= 7,650 mm^2

Arm Tension Stress, $\sigma_{net} = T_{max} / A_{bear}$ = 447.13 MPa

Stress Allowable, σ_{allow} = 1.35 x 437.2 MPa = 590.2 MPa (@50°C per Table 2.2.1-1) Factor of Safety, FS = σ_{allow} / σ_{net} = 590.2 / 447.13 = 1.32 > 1.0

Arm Tear-Out Stress at Hole
Arm Tear-out Area, A_{tear} = 18,700 mm^2
Arm Tear-out Stress, τ_{tear} = T_{max} / A_{tear} = 182.92 MPa
Tear-out Stress Allowable, τ_{allow} = 0.6 x 437.2 = 262.3 MPa
Factor of Safety, FS = τ_{allow} / τ_{tear} = 262.3 / 182.92 = 1.43 > 1.0

Arm Tension Stress at Main Cross Section
Arm Area, A_{arm} = 9,100 mm^2
Arm Tear-out Stress, σ_{arm} = T_{max} / A_{arm} = 375.89 MPa
Tear-out Stress Allowable, σ_{allow} = 437.2 MPa
Factor of Safety, FS = σ_{allow} / σ_{arm} = 437.2 / 375.89 = 1.16 > 1.0

As shown in the summary above, the stresses in the limiting tie-down arm are below the yield stress allowables.

2.5.2.4 Tie-down Arm & Plate Weld Evaluation

The stresses in the welds attaching the tie-down arms to the tie-down plates and the plates to the cask body are found by applying the loads from the attachment arms to the weld around the perimeter of the plates. The maximum load on the tie-down arm welds are the sum of the loads in two connecting arms. Thus, from inspection of Figure 2.5.2-2, the maximum tie-down arm load is calculated as follows:

Tie-down Arm Weld Force, $F_{total} = 2T_x + T_y + 2T_z$ = 5269.76 kN

Weld axial load	$Fx = F_{total}$ x (b / L) = 3564.43 kN
Weld vertical load	$Fy = F_{total}$ x (c / L) = 2594.96 kN
Weld transverse load	$Fz = F_{total}$ x (a / L) = 2886.42 kN

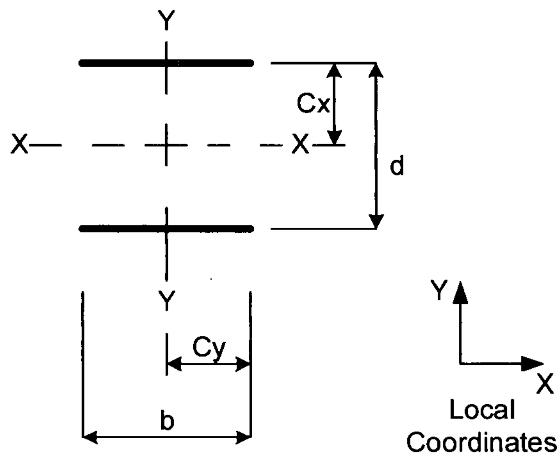
Arm tensile strength:	437.2 MPa
Cask tensile strength:	199.3 MPa
Weld tensile strength:	450 MPa, weld between tie-down arm and plate [Ref. 34]
	420 MPa, weld between tie-down plate and cask [Ref. 34]

The weld length, b, is 1583.36 mm, the weld height "d" for the tie- down arm plate is the 260 mm height of the arm, and weld height "d" for the weld between tie- down plate and cask body is 388.03 mm (Calculation Package RTL-001-CALC-ST-0202 Rev. 4 [Ref. 34]). These dimensions and loads are used in the following weld stress calculations.

2.5.2.4.1 Tie Down Arm-to-Plate Weld Stress

The stresses in the welds attaching the tie-down arm to the tie-down plate are found by applying the weld loads as specified in Section 2.5.2.4. The stresses and allowables are determined as described in "Design of Welded Structures" [Ref. 25] and Calculation Package RTL-001-CALC-ST-0202, Rev. 4 [Ref. 34].

Weld properties are as follows:



$b = 1.583$ m
$d = 0.260$ m
$C_y = b/2 = 0.79$ m
$C_x = d/2 = 0.13$ m
$A_w = 2 \times b = 3.172\ m^3/m$
$S_x = b \times d = 0.41\ m^3/m$
$S_y = b^2/3 = 0.84\ m^3/m$
$J_w = b\,(3d^2 + b^2) / 6 = 0.71\ m^4/m$

Weld Throat Size = 0.022 m

Weld stress is calculated as follows:

$f_t = (F_Z / A_W) + (M_X / S_X) + (M_Y / S_Y) = 911.69$ kN/m
$f_{vy} = (F_Y / A_W) + ((M_Z \times C_Y) / J_W) = 819.63$ kN/m
$f_{vx} = (F_X / A_W) + ((M_Z \times C_X) / J_W) = 1125.85$ kN/m
$f_w = (f_t^2 + f_{vy}^2 + f_{vx}^2)^{1/2} = 1664.49$ kN/m

Weld Allowable Stress = 0.6 x F_w x Weld Size x 1000 = 5940 kN/m

Weld Metal Factor of Safety, FS = 5940 / 1664.49 = 3.56 > 1.0

Tie-Down Arm Shear Allowable = 0.6 x F_w x Weld Size / 0.7071 x 1000 = 8158 kN/m

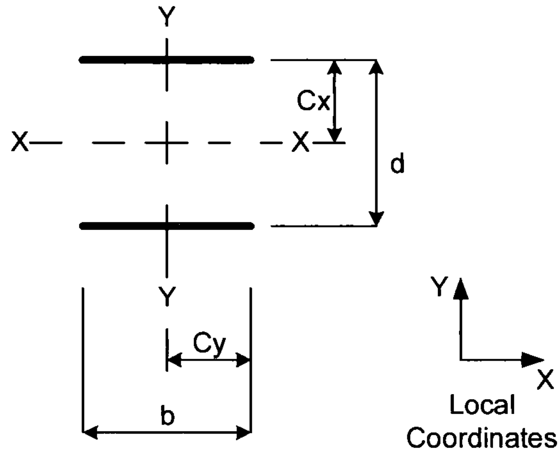
Tie-Down Arm Factor of Safety, FS = 8158 / 1664.49 = 4.90 > 1.0

2.5.2.4.2 Tie Down Plate-to-Outer Shell Weld Stress

The stresses in the welds attaching the tie-down plate to the cask outer shell are found by applying the weld loads as specified in Section 2.5.2.4. The stresses and allowables are determined as described in "Design of Welded Structures" [Ref. 25] and Calculation Package RTL-001-CALC-ST-0202, Rev. 4 [Ref. 34].

Weld properties are as follows:

$b = 1.583$ m
$d = 0.388$ m
$C_y = b/2 = 0.79$ m
$C_x = d/2 = 0.19$ m
$A_w = 2 \times b = 3.172\ m^3/m$
$S_x = b \times d = 0.615\ m^3/m$
$S_y = b^2/3 = 0.84\ m^3/m$
$J_w = b\,(3d^2 + b^2) / 6 = 0.78\ m^4/m$



Weld Throat Size = 0.017 m

Weld stress is calculated as follows:

$f_t = (F_Z / A_w) + (M_x / S_x) + (M_y / S_y) = 911.69$ kN/m

$f_{vy} = (F_y / A_w) + ((M_Z \times C_y) / J_w) = 819.63$ kN/m

$f_{vx} = (F_x / A_w) + ((M_Z \times C_x) / J_w) = 1125.85$ kN/m

$f_w = (f_t^2 + f_{vy}^2 + f_{vx}^2)^{1/2} = 1664.49$ kN/m

Weld Allowable Stress = 0.6 × F_w × Weld Size x 1000 = 4284 kN/m

Weld Metal Factor of Safety, FS = 4284 / 1664.49 = 2.57 > 1.0

Outer Shell Shear Allowable = 0.6 × F_W × Weld Size / 0.7071 × 1000 = 2.875 kN/m

Outer Shell Factor of Safety, FS = 2875 / 1664.49 = 1.73 > 1.0

2.5.2.5 Tie-Down Evaluation Summary

As shown in the previous sections, all components of the tie-down components that are a structural part of the cask maintain positive safety margins when subjected to the simultaneous loadings specified in 10 CFR 71.45 [Ref. 2]. The smallest factor of safety is 1.16 against tie-down arm tension. Under excessive loading, the failure of the tie-down system occurs by yielding in the tie-down arm. This failure does not impair the package's ability to meet other regulatory requirements since the tie-down arms are welded to a plate that is in-turn welded to the cask body. Damage to the tie-down arm does not damage any component integral to the cask body and therefore, does not compromise the cask body shell.

2.6 Normal Conditions of Transport

This Section describes the RT-100 evaluation for the normal conditions of transport specified in 10 CFR 71.71[Ref. 2]. The requirements of 10 CFR 71.71 state that the RT-100 shall be structurally adequate for the following normal conditions of transport:

- Heat
- Cold
- Reduced external pressure

- Increased external pressure
- Vibration
- Water spray, free drop
- Corner drop
- Compression, and
- Penetration.

During the free drop analyses, the cask impact orientation evaluated is the orientation that inflicts the maximum damage to the cask. Also, the requirements of 10 CFR 71.71 [Ref. 2] specify that the evaluation of the RT-100 for the normal conditions of transport be evaluated at the most unfavorable ambient temperature in the range from -29°C to +100°C. The normal conditions of transport evaluations presented in this section show that the package satisfies the applicable performance requirements specified in the 10 CFR 71.71 [Ref. 2]. The scale drop testing and analytical analyses demonstrate that there is no decrease in the RT-100 Cask Package effectiveness as follows:

- No loss or dispersal of contents
- No structural changes reducing the effectiveness of components required for shielding, for heat transfer, or for maintaining subcriticality or containment
- No changes to the package affecting its ability to withstand HAC.

The normal conditions evaluations described in the following sections are performed in accordance with the design criteria and load combinations as identified in Section 2.1.2. Each of the following subsections addresses each normal conditions requirement.

2.6.1 Heat

The RT-100 cask body and closure lids are analyzed for structural adequacy in accordance with the thermal evaluation of the RT-100 for the temperatures specified in 10 CFR 71.71(c)(1) [Ref. 2] is presented in Chapter 3. The thermal evaluation demonstrates that the cask component temperatures are maintained within their safe operating ranges for all normal conditions of transport. The following subsections discuss the structural evaluation of the RT-100 using the appropriate component temperatures as determined in Chapter 3.

2.6.1.1 Summary of Pressures and Temperatures

The pressures and temperatures occurring in the RT-100 as a result of the 10 CFR 71 [Ref. 2] normal conditions of transport thermal conditions are an important consideration for the structural evaluations presented in this chapter. The internal pressure induces stresses on the containment system; the temperatures affect the selection of temperature-dependent material properties as well as, the internal pressures that occur as a result of the ambient temperatures and solar insolation specified in 10 CFR 71.71 [Ref.2]. The material properties utilized are based on the maximum calculate temperatures of each component or higher temperatures which are conservative.

The maximum normal operating pressure evaluation for the RT-100 is presented in Chapter, 3 Section 3.3.2. As described in this section, the calculated maximum pressure for normal

conditions is 182.71 kPa (26.5 psia). For conservatism, the structural evaluations involving internal pressure use a maximum normal operating condition pressure of 342.7 kPa (49.7 psia or 35 psig).

The maximum component temperatures in the RT-100 for normal conditions are presented in Chapter 3, Table 3.1.3-1 "RT-100 Maximum Normal Condition Temperature Summary" (Found in Chapter 3). The temperatures are utilized to determine the stress allowables used in the structural evaluation for the normal conditions of transport.

2.6.1.2 Differential Thermal Expansion

As shown in Chapter 3, Table 3.1.3-1, the temperatures of the components of the cask differ by only a few degrees under normal conditions of transport thermal ambient conditions. This difference is due in part to the relatively low decay heat of the contents. The RT-100 is evaluated for differential thermal expansion as described in Section 2.6.7 in combination with normal pressure and inertial loads under the following conditions:

- Ambient temperature, 38°C
- Initial temperature, 38°C
- Heat transfer to ambient by natural convection, still air
- Heat transfer to ambient by radiation
- Steady-state solar insolation
- Internal heat load as a uniform heat flux, 13.04 W/m^2

2.6.1.3 Stress Calculations

Regulatory Guide 7.6 [Ref. 4] requires that the range of primary plus secondary stress intensities during normal conditions of transport be less than 3.0 S_m. To evaluate this condition, the range of primary plus secondary stresses for the combined normal events (including heat, cold, normal operating pressure, 0.3-m end drop, and 0.3-m side drop conditions) are analyzed using the finite element model presented in 2.6.7.2.

2.6.1.4 Comparison with Allowable Stresses

The combined stress results are presented in Tables 2.6.7-1 and 2.6.7-2. Since the margins of safety are all positive, the RT-100, therefore, satisfies the requirements of 10 CFR 71.71(c)(1) [Ref. 2] for the heat (normal transport) condition.

2.6.2 Cold

The RT-100 cask body and closure lids are analyzed for structural adequacy in accordance with the thermal evaluation of the RT-100 for the temperatures specified in 10 CFR 71.71(c)(2) [Ref. 2] is presented in Chapter 3. The thermal evaluation demonstrates that the RT-100 component temperatures are maintained within their safe operating ranges for all normal conditions of transport. Using the same methodology presented in Section 2.6.1, the RT-100 is evaluated for cold conditions. The following thermal case is used to calculate the thermal stress under cold conditions:

- Ambient temperature, -40°C
- Initial temperature, -40°C

- Heat transfer to ambient by natural convection, still air
- Heat transfer to ambient by radiation
- No solar insolation, in shade
- Internal heat load as a uniform heat flux, 13.04 W/m^2

The combined stress results are presented in Tables 2.6.7-1 and 2.6.7-2. Since the margins of safety are all positive, the RT-100, therefore, satisfies the requirements of 10 CFR 71.71(c)(2) [Ref. 2] for the cold (normal transport) condition.

2.6.3 Reduced External Pressure

The drop in atmospheric pressure to 24 kPa (3.5 psia), as specified in 10 CFR 71.71(c)(3) [Ref. 2], effectively results in an additional internal pressure in the cask of 77 kPa (11.2 psig). This additional pressure has a negligible effect on the RT-100 because, in Section 2.6.1.1, the cask is analyzed for a normal transport conditions internal pressure of 241 kPa (35 psig). Maximum internal pressure is included in combination with internal loads (see Tables 2.6.7-1 and 2.6.7-2). Since the margins of safety are all positive, the RT-100 satisfies the requirements of 10 CFR 71.71(c)(3) for reduced external pressure.

2.6.4 Increased External Pressure

An increased external pressure of 20 psia (5.3 psig external pressure), as specified in 10 CFR 71.71(c)(4) [Ref. 2], has a negligible effect on the RT-100 because of the thick outer shell and end closures of the cask. Section 2.6.7 addresses many different loading cases which exceed these prescribed external pressure requirements. Therefore, the requirements of 10 CFR 71.71(c)(4) [Ref. 4] are satisfied.

2.6.5 Vibration

10 CFR 71.71 (c)(5) [Ref.4] requires that "vibration normally incident to transport" be evaluated. The RT-100 package consists of think section materials that are unaffected by vibration normally incident to transport, such as over the road vibrations.

2.6.5.1 Vibration Evaluation of the RT-100 Cask Primary Lid Bolts

The RT-100 may be subjected to a cycle range typically associated with high-cycle fatigue (> 10^8 cycles). Therefore, the endurance limit of the material for the high cycle fatigue can be approximated by using a 60% reduction, r_h, of the ultimate tensile strength (AISC [Ref. 26]) with an additional 10% reduction r_g, for the connection surface (Machinery's Handbook [Ref. 27]). Thus the endurance limit for the material is:

$$S_a = (1-r_h)\times(1-r_g)\times S_{ub}$$

where:

S_{ub} = Bolt Ultimate Stress

= 1030 MPa (ASTM A354 Grade B, Table 2.2.1-3)

$$S_a = (1 - 0.60) \times (1 - 0.10) \times 1030$$
$$= 370.8 \text{ MPa}$$

NUREG-0128 [Ref. 30] gives the following RMS vibration load factors for the road travel:

f_v = Vertical Vibration Load Factor
= 0.52

f_L = Longitudinal Vibration Load Factor
= 0.27

f_t = Transverse Vibration Load Factor
= 0.19

The RT-100 is transported in the vertical orientation. The cask lid is subjected to vibration in the vertical direction. A notch factor, f_N, of 3.0 is used and is conservative (AISC [Ref. 26]). The vibration stress in the bolts is:

$$s_v = \frac{F_b \times f_N}{A_b}$$

where:

F_b = Bolt Force due to Vibration

$$= \frac{f_v \times W_{Lp} \times g}{N_b}$$

A_b = Bolt Stress Area
= 1470 mm^2 [Ref. 27]

W_{Lp} = Cask Lid Weight
= 3648 kg, use 3650 kg

N_b = Number of Bolts
= 32

$$F_b = \frac{0.52 \times 3650 \times 9.81}{32} \times \frac{1 \text{kN}}{1000 \text{N}}$$
$$= 0.58 \text{ kN}$$

$$s_v = \frac{0.58 \times 3.0}{0.001470} \times \frac{1 \text{ MPa}}{1000 \text{ kN}/\text{m}^2}$$
$$= 1.19 \text{ MPa} \ll S_a = 370.8 \text{ MPa}$$

Since the stress in the bolts is well below the endurance limit of the material, the primary lid bolts are not subjected to transportation-related fatigue damage during their service life.

The maximum shock loading coefficient for the three orthogonal directions is specified as 2.9 (NUREG-0128 [Ref. 30]). The RT-100 primary lid is subjected to shock loading during transport. The primary lid closure bolts are shown to withstand a 125g impact load (Section 2.13.3.3), which is much larger than the 2.9W shock loading during transport. Therefore, the primary lid closure bolts are acceptable for shock loading by comparison.

2.6.5.2 Vibration Evaluation of the RT-100 Cask Secondary Lid Bolts

Per Section 2.6.5.1, the components of the package are in the high-cycle fatigue range (> 10^8 cycles). The endurance limit of the material for the high cycle fatigue for the secondary lid bolts is the same as for the primary lid bolts. The RT-100 lid is subjected to vibration in the vertical direction. A notch factor, f_N, of 3.0 is used and is conservative (AISC [Ref. 26]). The vibration stress in the bolts is:

$$s_v = \frac{F_b \times f_N}{A_b}$$

where:

F_b = Bolt Force due to Vibration

$$= \frac{f_v \times W_{Lp} \times g}{N_b}$$

A_b = Bolt Stress Area

= $817\ mm^2$ [Ref. 27]

W_{Ls} = Cask Lid Weight

= 857 kg

N_b = Number of Bolts

= 18

All other quantities are defined in Section 2.6.5.1

$$F_b = \frac{0.52 \times 857 \times 9.81}{18} \times \frac{1\,kN}{1000\,N}$$

= 0.24 kN

$$s_v = \frac{0.24 \times 3.0}{0.000817} \times \frac{1\,MPa}{1000\,kN/m^2}$$

= 0.89 MPa << S_a = 370.8 MPa

Since the stress in the bolts is well below the endurance limit of the material, the secondary lid bolts are not subjected to transportation-related fatigue damage during their service life.
The maximum shock loading coefficient for the three orthogonal directions is specified as 2.9 (NUREG-0128 [Ref. 30]). The cask primary lid is subjected to shock loading during transport. The secondary lid closure bolts have been show to withstand a 125g impact load (Section 2.12.4.1), which is much larger than the 2.9W shock loading during transport. Therefore, the secondary lid closure bolts are acceptable for shock loading by comparison.

The RT-100 satisfies the requirements for normal vibration incident to transport as required by 10 CFR 71.71(c)(5) [Ref. 2].

2.6.6 Water Spray

Water causes negligible corrosion of the stainless shell of the RT-100. The cask contents are protected in the sealed cavity. A water spray as specified in 10 CFR 71.71(c)(6) [Ref. 2] has no adverse impact on the package. The cask surface temperature specified during the water spray is between 38°C and -29°C. Consequently, the induced thermal stress in the cask components is less than the thermal stresses that occur during the extreme temperature conditions for normal transport. Therefore, the requirements of 10 CFR 71.71(c)(6) [Ref. 2] are satisfied.

2.6.7 Free Drop

The RT-100 is shown to meet the free drop requirements of 10 CFR 71.71 [Ref. 2] through a combination of classic calculations, finite element analyses and scale model drop testing (RTL-001-CALC-ST-0402, Rev. 4 [Ref. 35]). The evaluations include the qualification of the RT-100 cover bolt design for the combined effects of free drop impact force, internal pressures, thermal stress, O-ring compression force, and bolt preload following the methodology of NUREG/CR-6007 [Ref. 10] (Appendix 2.13). The combined effects of inertial loads, internal pressures, and thermal stress are considered for packaging components.

2.6.7.1 Methodology

The RT-100 is designed in accordance with Regulatory Guide 7.6 [Ref. 4]. The design criteria for NCT and HAC are presented in Table 2.1.2-2. Load combinations for the structural analysis of shipping casks for radioactive materials are defined by Regulatory Guide 7.8 [Ref. 3]. The load combinations for all normal and accident conditions and corresponding ASME service levels are shown in Table 2.1.2-1. Material properties used in this evaluation are presented in Section 2.2.1. Stress intensities caused by pressure, thermal expansion, and mechanical loads are combined before comparing to ASME, Section III, Subsection ND [Ref.7] stress allowables, which are listed in Table 2.2.1-3.

2.6.7.2 Finite Element Analysis

The finite element code ANSYS [Ref. 28] is used to generate a three-dimensional model of the RT-100 and to determine its response to normal conditions of transport (NCT) and hypothetical accident conditions (HAC) (Section 2.7.1). Specifically, a one-half (180°) 3D model of the RT-100 inner and outer shells, outer and inner lids, bottom plate and lead shields is constructed using ANSYS [Ref. 28] solid elements. The interaction between components is modeled using gap elements. Stability of the model is assured by using weak springs. Boundary conditions are

applied to the model simulating the loading conditions the cask will experience during normal and accident transport conditions. Pressure loads are applied to the cask inner shell to simulate bounding contents loads and internal pressurization. Thermal stresses are calculated using input temperatures from the NCT thermal analyses. Bolt preloads are applied to represent the bolt torque at the time the cask is readied for shipment. Post-processing is accomplished by linearizing the stress across locations where maximum stresses are calculated. The analyses assume linear elastic behavior of the cask. Therefore, calculated stress intensities are compared to appropriate allowables (Table 2.2.1-1) and the margin of safety is calculated.

2.6.7.2.1 Model Description

Finite element analysis methods are used to perform the stress evaluation of the RT-100 for normal and accident free drop conditions. Each drop condition is analyzed using a three-dimensional finite element model using the computational modeling software ANSYS [Ref. 28]. Figure 2.6.7-1 shows the major components of the RT-100 represented in the model including the inner and outer shells, flange, bottom plate, primary and secondary lids, and closure bolts.

As shown in Figure 2.6.7-1, the model (which corresponds to half (180°) of the cask body) is generated by de-featuring the SolidWorks® solid model used to develop the manufacturing drawings and exporting the model to a .STEP file format. The .STEP file is imported directly into ANSYS [Ref.28] where the finite element model is developed following the guidance presented in ISG-21 [Ref. 53]. The resulting finite element model of the cask body is represented using solid elements, contact elements, mass elements and spring/damper elements (Figure 2.6.7-2).

The solid portion of the model is constructed using ANSYS solid (SOLID185) elements. Surface-to-surface contact elements are used to simulate the interaction between adjacent components. Specifically, contact between the cask shells and lead shielding are modeled using CONTAC174/TARGE170 surface-to-surface contact elements with zero friction, which allows the lead to float between the inner and outer shells. Contact elements are also used to bond dissimilarly meshed components. To simulate the impact limiters, the interaction between the cask body and impact limiters is modeled using CONTAC52 gap elements (Figure 2.6.7-3), which acts as a compression only element. The size of the CONTAC52 gaps is determined from nominal dimensions between the impact limiter and cask body. Spring elements (COMBIN14) are inserted automatically during the solution to help stabilize the model. ANSYS [Ref. 28] assigns low spring stiffness so their presence does not adversely affect the accuracy of the solution.

Finite element model verification and mesh density study are presented in Appendix A.4 of Calculation Package RTL-001-CALC-ST-0402, Rev. 4 [Ref. 35]. During the development of the finite element model each part and interface was considered on an individual basis. The RT-100 outer shell was meshed using the sweep method and the element size was varied until there was a sufficient number of elements across the shell thickness. The element ratio was reviewed to ensure adequate results. To test a component, in this case the outer shell, the ends were fixed and a pressure load was applied to the inner surface and a solution was obtained. If a singularity or discontinuity was noted, the mesh was refined until uniform results were obtained. As a second check, a hand calculation was performed on to ensure that the stress calculated by ANSYS

[Ref. 28] is giving expected results. Hoop stresses were also calculated and compared to the results. As the model was developed the same philosophy was applied to the intersection of the shell and bottom plate. Using Roark's equations ("Roark's Formulas for Stress and Strain" [Ref. 29]), the interface stress was checked to ensure the bending stress was in the expected range.

The choice of element type was evaluated by running a series of sensitivity studies. For this case, a high order 8-node brick element was chosen over brick element with mid-side nodes. This choice was made because of the relatively thin section of the RT-100 shell versus the length, which made it possible to increase the total number of elements without compromising the run time performance. Several cases were run to vary the total mesh density to see how the stress results varied versus performance of the model. In the extreme case, an overly dense mesh produced excessively long run times and un-converged solutions. Models with low mesh densities that were too low resulted in unrealistic stress results. After numerous runs a balance was found between consistent results and model performance with variations in stress results of less than 1% when comparing high mesh densities to adequate mesh densities. Therefore, it was concluded that the cask model was a quality model and met the intent of ISG-21 [Ref. 53].

At the time the analyses were performed, analyses were generally compared to models previously generated for other 10 CFR 71 [Ref. 2] cask designs. The results of the RT-100 cask analysis are consistent with these previous designs and where peak stress are expected. Additionally, confirmatory scale model testing of the RT-100 demonstrated that the methods used to calculate the cask accelerations and impact limiter deformation are consistent with the drop test results. Therefore, the inertial loads applied to the cask body are conservative.

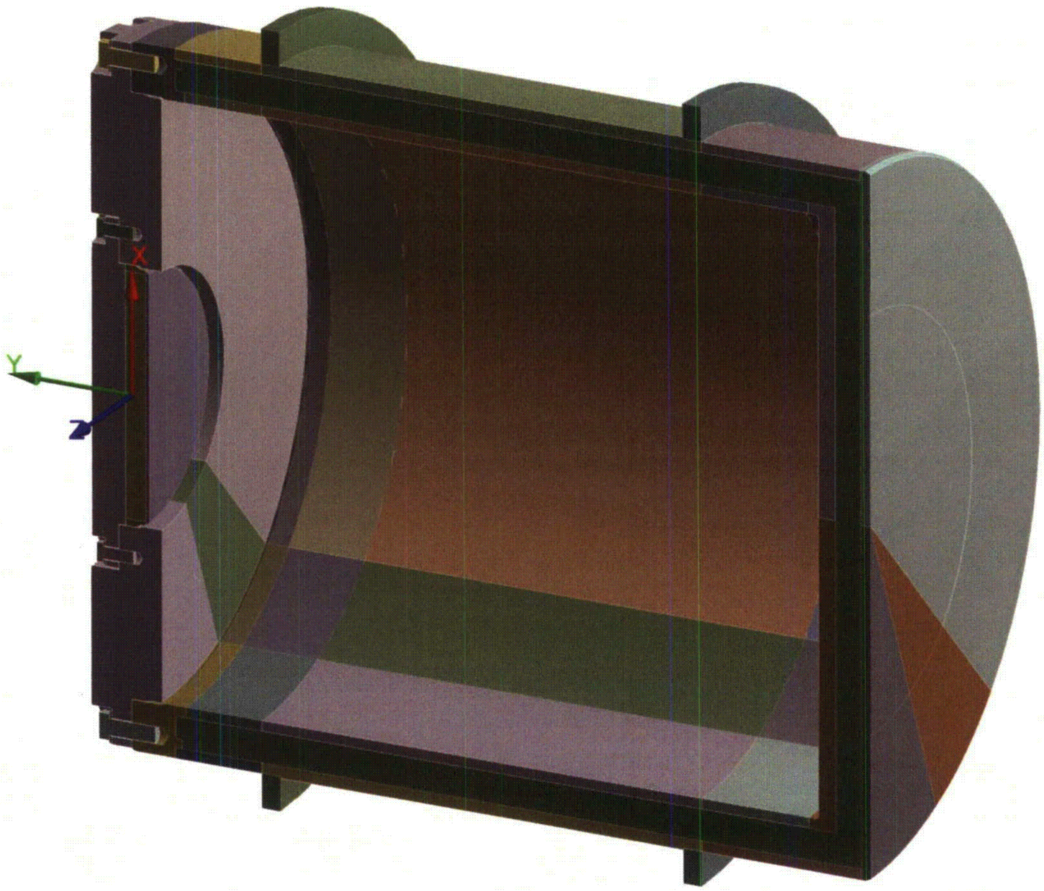


Figure 2.6.7-1 RT-100 Solid Model

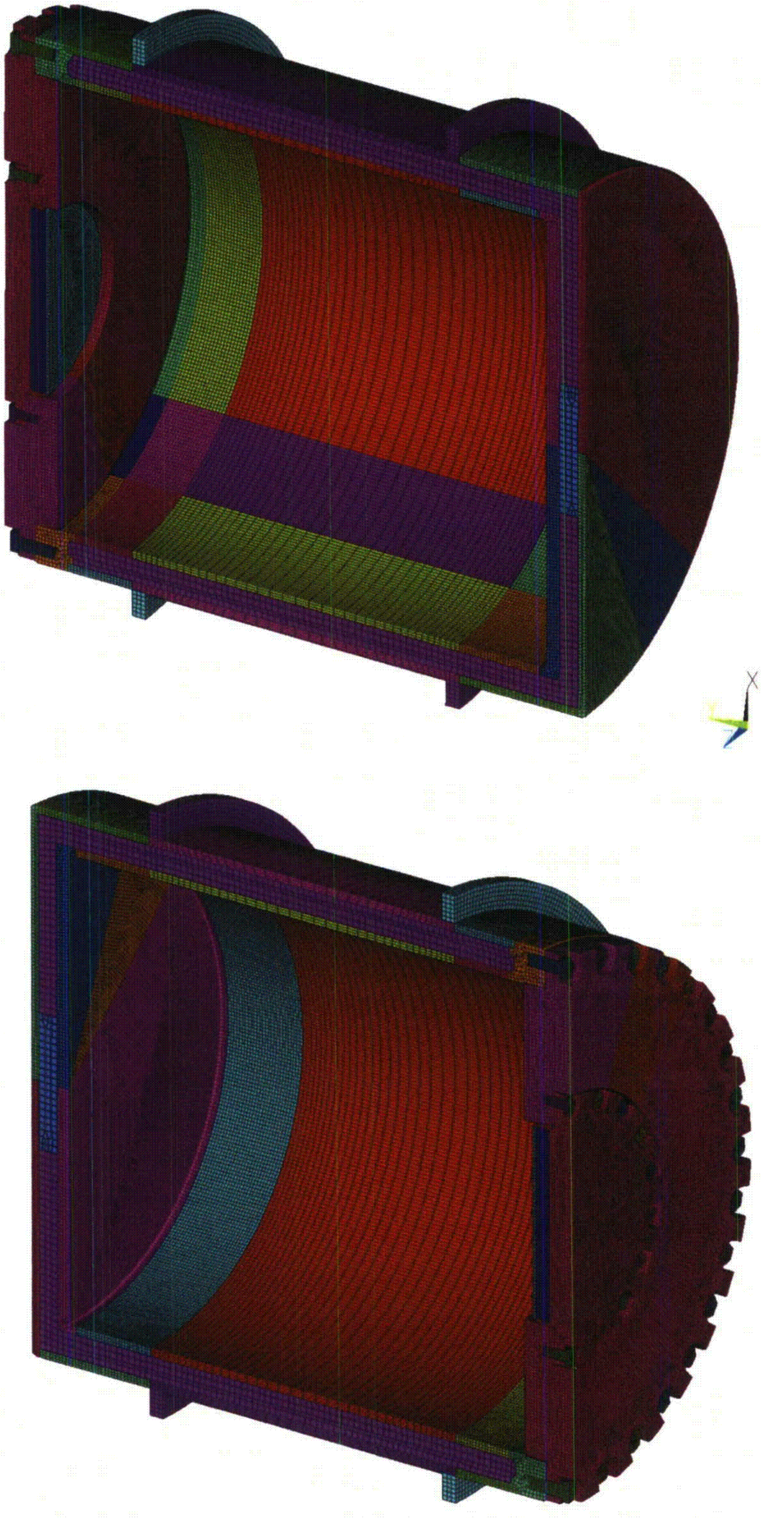


Figure 2.6.7-2 RT-100 Finite Element Model

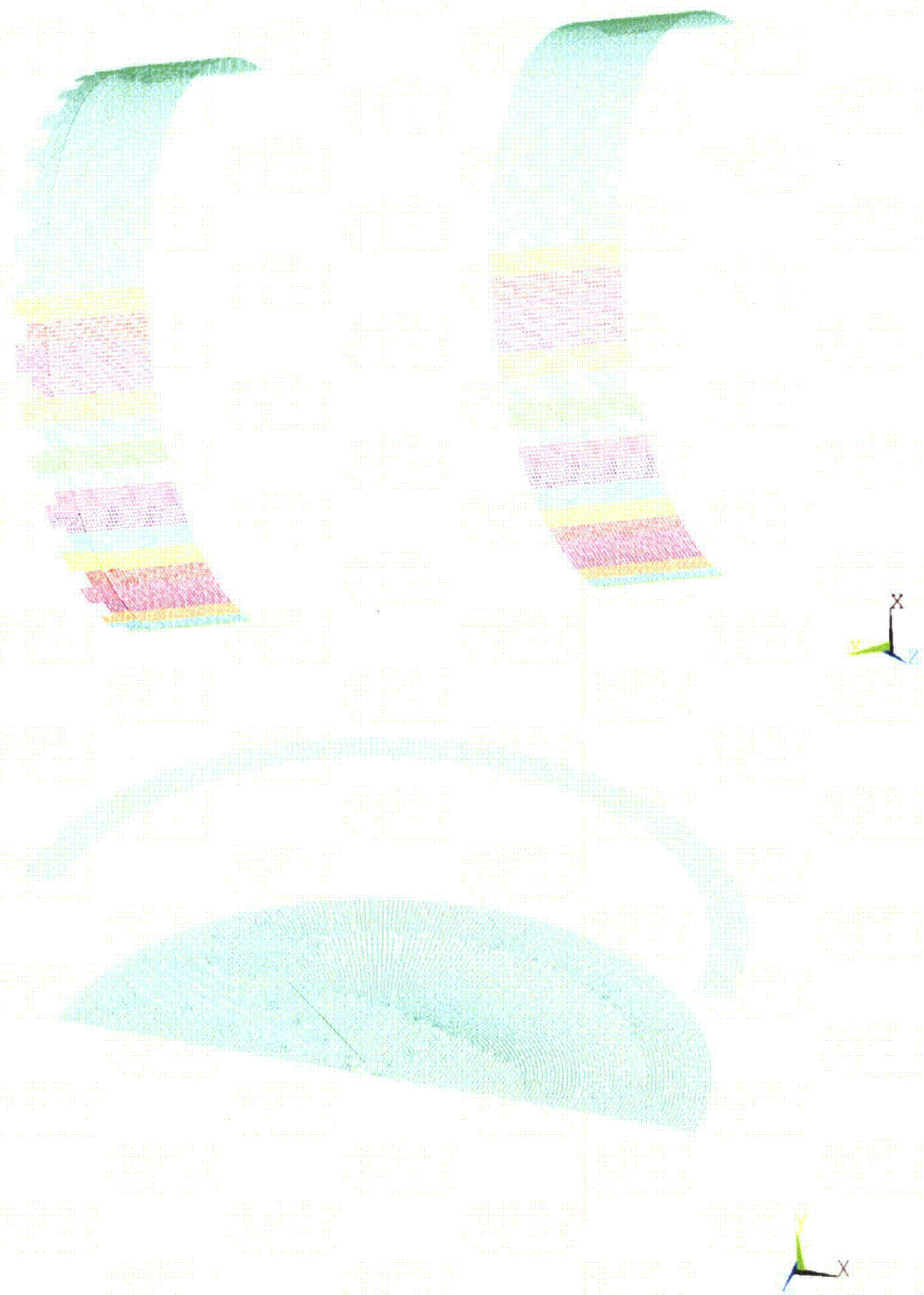


Figure 2.6.7-3 Gap Elements Used to Represent the Impact Limiters for Side and End Drop Configurations

2.6.7.2.2 Boundary Conditions

Boundary conditions are applied to the model to simulate the loading conditions the RT-100 experiences during NCT and HAC. The five categories of cask loading considered in the free drop event are closure lid bolt preload, internal pressure load, thermal load, inertial body load and displacement.

- Closure Lid Bolt Preload: The required total bolt preloads on the cask outer and inner lid bolts are 130.6 kN and 72.2 kN, respectively (10). To apply the bolt preload ANSYS [Ref. 28] pre-tension elements (PRETS179) are used to define the 3-D pre-tension section within the meshed bolt. The PRETS179 element uses a single translation degree of freedom to define pretension direction (Figure 2.6.7-4). The pretension Section is modeled by a set of pretension elements defined by the bolt shaft.

- Pressure Loading: A pressure of 241 kPa (35 psig) is used to envelope the maximum normal operating pressure for all impact loadings considered (Calculation Package RTL-001-CALC-TH-0102, Rev. 6 [Ref, 42]). For accident conditions, a pressure value of 588 kPa (85.3 psig) is used to represent the pressure experienced during fire conditions (Calculation Package RTL-001-CALC-TH-0202, Rev. 6 [Ref. 43]). The internal pressure load is applied as an equivalent static pressure load uniformly applied on the interior surface of the cask.

- Pressure loading contents—cask end drop: For the end drop analyses, the content weight is assumed to be uniformly distributed on the cask end and over an area determined by the inside diameter of the RT-100. Therefore, one-half the contents weight of 6,804 kg (15,000 lb) is applied to the cask inner shell bottom plate. The contents pressure load is multiplied by the appropriate g-load to accurately represent the 304.8 mm (1-foot) and 9144 mm (30-foot) end drop. The pressure value is conservatively multiplied by 1.05 to account for the difference between the solid model surface and the tessellated area of the element mesh.

- Pressure loading contents—side drop: For the side drop condition, the contact area between the contents and the cask cavity is approximately 180° (90° on each side of the drop centerline). The inertial load produced by the 6,804 kg (15,000 lb) contents weight is represented as an equivalent static pressure applied on the interior surface of the RT-100. The pressure is uniformly distributed along the cavity length and is varied in the circumferential direction as a cosine distribution. The pressure value is conservatively multiplied by 1.05 to account for the difference between the solid model surface and the tessellated area of the element mesh. The maximum pressure occurs at the impact centerline; the pressure decreases to zero at locations that are 90° either side of the impact centerline, as illustrated in Figure 2.6.7-5. The following formula is used to determine the contents pressures for the side drop analyses, which

vary around the circumference.

This method uses a summation scheme to approximate the integration of the cosine-shaped pressure distribution:

$$F_{total} = \sum_{i=1}^{18} P_{max} A_i \cos(\theta_i) \cos(\theta'_i)$$

$$F_{total} = 6{,}804/2 \text{ kg}$$

Where

P_{max} = maximum pressure (at impact centerline)
θ_i = average angle of subtended arc of i^{th} element measured from centerline at point of impact to obtain vertical component of pressure
i = i^{th} circumferential sector
θ'_i = normalized angle to peak at 0° and to be zero at 90°
A_i = i^{th} circumferential area over which the pressure is applied

Gap elements are defined at both ends of the cask to simulate the pressure applied by the impact limiters during side drop conditions. This is accomplished by defining the gap stiffness as a cosine function from a maximum value 175×10^6 N/m (1×10^6 lb/in) at the center line to 15.3×10^6 N/m (87,156 lb/in) at 85° from the center line of impact, and a minimal value 175×10^3 N/m (100 lb/in) from 90° to 180°. The load distribution that results from the crushing of the impact limiter is shown in Figure 2.6.7-3.

- Thermal: According to Regulatory Guide 7.8 [Ref. 3], four credible thermal conditions must be considered

Condition 1 – Hot Case 1:

a. Ambient temperature, 38°C
b. Initial temperature, 38°C
c. Heat transfer to ambient by natural convection, still air
d. Heat transfer to ambient by radiation
e. Steady-state Solar insolation
f. Internal heat load as a uniform heat flux, 13.04 W/m^2

Condition 2 – Hot Case 2:

a. Ambient temperature, 38°C
b. Initial temperature, 38°C
c. Heat transfer to ambient by natural convection, still air
d. Heat transfer to ambient by radiation
e. No solar insolation, in shade
f. Internal heat load as uniform heat flux, 13.04 W/m^2

Condition 3 – Cold Case 1:

a. Ambient temperature, -40°C
b. Initial temperature, -40°C
c. Heat transfer to ambient by natural convection, still air
d. Heat transfer to ambient by radiation
e. No solar insolation, in shade
f. Internal heat load as a uniform heat flux, 13.04 W/m^2

Condition 4 – Cold Case 2:

a. Ambient temperature, -29°C
b. Initial temperature, -29°C
c. Heat transfer to ambient by natural convection, still air
d. Heat transfer to ambient by radiation
e. No solar insolation
f. Internal heat load as a uniform heat flux, 13.04 W/m^2

Heat Conditions 1 and 3 bound the differential the worst case thermal expansion between dissimilar materials. Therefore, Heat Conditions 2 and 4 are not considered.

The cask temperature distributions calculated for Conditions 1 and 3 are used as inputs to the ANSYS [Ref. 28] analyses. The ANSYS analyses determine the stresses arising from the thermal expansion of the cask from its initial 21°C condition, including the effects of the differential thermal growth within the components; these effects are a result of the temperature difference across the cask walls. The cask temperature distributions are also used to determine the values of the temperature-dependent material properties.

The temperatures for the structural analysis are obtained from the results file and database file of the thermal analysis by writing the results to an ASCII file using the ANSYS BFINT command. Nodes for the structural model are transferred to the same coordinate system as used by the thermal run and the thermal results are interpolated for each thermal condition.

- Inertial body load: The inertial effects, which occur during impact, are represented by equivalent static forces, in accordance with the D'Alembert's principle. The inertial body load includes the weight of the empty cask and the weight of the cavity contents. Accelerations are calculated in Appendix 2.13. An acceleration of 44g and 52g are applied to the model to simulate end drop and side drop conditions, respectively. The inertial load is applied to the cask body using the ANSYS ACEL command equivalent to the normal and accident conditions accelerations corresponding to the 0.3 meter and 9 meter drop cases. Since the lead shield is attached to the steel shells with frictionless contact elements, the lead represents the largest physical load applied to the cask structure.

- Displacement boundary conditions: Displacement boundary conditions are applied to enforce symmetry at the cut boundary of the 3D model. All nodes on the symmetry plane are fixed in the UZ direction. The overall model is stabilized by the gap elements (CONTAC52) that represent the impact limiter, which are connected to the cask body with the outer nodes or "ground" nodes representing the impact limiter fixed.

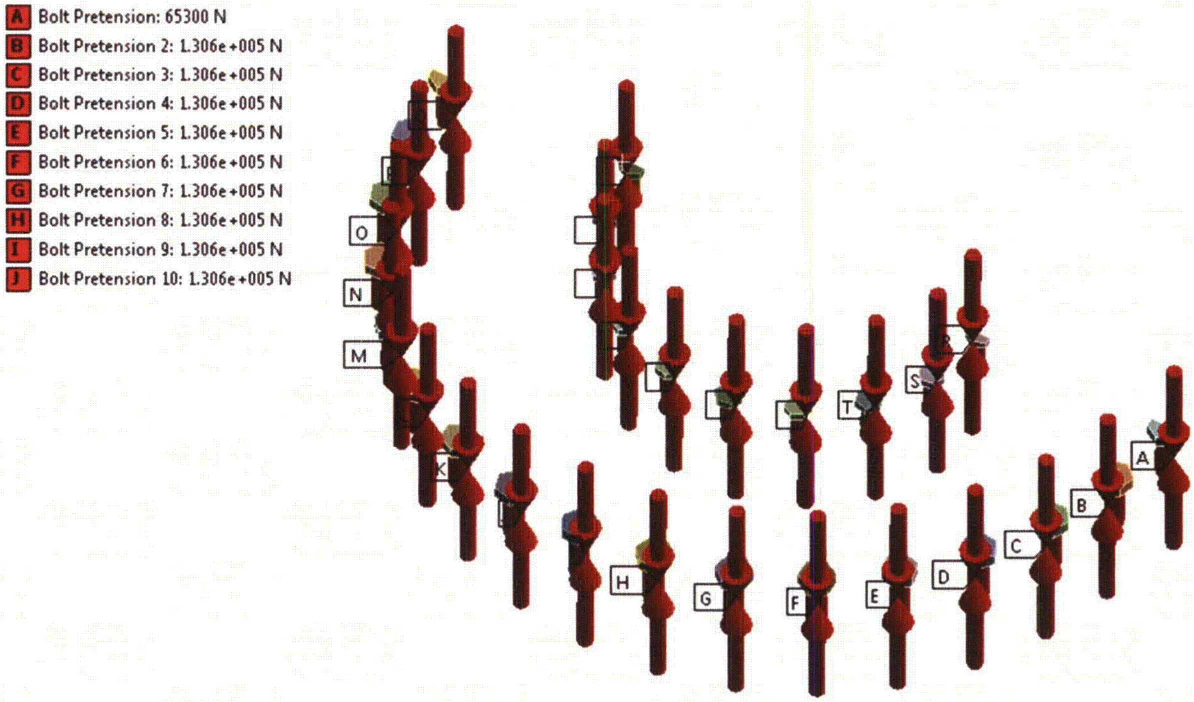


Figure 2.6.7-4 Bolt Pre-load Using ANSYS Pre-Tension Elements (PRETS179)

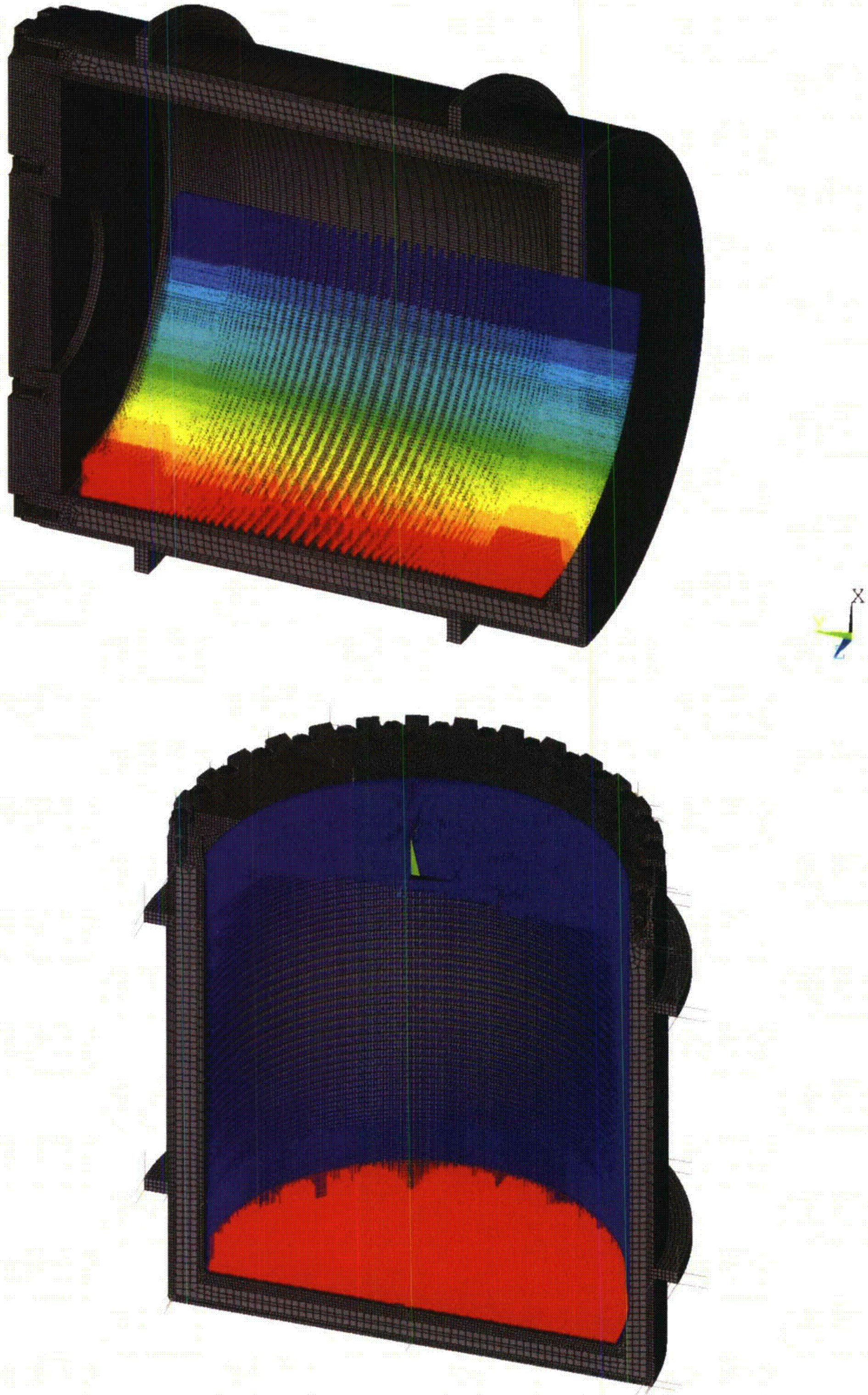


Figure 2.6.7-5 Pressure Distribution Used to Simulate the Contents