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# Model 2000 Radioactive Material Transport Package Safety Analysis Report

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# ACRONYMS

| Term | Definition |
|---|---|
| 3D | Three-Dimensional |
| ALARA | As Low As is Reasonably Achievable |
| Amb. | Ambient |
| ANSI | American National Standards Institute |
| APDL | ANSYS Parametric Design Language |
| ASME | American Society of Mechanical Engineers |
| ASNT | American Society for Nondestructive Testing |
| ASTM | American Society for Testing and Materials |
| Aux. | Auxiliary |
| B&PVC | Boiler and Pressure Vessel Code |
| CFR | Code of Federal Regulations |
| C.G. | Center of Gravity |
| CSI | Criticality Safety Index |
| DOF | Degree-of-Freedom |
| $\dot{D}\dot{R}$ | Dose Rate per unit Mass |
| DU | Depleted Uranium |
| EALF | Energy of Average Lethargy Causing Fission |
| EPDM | Ethylene Propylene Diene Monomer |
| FEA | Finite Element Analysis |
| GE | General Electric |
| GEH | GE-Hitachi Nuclear Energy Americas, LLC |
| HAC | Hypothetical Accident (Transport) Conditions |
| HEPA | High Efficiency Particulate Air |
| HPI | High Performance Insert |
| H/X | Moderator to Fissile Material Ratio |
| IAEA | International Atomic Energy Agency |
| ID | Inner Diameter |

| Term | Definition |
|---|---|
| MCNP | Monte Carlo N-Particle |
| MS | Margin of Safety |
| MSLD | Mass Spectrometer Leak Detector |
| NBS | National Bureau of Standards |
| NCT | Normal Conditions of Transport |
| NDE | Nondestructive Examination |
| Nom. | Nominal |
| NPT | National Pipe Taper (Thread) |
| NRC | Nuclear Regulatory Commission |
| O&M | Operations and Maintenance |
| OD | Outer Diameter |
| OR | Outer Radius |
| PNNL | Pacific Northwest National Lab |
| QAP-1 | GEH Quality Assurance Program |
| SF | Spontaneous Fission |
| S/N | Serial Number |
| SNM | Special Nuclear Material |
| SS | Stainless Steel |
| Std. | Standard |
| TCC | Thermal Contact Conductance |
| UNC | Unified Coarse |
| U.S. | United States |
| USL | Upper Subcritical Limit |

# 1 GENERAL INFORMATION

## 1.1 Introduction

The Model 2000 Radioactive Material Transport Package was developed at Vallecitos Nuclear Center. The primary use of the packaging is to provide containment, shielding, impact resistance, criticality safety, and thermal resistance for its contents during normal and hypothetical accident conditions. The packaging is designed to transport Type B quantities of radioactive materials and fissile materials in solid form. It complies with the Nuclear Regulatory Commission (NRC) regulations contained in the Code of Federal Regulations, Title 10, Part 71 (10 CFR 71) (Reference 1-1). The package is to be shipped in all modes of transportation, except air. The Model 2000 Transport Package may only be shipped exclusive use. The number of packages per shipment is determined in accordance with the package/content Criticality Safety Index (CSI), which is 50.

Calculations, engineering logic, and all related documents that demonstrate compliance with regulations are presented in subsequent sections of this report.

The GEH Quality Assurance Program (QAP-1) (Reference 1-2) controls design, purchase, fabrication, handling, shipping, storing, cleaning, assembly, inspection, testing, operation, maintenance, repair and modification of the packages. The NRC has approved QAP-1 under docket number 71-0171 upon demonstration that the QA plan meets the requirements of Subpart H of 10 CFR 71.

## 1.2 Package Description

The Model 2000 Transport Package, shown in Figure 1.2-1, is transported exclusive use, in the upright position. The approximate overall packaging dimensions are 131.5 inches in height and 72 inches in diameter. The approximate total weight of the package (packaging plus the contents) is 33,550 lb. Table 2.1-3 shows the breakdown of the component weights for the Model 2000 Transport Package.

The Model 2000 Transport Package and contents are described below:

Packaging

- Cask
- Overpack

Contents

- High performance insert (HPI)
- HPI material basket
- Solid radioactive and fissile materials

### 1.2.1. Packaging

#### 1.2.1.1. Cask

The cask body (the containment vessel), shown in Figure 1.2-2, is constructed of two concentric, 1-inch thick stainless steel (SS) SS304 cylindrical shells (ASTM A240 / ASME SA 240). The shells are joined at the bottom end by a type SS304 forging (ASTM A182 / ASME SA 182). A SS304 forging connects the cask shell and cavity shell at the top end of the cask. This flange is part of the cask lid sealing joint and has an electropolished finish on the sealing surface. The annulus between the two shells is approximately 4 inches thick and filled with lead. The cask body height is approximately 71 inches and the outer diameter (OD) is approximately 38.5 inches. The cavity is approximately 26.5 inches in diameter and 54 inches deep.

The cask lid is made of SS304 and lead. It has a stepped design and is fully recessed into the cask top flange. The lid sealing surface is on the underside of the top flange and has an electropolish finish. The cask lid seal is composed of four rings of contoured [[ ]] material (two on the top and two on the bottom) bonded to a [[ ]]-inch thick metal retainer with an OD of 34 inches. The area between the inner and outer seal is designed to permit flow for a seal test port to verify leak-tightness of the package by evaluating the performance of the inner seal. The cask lid [[ ]] and metal retainer material designs are based on two content decay heat configurations; see Table 1.2-1. Configuration 1 is evaluated to support 1500 W decay heat, and Configuration 2 is evaluated to support 3000 W decay heat. The cask lid seal for Configuration 1 is a [[ ]] retainer with four Parker Compound No. [[ ]] rings. The cask lid seal for Configuration 2 is a [[ ]] retainer with four Parker Compound No. [[ ]] rings. The material specifications are included in Section 1.3.2.1. The cask lid is secured to the cask body by fifteen (15) 1¼-inch diameter socket head screws.

The cask has three penetrations. Only two of the three penetrations are within the cask containment boundary. They include: the drain and vent ports for the cask cavity. The drain port hole leads from the center of the cavity bottom out the side of the outer shell. The vent port line spirals through the cask lid near the cask centerline. The third penetration, that is not within the containment boundary, is the test port, which is used to test the adequacy of the seal joint after the cask body and lid are assembled. The test port path leads from the side of the top forging to the region between the inner and outer seals and is sealed in the same manner as the other penetrations.

All of the cask port seals are composed of ½ National Pipe Taper (NPT) thread socket head pipe plugs, followed by an exterior plug cover with O-ring to seal the port. The plug cover and O-ring provide a backup seal to the pipe plug, and they are not considered part of the containment boundary. The O-ring [[ ]] is designed based on the content decay heat; see Table 1.2-1. For Configuration 1, the material is an [[ ]] compound. For Configuration 2, the material is Parker Compound No. [[ ]].

The cask body utilizes attachment plates for lifting devices that are detached during transport and rendered inoperable. There are three types of lifting devices use in the Model 2000 cask: (1) standard ears used for crane and fork truck handling; (2) auxiliary ears used for crane only

handling; and (3) optional ears that function as a trunnion. Except for these devices, there are no other devices or features of the cask that could be used for lifting the package, once the cask is within the overpack.

#### 1.2.1.2. Overpack

The cask is positioned inside a protective overpack, shown in Figure 1.2-3, for transport. The overpack is constructed of two 0.5-inch thick SS304 concentric cylindrical shells (ASTM A240/ASME SA 240), which are separated radially by eight equally spaced tubes along the length of the shells, and by two tube sections around the perimeter of the shells. A toroidal shell impact limiter made of SS304 is attached to each end of the overpack shells. The overpack opens just above the lower impact limiter for access to the cask. The top section of the overpack is joined to the base by fifteen (15) $1^{3}/_{8}$-inch diameter shoulder screws. Gussets on the top and bottom impact limiters provide tie-down points for the package.

Additional impact protection is provided by aluminum honeycomb impact absorbers permanently positioned on the inside of the overpack at the top and bottom ends of the cask.

The cask sits on a 0.5-inch thick, 42-inch diameter plate called the cask support plate. It features eight square cross-section prongs welded to the plate perimeter to ensure cask concentricity within the overpack. The cask support plate material of construction is SS304; however, there are two cask support plate options. One option is solid SS304, while the other option includes a tungsten insert.

### 1.2.2. Contents

#### 1.2.2.1. High Performance Insert

The Model 2000 Transport Package is equipped with a high performance insert (HPI), shown in Figure 1.2-4, to increase the shielding capability of the package. The HPI is [[ ]] inches tall and [[ ]] inches in diameter. The cavity is approximately [[ ]] inches in diameter and [[ ]] inches deep. The HPI body consists of [[ ]] inch SS concentric cylindrical shells. The annulus between the two shells is filled with [[ ]]-inch thick depleted uranium. The HPI body is positioned in the cask cavity by [[ ]] to provide uniform support. The [[ ]] are joined together by [[ ]] arms that function as the primary lifting fixture. The HPI body assembly is completed with the addition of ASME [[ ]] at each end of the cylindrical sub-assembly.

Closure of the HPI is provided by top and bottom [[ ]] joined to the ASME [[ ]]. The bottom [[ ]] is a stepped design comprised of a [[ ]]-inch circular [[ ]] plate and a [[ ]]-inch thick depleted uranium cylinder encapsulated by a [[ ]]-inch [[ ]] shell. Holes are machined in the [[ ]]-inch circular plate to align with the ASME [[ ]] on the HPI body. The bottom [[ ]] is attached to the bottom [[ ]] with [[ ]] screws and [[ ]]. The top plug is a stepped design comprised of a [[ ]]-inch depleted uranium cylinder encapsulated by a [[ ]] inch [[ ]] shell. To facilitate lifting of the top plug, [[ ]] hoist rings are recessed into the [[ ]] inch [[ ]] circular plate. The top plug is held in position by [[ ]]. Attachment of the

top and bottom [[ ]] does not produce a pressure boundary. Grooves are cut into the surface of the plugs to allow moisture to escape during the vacuum drying process.

#### 1.2.2.2. HPI Material Basket

The material basket is shown in Figure 1.2-5 with an example of supplemental dunnage. The material basket is constructed of [[ ]], which form a [[ ]] pattern and are identified as Item 1 on Drawing 001N8424. See Figure 1.2-6 for material basket details. The outer [[ ]] of the material basket form a composite section with the addition of [[ ]] with [[ ]]. The center location of the material basket is a developed cell, which is created by the surrounding [[ ]]. To allow for the proper insertion of supplemental dunnage and facilitate fabrication, [[ ]] are inserted at the top and bottom of the developed cell and are identified as Item 2 on Drawing 001N8424. Therefore, the exterior view of the material basket shows [[ ]] locations. [[ ]] circular [[ ]] facilitate loading and positioning of the material basket within the HPI cavity. Parts List 001N8424G001 is provided in Section 1.3.

#### 1.2.2.3. Radioactive Material Contents

The Model 2000 Transport Package is designed to transport Type B quantities of radioactive materials and fissile materials. This may include irradiated fuel rods, irradiated hardware and byproducts, Co-60 isotope rods, or special nuclear material (SNM). The following are requirements for all shipments:

a) The maximum quantity of material per package shall not exceed 5,450 lb, including all cask internals and contents.
b) All contents shipped shall be in solid form.
c) All configurations require the use of the HPI.
d) All contents shall be shipped in Configuration 1 or Configuration 2 depending on decay heat. The decay heat limits for shipping Configuration 1 and Configuration 2 are outlined in Table 1.2-1. See content specifics below as to whether a content configuration requires the use of the HPI material basket.

**Table 1.2-1. Model 2000 Transport Package Shipping Configurations**

| Configuration | Material Basket | Minimum Decay Heat (W) | Maximum Decay Heat (W) |
|---|---|---|---|
| 1 | Optional | 0 | 1500 |
| 2 | Required | 500 | 3000 |

The specific radioactive and fissile material contents transported in the Model 2000 cask are:

1. Irradiated Cut or Segmented Fuel Rods
    a. Must be shipped in the upright position and confined within a shoring device demonstrated to withstand both NCT and HAC.
    b. U-235 equivalent mass up to 1750 grams, with initial enrichment up to 6 wt% U-235.
    c. The active fuel length of any segment must be at least 10 inches.
    d. Burnup up to 72 GWd/MTU.
    e. Equivalent pellet diameter greater than 0.157 inch (0.4 cm).
    f. Minimum cooling time of 120 days.
    g. Refer to loading table provided in Section 7.5.1.
    h. CSI = 50.
2. Irradiated Hardware and Byproducts
    a. Irradiated hardware components composed of stainless steels, carbon steels, nickel alloys, and zirconium alloys.
    b. Irradiated byproducts such as control rods and/or blades composed of hafnium and boron carbide.
    c. Minimum decay time shall be at least 30 days prior to shipment.
    d. Refer to loading table provided in Section 7.5.2
3. Cobalt-60 Isotope Rods
    a. Must be shipped in the upright position and confined per 3.b and demonstrated to meet NCT.
    b. Content shall be in the form of pellets or cylindrical solid rods with the source(s) evenly distributed and encapsulated in normal or special form.
    c. Rod [[ ]] peak activity concentration ≤ 17,000/N Ci, where N is the number of rod [[ ]] loaded into a single shipment.
4. Special Nuclear Material
    a. U-235 equivalent mass up to 430 g. The U-235 equivalent mass is determined by U-235 mass plus 1.63 times Pu-239 mass, 2.87 times Pu-241, and 1.37 times U-233 mass. The content may contain other uranium and plutonium isotopes.
    b. CSI = 50.

Shipment of combined contents is allowed except that SNM and irradiated fuel cannot be combined.

### 1.2.3. Special Requirements for Plutonium

All contents in the Model 2000 Transport Package are in solid form. Thus, any plutonium in excess of 0.74 TBq (20 Ci) per package shall be in solid form.

### 1.2.4. Operational Features

The Model 2000 Transport Package description in Section 1.2.1 shows that the packaging is not a complex system. There are no valves or items that require specialized knowledge for proper

operation, and cooling is provided through natural convection and radiation. Two cask lid alignments pins aid in seal alignment during installation, and only normal practices for seal handling (e.g., cleanliness) are required.

The Model 2000 Transport Package operation is described in Chapter 7. The loading operation is a dry or wet-loaded operation. If wet-loaded, the cask and cask internals contain features to allow easy drainage of water for underwater loading. To vacuum dry the cask, its cavity pressure is reduced below the vapor pressure of water and maintained at or below this pressure level for a period of time.

Content shoring may include components such as the rod [[ ]] holders shown in Figure 1.2-5. This example shoring is designed to fit into the HPI material basket (Drawing 001N8424), but other shoring components may be placed directly into the HPI cavity (Drawing 001N8423). The HPI material basket is loaded into the HPI cavity (Figure 1.2-4) if required for a specific content.

When the HPI top plug is installed (Drawing 001N8427), additional shoring plates are added to ensure the [[ ]] gap between the bottom of the cask lid and the top of the HPI does not exceed 0.25 inches. However, no credit for these spacers is given in the Normal Conditions of Transport (NCT) and Hypothetical Accident Conditions (HAC) evaluations. The required evaluations are included in this application to demonstrate safe transport of the Model 2000 Transport Package for the included contents with specified required internals and associated cask lid seal and port decay heat configuration designs.

Once the package is loaded onto the transport vehicle, external temperature measurements are taken of the loaded overpack. If any temperature exceeds 185°F, a protective personnel barrier is installed around the package to block access as discussed in Section 3.3.1. The cask containment boundary is illustrated in Figure 4.1.3-1.

[[

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**Figure 1.2-1. Model 2000 Packaging with High Performance Insert**

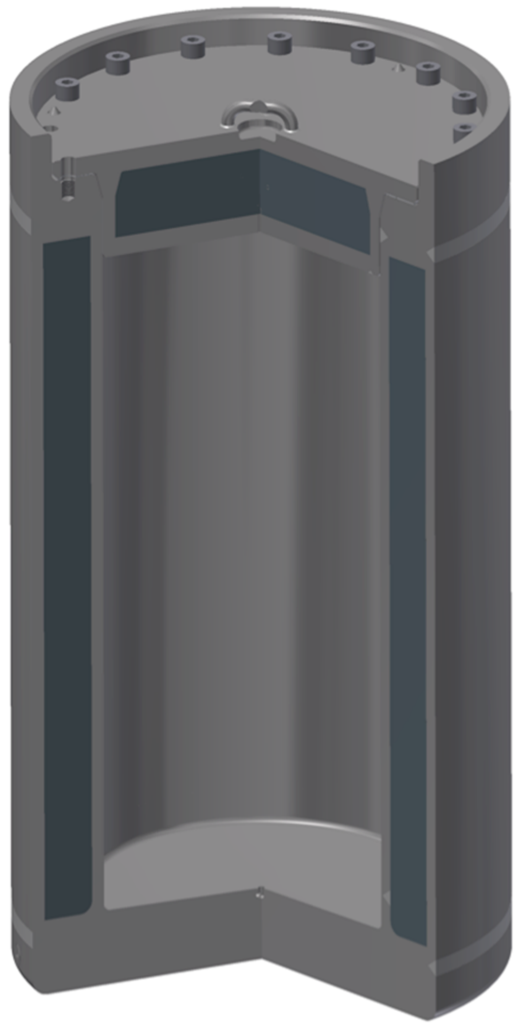

**Figure 1.2-2. Model 2000 Cask**

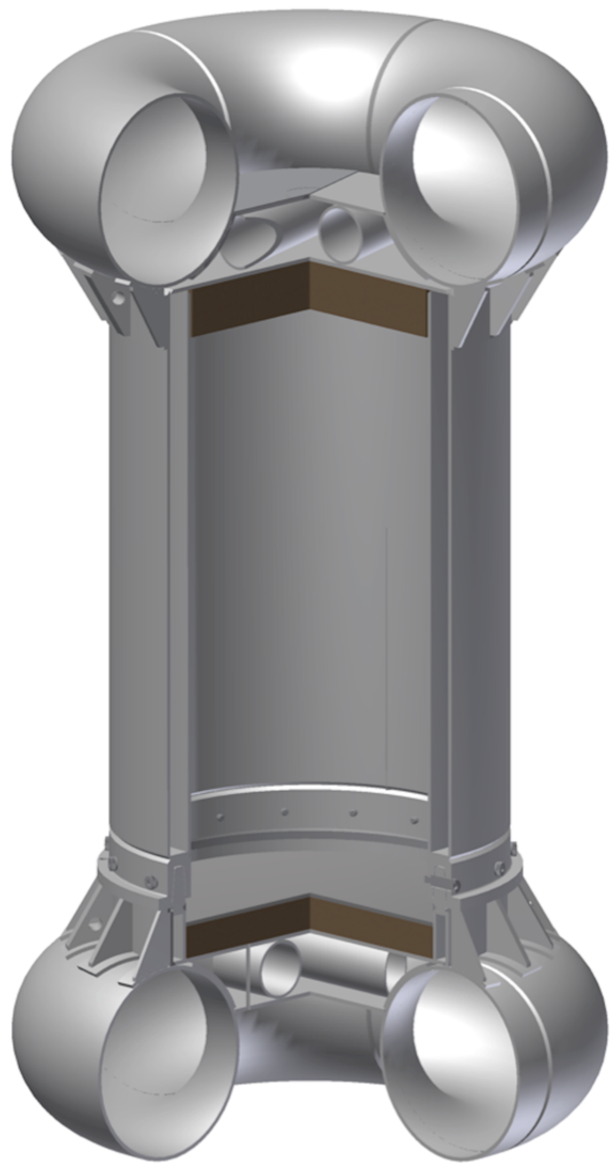

**Figure 1.2-3. Model 2000 Overpack**

[[

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**Figure 1.2-4. Model 2000 High Performance Insert with Material Basket**

[[

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**Figure 1.2-5. Material Basket and Rod [[ ]] Holder**

[[

]]

**Figure 1.2-6.  Material Basket Details**

## 1.3 Appendix

### 1.3.1. Drawings

This section contains the Model 2000 Transport Package licensing drawings and bill of materials. Table 1.3-1 provides a list of current licensing drawings, which follow, and current revision level.

**Table 1.3-1. Model 2000 Packaging Licensing Drawings**

| Drawing Number | Title | Revision |
|---|---|---|
| 001N8422 | GE 2000 HPI and Material Basket Licensing Drawing | 1 |
| 001N8423 | GE 2000 HPI Licensing Drawing | 1 |
| 001N8424 | GE 2000 HPI Material Basket Assembly Licensing Drawing | 1 |
| 001N8425 | GE 2000 HPI Body Licensing Drawing | 1 |
| 001N8427 | GE 2000 HPI Top Plug Assembly Licensing Drawing | 1 |
| 001N8428 | GE 2000 HPI Bottom [[ ]] Assembly Licensing Drawing | 1 |
| 101E8718 | Model 2000 Shipping Cask S/N 2001 | 16 (Sheet 1)<br>15 (Sheet 2) |
| 105E9520 | Model 2000 Shipping Cask all S/N’s Except S/N 2001 | 8 (Sheet 1)<br>7 (Sheet 2) |
| 129D4946 | Model 2000 Transport Container | 12 |
| 101E8719 | Model 2000 Shipping Cask Overpack S/N 2001 | 13 |
| 105E9521 | Model 2000 Shipping Cask Overpack all S/N’s Except S/N 2001 | 6 |

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### 1.3.2. Material Specifications

#### 1.3.2.1. Seal Specifications

The Parker [[ ]] material specifications Parker Compounds [[ ]] for the cask lid seal and port "O" rings are provided in the following pages.

**Reference 1- 3**

**[[**

]]

**Reference 1-4**

[[

]]

**Reference 1-5**

[[

]]

### 1.4 References

1-1. U.S. Nuclear Regulatory Commission Code of Federal Regulations, Title 10 Part 71, "Packaging and Transport of Radioactive Material," April 2016.

1-2. GE-Hitachi Nuclear Energy, "Quality Assurance Program for Shipping Packages for Radioactive Material (Docket 71-0170)," QAP-1, Latest Revision.

1-3. Parker O-Ring Division, "General Evaluation of Parker Compound [[ ]]," October 2000.

1-4 Parker Hannifin Corporation, "Gask-O-Seal and Integral Seal Design Handbook," CSS 5124, 2010.

1-5 Parker Hannifin Corporation, "Parker O-Ring Handbook," Cleveland, OH, Handbook ORD 5700, 2007.

# 2 STRUCTURAL ANALYSIS

This chapter presents the structural evaluation of the Model 2000 Transport Package, and demonstrates that the design meets all applicable structural criteria. All components that comprise the Model 2000 Transport Package are evaluated to the applicable regulatory requirements that includes the NCT and HAC, in accordance with 10 CFR 71 (Reference 2-1). Detailed description of each package component is provided in in Section 2.1.1. Analyses comply with the methodology and criteria presented in Section 2.1.2. The structural design of the Model 2000 Transport Package is based on the following critical characteristics:

- Ensure the maximum content weight does not exceed 5,450 pounds.
- Maintain structural integrity when subjected to the thermal conditions (3000 W maximum) associated with NCT and HAC in Chapter 3. This section demonstrates packaging integrity at extreme thermal conditions during NCT and HAC.
- Maintain containment integrity to remain leaktight during NCT and HAC as documented in Chapter 4. This section demonstrates cask containment integrity during NCT and HAC.
- Maintain integrity of lead and depleted uranium shielding boundaries during NCT and HAC to support Chapter 5. This section demonstrates that the shielding integrity is maintained during NCT and HAC to support the shielding analysis assumptions.
- Maintain structural integrity of the cask and HPI during NCT and HAC to support the criticality analysis assumptions presented in Chapter 6. This shows that the geometry of the package is maintained during NCT and HAC to support the criticality analysis assumptions.

## 2.1 Description of Structural Design

### 2.1.1. Discussion

The Model 2000 Transport Package consists of a welded overpack structure containing a steel-encased, lead cask structure. The cask structure is a lead-filled SS304 weldment, cylindrical in shape, and measuring approximately 38.5 inches OD by 71 inches high. The inner cavity is 26.5 inches ID by 54 inches high. The lead shielding provided is approximately 4 inches of lead on the sides.

The cask body shell is made of 1 inch thick SS304 plate. At the bottom, the shells are welded to a 6-inch thick SS304 forging. At the upper section, the containment shell joins a 9-inch thick SS304 forging. This forging provides support and sealing surface to the cask seal. Also, it contains 15 equally spaced, internally threaded holes on a 32.25-inch diameter bolt circle. Fifteen 1¼-inch diameter ASTM A540 socket head screws attach the lid to the cask body during operation. The cask lid is SS304 encasing a lead cylinder. The lid has a lifting lug for handling.

There are three penetrations into the cask cavity. One serves as a drain for the cask cavity and another one as a vent. The drain hole goes from the center of the cavity bottom to the side of the outer surface. The vent line spirals through the cask lid around the center. These penetrations

provide means to eliminate water from the cask cavity collected during underwater operations. A ½ NPT socket head pipe plug followed by a 1¾ - 12 UN-2A cap closes both penetrations. The cap O-ring provides backup sealant to the pipe plug. The third penetration is used as a testing port for the cask seal joint. It is located in the upper forging on the side surface of the cask.

There are two cask lid seal and port O-ring material options. For content heat loads between 0 and 500 W, the cask lid seal and O-rings use the Parker Compound No. [[ ]] and [[ ]] material retainer option. For content heat loads between 500 and 3000 W, the cask lid seal and O-rings use the Parker Compound No. [[ ]] and the SS304 material retainer option. The cask lid seal retainer has a 34 inch OD and 28 inch ID.

The welded SS304 overpack structure is composed of two concentric cylinders, separated vertically by eight equally spaced [[ ]] and horizontally by two [[ ]] sections. The external cylinder has a 48.5-inch OD. The internal cylindrical shell is 40.5-inch ID. A 24-inch [[ ]] diameter toroidal shell is attached at both ends of the external cylinder, and a circular plate is welded across the inner region of the torus. The internal cylinder is closed at each end by circular plates. All materials are 0.5 inches thick with the exception of the space [[ ]] and toroidal shells. The vertical [[ ]] are 3 inches OD, 0.25 inches thick, and the horizontal [[ ]] sections are 7.25 inches OD, 0.375 inches thick.

The toroidal shells may be fabricated using four 90° elbows (or two 180° returns). However, the Model 2000 toroidal shell wall thickness range is limited to 0.5 inches minimum to 0.76 inches maximum. The overpack structure separates near the bottom end to allow access to the lead cask. A collar 0.75 inches thick is attached in this area to provide bearing surface for the connecting bolts. A total of 15 1-⅜ inches diameter ASTM A540 shoulder screws join both portions of the overpack structure. The toroidal shell of the overpack structure acts as an energy-absorbing device during the postulated drop conditions. In addition, the overpack structure provides thermal shielding for the lead cask in the event of a fire.

A total of 20 reinforcing ribs cradle the toroidal shell to the vertical cylinder. Four of the ribs provide tie-down points for the package during transport. These ribs also provide a means for lifting and removing the overpack top section using a spreader bar. The spreader bar is not part of the transport packaging.

There is a 6-inch thick aluminum honeycomb pad attached to the top inner surface of the overpack structure. A 4-inch thick aluminum honeycomb pad covered by a ½ inch thick circular plate provides a surface base for the lead cask structure. These honeycomb pads are included in the overpack structure design to assure a uniform loading distribution on the cask surface during the postulated free-drop events.

The Model 2000 Transport Package is equipped with an HPI to increase the shielding capability of the package. The HPI is [[ ]] inches tall and [[ ]] inches in diameter. The cavity is approximately [[ ]] inches in diameter and [[ ]] inches deep. The HPI body consists of [[ ]] inch stainless steel concentric cylindrical shells. The annulus between the [[ ]] shells is filled with [[ ]]-inch thick depleted uranium. The HPI body is positioned in the cask cavity by five [[ ]] arranged axially to provide uniform support. The [[ ]] are joined together

by four [[ ]] vertical lifting arms that function as the primary lifting fixture. The HPI body assembly is completed with the addition of ASME [[ ]] each end of the cylindrical sub-assembly.

Top and bottom [[ ]] joined to the ASME [[ ]] provide closure of the HPI. The bottom [[ ]] is a stepped design comprised of a [[ ]] plate and a [[ ]]-inch thick depleted uranium cylinder encapsulated by a [[ ]] shell. Holes are machined in the [[ ]]-inch circular plate to align with the ASME [[ ]] on the HPI body. The bottom [[ ]] is attached to the bottom [[ ]] with eight (8) $^{7}/_{8}$-inch socket head cap screws and four alignment pins. The top plug is a stepped design comprised of [[ ]]-inch depleted uranium cylinder encapsulated by a [[ ]] shell. To facilitate lifting of the top plug, four hoist rings are recessed into the [[ ]] circular plate. The top plug is held in position by 4 alignment pins. Attachment of the top and bottom [[ ]] does not produce a pressure boundary. Grooves are cut into the surface of the plugs to allow moisture to escape during the vacuum drying process.

The material basket is a shoring device, which may be used for carrying various contents. The material basket is constructed of 18 full-length 1-¼ schedule 5 [[ ]] (ID = [[ ]] inches, OD = [[ ]] inches), which form a [[ ]] pattern and are identified as Item 1 on drawing 001N8424. See for material basket details. The outer [[ ]] of the material basket form a composite section with the addition of stiffener plates welded to adjacent [[ ]] with full penetration groove welds. The center location of the basket is a developed cell, which is created by the surrounding pipes. To allow for the proper insertion of additional content shoring and facilitate fabrication, two partial length [[ ]]-inch long [[ ]] are inserted at the top and bottom of the developed cell and are identified as Item 2 on drawing 001N8424. Therefore, the exterior view of the basket shows [[ ]] locations. Four circular [[ ]] evenly spaced in the axial direction facilitate loading and positioning of the material basket within the HPI cavity. In addition, dunnage (for example rod [[ ]] holders) may be used as a cask loading mechanism and to shore the contents during transport.

### 2.1.2. Design Criteria

This section defines the stress allowables for all the stresses resulting from the regulatory load combinations given in NRC Regulatory Guide 7.8 (Reference 2-2).

The cask is evaluated per ASME Service Levels A and D, normal and accident conditions, respectively. The analyses methods and stress criterion allowed by the ASME Code, Section III-Subsection NB is employed. Stress intensities caused by mechanical loads are combined before comparing to ASME code stress allowables, which are listed in Table 2.1-1.

**Table 2.1-1. Structural Design Criteria for Model 2000 Cask**

| ASME CLASS 1 DESIGN | STRESS LIMITS |
|---|---|
| Normal conditions: Service Level A | $P_m \leq S$<br>$P_m + P_b \leq 1.5\ S_m$<br>$P_m + P_b + Q \leq 3\ S_m$<br>Bearing Stress $\leq S_y$ at temperature |
| Accident conditions: Service Level D | $P_m \leq 2.4\ S_m$ or $0.7\ S_u$ (whichever is less)<br>$P_m + P_b \leq 3.6\ S_m$ or $1.0\ S_u$ (whichever is less) |

Note: $P_m$ = primary membrane stress intensity, $P_b$ = primary bending stress intensity, $S_m$ = design stress intensity, $S_y$ = yield strength, $S_u$ = ultimate strength, Q = secondary stress associated with thermal expansion.

The HPI is evaluated per ASME Service Levels A and D, normal and accident conditions, respectively. The analyses methods and stress criterion allowed by the ASME Code, Section III-Subsection NF is employed. Allowable stresses are based on section NF-3200. For normal conditions (Service Level A), design limits are defined in paragraph NF-3221.1. For accident conditions (Service Level D), design limits are defined in Appendix F of ASME Code, Section III (Reference 2-3). Note the evaluation of thermal stresses is not required per ASME Code III-NF (NF-3121.11). Stress intensities caused by mechanical loads are combined before comparing to ASME code stress allowables, which are listed in Table 2.1-2.

**Table 2.1-2. Structural Design Criteria for HPI and Material Basket**

| ASME CLASS 1 DESIGN | STRESS LIMITS |
|---|---|
| Normal Conditions: Service Level A (NF-3221.1) | $P_m \leq S_m$<br>$P_m + P_b \leq 1.5\ S_m$ |
| Bearing Loads: Service Level A (NF-3223.1) | $S_y$ at temperature |
| Pure Shear: Service Level A (NF-3223.2) | $0.6S_m$ |
| Bearing Loads: Service Level D (Appendix F, F-1332.3) | Except for pinned and bolted joints, bearing stresses need not be evaluated for loads for which Level D Service Limits are specified. |
| Pure Shear: Service Level D (Appendix F, F-1332.4) | $0.42S_u$ |
| Accident Conditions: Service Level D (Appendix F, F-1332) | $P_m > 1.2\ S_y$ and $1.5\ S_m < 0.7\ S_u$<br>$P_m + P_b <$ 150% of the limit for general primary stress intensity $P_m$ |

Note: Pm = primary membrane stress intensity, Pb = primary bending stress intensity, Sm = design stress intensity, Sy = yield strength, Su = ultimate strength.

### 2.1.3. Weights and Centers of Gravity

The weights and center of gravity of the Model 2000 Transport Package and detailed contents are presented in Table 2.1-3. Refer to Section 1.3.1 for component dimensions.

**Table 2.1-3. Summary of Maximum Weights**

| DESCRIPTION | DRAWING NUMBER | WEIGHT (LB) | C.G. (IN)* |
|---|---|---|---|
| **Total Packaging Weight** | **—** | **28,100** | **63.9** |
| Cask Overpack | 101E8719/ 105E9521 | 10,200 | — |
| Cask Body | 101E8718/ 105E9520 | 16,000 | — |
| Closure Lid | 101E8718/ 105E9520 | 1,900 | — |
| **Allowed Contents Weight** | **—** | **5,450** | **62.3** |
| HPI Assembly | 001N8423 | [[ ]] | — |
| • HPI Body | 001N8425 | [[ ]] | — |
| • Top Plug | 001N8427 | [[ ]] | — |
| • Bottom [[ ]] | 001N8428 | [[ ]] | — |
| Material Basket | 001N8424 | [[ ]] | — |
| Contents plus Shoring | — | [[ ]]** | — |
| **Total Package Weight** | **—** | **33,550** | **63.6** |

Notes: *C.G. measured from component base.
** If material basket is not included in contents, contents plus shoring maximum weight is [[ ]] lb.

### 2.1.4. Identification of Codes and Standards for Package Design

This section identifies the established codes and standards proposed for use in the Model 2000 Transport Package design, fabrication, assembly, testing, maintenance, and use.

The Model 2000 cask with HPI and material basket is designed to ship a maximum of 3000 W of various radioactive contents. Per Regulatory Guide 7.11 (Reference 2-4), the package is considered Category I—Greater than 3,000 $A_2$ or greater than 30,000 Ci. From NUREG/CR-3854 (Reference 2-5), the fabrication code and standard is:

- The criteria for fabricating metal components of shipping containers used for transporting radioactive materials are based on the ASME Code Section III (Reference 2-3). ASME Code Section III is used for the design and fabrication of the HPI and material basket.

#### 2.1.4.1. Category I Requirements

Acceptable criteria for the fabrication of metal components of shipping containers are contained in the ASME Code Section III, Subsection NB for containment components; Subsection NG for criticality components and Section VIII, Division I or Section III, Subsection NF for other safety components.

- The Model 2000 cask provides containment. Therefore, the cask shall be fabricated to Section III, Subsection NB.
- The HPI and material basket are relied upon for shielding, which falls under Component Safety Group "Other Safety". Therefore, the insert shall be fabricated to Section VIII, Division 1 or Section III, Subsection NF.

#### 2.1.4.2. Component Classification According to Importance to Safety

The parts lists in Section 1.3.1 identify the Category A, B and C items for the Model 2000 cask, overpack, HPI, and material basket. The safety classification of all components is based on importance to safety criteria per NUREG/CR-6407 (Reference 2-6).

- For the Model 2000 cask, the components that comprise the cask inner shell, top forging, cask seals and lid are considered part of the containment boundary. Therefore, these items are Category A. Components such as the lead shielding, lifting and tie-down devices meet the definition of Category B items. See the parts lists in Section 1.3.1 for Drawing 101E8718 and 105E9520 for the Model 2000 cask assembly parts classification.
- See the parts list, Section 1.3.1, Drawing 001N8424, for the material basket assembly parts classification.
- The material basket is considered dunnage, and is not required to reduce impact loading on the containment boundary. However, it is required to maintain geometry during NCT to support the shielding analysis assumptions. Therefore, it is considered a Category B item. In addition, for fabrication, [[ ]] welds are Safety Category B. See the parts list in Section 1.3.1 for Drawing 001N8424 for the material basket assembly parts classification.

## 2.2 Materials

This section presents the mechanical properties of materials used to evaluate the performance of the Model 2000 cask, overpack, HPI, and material basket. Materials of construction for each component are found in Section 1.3.1, in the parts lists that accompany drawings.

### 2.2.1. Material Properties and Specifications

The material properties used in the structural analysis of the Model 2000 cask, HPI and material basket are presented in Tables 2.2-1 through 2.2-9. Material properties specific to the impact analysis are presented in Section 2.12.1.

**Table 2.2-1. Structural Properties of Type 304 Stainless Steel**

| **Temperature (°F)** | **-20** | **70** | **200** | **300** | **400** | **500** | **600** | **700** | **800** | **900** | **1000** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Ultimate Tensile Strength $S_u$ (ksi) | 75.0 | 75.0 | 71.0 | 66.2 | 64.0 | 63.4 | 63.4 | 63.4 | 62.8 | 60.8 | 57.4 |
| Yield Strength $S_y$ (ksi) | 30.0 | 30.0 | 25.0 | 22.4 | 20.7 | 19.4 | 18.4 | 17.6 | 16.9 | 16.2 | 15.5 |
| Design Stress Intensity $S_m$ (ksi) | 20.0 | 20.0 | 20.0 | 20.0 | 18.6 | 17.5 | 16.6 | 15.8 | 15.2 | — | — |
| Modulus of Elasticity (E+3, ksi) | 28.8 [a] | 28.3 | 27.5 | 27.0 | 26.4 | 25.9 | 25.3 | 24.8 | 24.1 | 23.5 | 22.8 |
| Mean Coefficient of Thermal Expansion α (E-6, in/in/°F) | — | 8.5 | 8.9 | 9.2 | 9.5 | 9.7 | 9.9 | 10.0 | 10.1 | 10.2 | 10.3 |
| Poisson's Ratio | ⟵ 0.31 ⟶ | | | | | | | | | | |
| Density **($lb/in^3$)** | ⟵ 0.290 ⟶ | | | | | | | | | | |

References:
Reference 2-7 Ultimate Tensile Strength: Table U, Page 493, Line 22.
Reference 2-7 Yield Strength: Table Y-1, Page 610 & 611, Line 26.
Reference 2-7 Design Stress Intensity: Table 2A, Page 306, Line 19.
Reference 2-7 Modulus of Elasticity: Table TM-1, Material Group G, Page 738.
Reference 2-7 Mean Coefficients of Thermal Expansion: Table TE-1, Group 3, Coefficient B, Page 711.
Reference 2-7 Poisson's Ratio: Table PRD, High Alloy Steels (300 series), Page 744.
Reference 2-7 Density: Table PRD, High Alloy Steels (300 series), Page 744.
Note:
[a] This value was interpolated.

**Table 2.2-2. Structural Properties of ASME Type [[ ]]**

[[

]]

Note:
[a] Interpolated.

**Table 2.2-3. Structural Properties of ASME [[ ]]**

[[

]]

Note:
[a] Interpolated.

**Table 2.2-4. Structural Properties of Depleted Uranium Metal**

| Temperature (°F) | -20 | 70 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Yield Strength $S_y$ (ksi) | — | 47.2 | 43.8 | 40.2 | 36.3 | 33.3 | 30.5 | 23.9 | 15.3 | 9.3 | 5.8 |
| Modulus of Elasticity (E+3, ksi) | — | 23.6 | — | — | — | — | — | — | — | — | — |
| Poisson's Ratio | ⟵ 0.335 ⟶ | | | | | | | | | | |
| Density (lbm/in$^3$) | ⟵ 0.674 – 0.689 ⟶ | | | | | | | | | | |

References:
Reference 2-8 Yield Strength: Figure 1, Page 671.
Reference 2-8 Density: Page 670.
Reference 2-9 Modulus of Elasticity: Table 7, Page 19.
Reference 2-9 Poisson's Ratio: Table 7, Page 19.

**Table 2.2-5. Structural Properties of Lead**

| Temperature (°F) | -40 | -20 | 70 | 200 | 300 | 400 | 600 |
|---|---|---|---|---|---|---|---|
| Modulus of Elasticity (E+3, ksi) | 2.58 | 2.55 [a] | 2.42 | 2.21 | 2.04 | 1.77 | 1.49 |
| Yield Strength (psi) | 795 | 763 [a] | 620 | 500 | 400 | — | — |
| Mean Coefficient of Thermal Expansion α (E-6, in/in/°F) | 15.6 [a] | 15.7 [a] | 16.1 [a] | 16.7 [a] | 17.3 [a] | 18.5 [b] | — |
| Poisson's Ratio | ⟵ 0.4 ⟶ | | | | | | |
| Density (lb/in$^3$) | ⟵ 0.4097 ⟶ | | | | | | |

References:
Reference 2-10 Modulus of Elasticity: Figure B-8.
Reference 2-11 Yield Strength at (-40°F – 70°F ).
Reference 2-12 Yield Strength: (200°F – 300°F ): Figure 12.
Reference 2-10 Mean Coefficient of Thermal Expansion: Figure A-3.
Reference 2-13 Poisson's Ratio: Table 6.1.9, Page 6-10.
Reference 2-13 Density: Table 6.4.1, Page 6-47.

Notes:
[a] Interpolated
[b] Value for 440.33°F (500 K) used.

**Table 2.2-6. Bolt – ASTM A-540 Grade B21 Class 3**

| Temperature (°F) | 150 | 455 |
|---|---|---|
| Ultimate Tensile Strength $S_u$ (ksi) | 145 | |
| Yield Strength $S_y$ (ksi) | 127.9 [a] | 117.2 [a] |
| Design Stress Intensity $S_m$ (ksi) | 42.6 [a] | 39.1 [a] |
| Modulus of Elasticity (E+3, ksi) | 29.2 [a] | 27.7 [a] |
| Mean Coefficient of Thermal Expansion α (E-6, in/in/°F) | 6.6 | 7.2 |
| Poisson's Ratio | ⟵ 0.30 ⟶ | |
| Density (lb/in$^3$) | ⟵ 0.280 ⟶ | |

References:
Reference 2-7 Tensile Strength: Table U, Page 473, Line 11
Reference 2-7 Yield Strength: Table Y-1, Page 562, Line 36
Reference 2-7 Design Stress Intensity: Table 4, Page 366, Line 20
Reference 2-7 Modulus of Elasticity: Table TM-1, Material Group C, Page 738
Reference 2-7 Mean Coefficient of Thermal Expansion: Table TE-1, Group 1, Coefficient B, Page 708
Reference 2-7 Poisson's Ratio: Table PRD, Low alloy steels: ½Cr to 1-¼Cr steels, Page 744
Reference 2-7 Density: Table PRD, Low alloy steels: ½Cr to 1-¼Cr steels, Page 744
Note:
[a] Interpolated

**Table 2.2-7. Internal Thread – ASME SA-182 F304**

| Temperature (°F) | 150 | 455 |
|---|---|---|
| Ultimate Tensile Strength $S_u$ (ksi) | 73 [a] | 63.7 [a] |
| Yield Strength $S_y$ (ksi) | 26.7 | 20 [a] |
| Design Stress Intensity $S_m$ (ksi) | 20.0 | 17.9 [a] |
| Modulus of Elasticity (E+3, ksi) | 27.8 [a] | 26.1 [a] |
| Mean Coefficient of Thermal Expansion α (E-6, in/in/°F) | 8.8 | 9.7 [a] |
| Poisson's Ratio | ⟵ 0.31 ⟶ | |
| Density (lb/in$^3$) | ⟵ 0.290 ⟶ | |

References:
Reference 2-7 Tensile Strength: Table U, Page 493, Line 16
Reference 2-7 Yield Strength: Table Y-1, Page 610, Line 11
Reference 2-7 Design Stress Intensity: Table 5A, Page 410, Line 25
Reference 2-7 Modulus of Elasticity: Table TM-1, Material Group G, Page 738
Reference 2-7 Mean Coefficient of Thermal Expansion: Table TE-1, Group 3, Coefficient B, Page 711
Reference 2-7 Poisson's Ratio: Table PRD, High Alloy Steels (300 series), Page 744
Reference 2-7 Density: Table PRD, High Alloy Steels (300 series), Page 744
Note:
[a] Interpolated

**Table 2.2-8. ASTM A-193 B6 Bolt Properties**

| | |
|---|---|
| Minimum Ultimate Tensile Strength $S_u$ (ksi) | 110 |
| Minimum Yield Strength $S_y$ (ksi) | 85 |
| Design Stress Intensity $S_m$ (ksi) | 26.5 [ab] |
| Modulus of Elasticity (E+3, ksi) | 28.1 [ab] |
| Mean Coefficient of Thermal Expansion α (E-6, in/in/°F) | 6.2 [b] |
| Poisson's Ratio | 0.31 |
| Density (lb/in$^3$) | 0.280 |

References:
Reference 2-7 Minimum Ultimate Tensile Strength: Table 3, Page 339, Line 17
Reference 2-7 Minimum Yield Strength: Table 3, Page 339, Line 17
Reference 2-7 Stress Intensity: Table 4, Page 366, Line 25
Reference 2-7 Modulus of Elasticity: Table TM-1, Material Group F, Page 738
Reference 2-7 Mean Coefficient of Thermal Expansion: Table TE-1; Coefficients for 12Cr, 12Cr-1Al, 13Cr, and 13Cr-4Ni Steels; Page 710.
Reference 2-7 Poisson's Ratio: Table PRD, High alloy steels (400 series), Page 744

Reference 2-7 Density: Table PRD, High alloy steels (400 series), Page 744
Notes:
[a] Interpolated
[b] Evaluated at 250°F

**Table 2.2-9. ASTM A-540 Grade B22 Class 3 Bolt Properties**

| | |
|---|---|
| Minimum Ultimate Tensile Strength $S_u$ (ksi) | 145 |
| Minimum Yield Strength $S_y$ (ksi) | 115.7 |
| Design Stress Intensity $S_m$ (ksi) | 37.6 [a1] |
| Modulus of Elasticity (E+3, ksi) | 27.4 [a1] |
| Mean Coefficient of Thermal Expansion α (E-6, in/in/°F) | 7.3 [a] |
| Poisson's Ratio | 0.30 |
| Density ($lb/in^3$) | 0.280 |

References:
Reference 2-7 Minimum Ultimate Tensile Strength: Table 3, Page 335, Line 25
Reference 2-7 Minimum Yield Strength: Table 3, Page 335, Line 25
Reference 2-7 Design Stress Intensity: Table 4, Page 366, Line 4
Reference 2-7 Modulus of Elasticity: Table TM-1, Group C, Page 738
Reference 2-7 Mean Coefficient of Thermal Expansion: Table TE-1, Group 1, Column B, Page 708
Reference 2-7 Density: Table PRD, Low alloy steels: ½-Cr to 1-¼Cr steels, Page 744
Notes:
[a] Evaluated at 500°F
[1] B21 Bolt properties used because data for B22 Bolts could not be found

### 2.2.2. Chemical, Galvanic, or Other Reactions

The Model 2000 cask is fabricated from SS304, SS316, and lead. The lead is completely encased in the SS. This construction excludes moisture at the stainless boundary, thus assuring no galvanic or deleterious reactions could occur. The cask contents contact the stainless cavity surface. The radioactive material contents are in solid form and typically are placed in supplemental shoring. GEH's experiences in operating other transport packages with similar arrangements show that chemical, galvanic or other reactions between the cask cavity surface and the radioactive material shoring, or between the shoring and their solid contents, do not occur.

The structural components of the HPI and material basket are fabricated from SS304, [[ ]] steels, which are chemically compatible. These materials are selected because of their strength, ductility, and high resistance to corrosion and brittle fracture over a broad temperature range and high levels of radiation. Therefore, no chemical or galvanic reaction is anticipated. The primary function of the HPI body, including top and bottom [[ ]], is to encapsulate the depleted uranium shield. [[ ]] is cast and machined to precise tolerance to form the required shield geometry. To prevent potential oxidation, assembly of the

shield is performed in an inert atmosphere. Once encapsulated, oxidation and galvanic reactions with stainless steel does not occur.

The cask containment features have no indication of chemical or galvanic reactions between [[ ]] compounds and stainless interfaces of the cask. This has been confirmed in the qualification of the cask containment.

### 2.2.3. Effects of Radiation on Materials

Gamma radiation has no significant effect on metal and therefore, the radiation produced by the contents does not cause any measurable damage to the packaging metallic components (stainless steel, aluminum, depleted uranium, and lead). Seals are inspected prior to each use. The Parker O-ring Handbook (Reference 2-14) states that when experiencing radiation levels 1 x $10^6$ rads the effects on all compounds are minor. The maximum absorbed dose rates that these [[ ]] seals could be exposed to through a year of continuous use, with the cask loaded and maximum cobalt-60 activity, are on the order of $10^2$ to $10^4$ rad. As the Model 2000 is not a storage cask, overall exposure time for the seals is significantly shorter than an entire year. With a 1-year replacement period on the [[ ]] seals and O-rings, there is no significant degradation of the seals due to irradiation.

## 2.3 Fabrication and Examination

### 2.3.1. Fabrication

Fabrication and examination of the Model 2000 Transport Package (i.e., overpack and cask) conform to the requirements of ASME Section, III, Subsection NB for Category A and B components. Components of the HPI assembly and material basket assembly that are Category B items are fabricated in accordance with ASME Section III, Subsection NF. Fabrication of package components follows the guidelines presented in NUREG/CR-3854, Fabrication Criteria for Shipping Containers (Reference 2-5). All package components are fabricated in accordance with an NRC approved quality assurance program.

### 2.3.2. Examination

Examination of the Model 2000 Transport Package (i.e., overpack and cask) conforms to the requirements of ASME Section, III, Subsection NB for Category A and B components. Components of the HPI assembly and material basket assembly that are Category B items are examined in accordance with ASME Section III, Subsection NF. All package components are examined in accordance with an NRC approved quality assurance program.

## 2.4 General Requirements for All Packages

This section addresses the requirements of 10 CFR 71.43**,** “General Standards for All Packages.”

### 2.4.1. Minimum Package Size

The smallest overall dimension of the Model 2000 Transport Package is 131.5 inches. The cask overall dimensions are 71.0 inches high and 38.5 inches OD.

### 2.4.2. Tamper-Indicating Feature

A lock wire and seal of the type that must be broken is installed across the overpack joint section. This seal while intact, would be evidence that unauthorized persons have not opened the package.

### 2.4.3. Positive Closure

The Model 2000 Transport Package is an assembly of components for shipping radioactive material contents inside of a cask with a design pressure of 30 psia. The cask is sealed using a gasket and fifteen 1¼-inch socket head screws. In turn, the cask is contained by the overpack structure, which is bolted closed during transport by 15 shoulder bolts. With this double closure, overpack and cask, inadvertent opening of the cask cannot occur. The vent and drain ports on the cask each are plugged and sealed by pipe plugs and straight thread caps with O-rings.

The evaluation of the closure bolts is presented in Section 2.12.4. Review of the closure bolt evaluation at 3000 W shows that the bolt preload does not change as a result of the increase in thermal load. The closure bolt calculation shows that the controlling loads for the bolt preload are the internal pressure and the pin puncture loads. Further review of the temperatures presented in Chapter 3 show that because of the thermal modeling methodology, the heat load is concentrated in the HPI and material basket. As a result, the temperature distribution in the closure bolt and flange are more uniform resulting in a smaller temperature delta and lower thermal stresses. To maintain positive closure during normal and hypothetical accident conditions, the closure bolts are torqued to 500 ft-lb.

## 2.5 Lifting and Tie-Down Standards for All Packages

The regulations require that lifting devices which are a structural part of the package shall be capable of supporting three times the weight of the loaded package without generating stress in any material of the package in excess of its yield stress. The following sections provide a summary of the lifting and tie-down evaluation, which is presented in Section 2.12.3.

### 2.5.1. Lifting Devices

The Model 2000 Transport Package lifting components are evaluated structurally in the following sections. The lifting and tie-down requirements are as specified in 10 CFR 71.45(a).

#### 2.5.1.1. Lifting Ear Evaluation

As shown in Figure 2.5.1-1, there are two types of lifting ear designs employed during the handling of the Model 2000 cask, standard and auxiliary. The ears are removed from the cask during transport and are shipped separately. The ear design identified as Standard is used for crane and fork truck lifting, and only one pair is required for these operations. The Auxiliary ear is used in crane lifting only, and 2 pairs or 4 ears are required. The user may combine the different types of ears as necessary including, 2 Standard/2 Auxiliary, 4 Auxiliary or 2 Standard.

Both ear designs are attached to the cask outer shell by means of four ASTM A193-B6 1-8 UNC-2-1/2 bolts. For this evaluation, the following loading conditions are considered:

- Load rating of W = 23,630 pounds, which includes the dead weight of the cask, lifting ears and the cask maximum payload.
- The two pairs of auxiliary ears are to support 3W such that the lifting cable does not make an angle of more than +30° measured from the vertical.
- The pair of standard ears is to support 3W.

Three load cases are considered for this evaluation: Case I – vertical lift by crane; Case II – angular lift 30° from vertical by crane; and Case III – fork truck lift at two different points on the standard ears only. Figure 2.5.1-1 provides a free-body diagram for Cases I and II. Case III is similar to Case I and is not shown.

The magnitude and direction of loading in the ear analysis is shown in Figure 2.5.1-2. The analysis of each type of ear is presented in Section 2.12.3.

Material properties are based upon 250°F for the outer cask. The 249°F temperature is the maximum temperature under normal conditions for the cask outer surface (Section 3.3.1). Both standard and auxiliary ears and the cask outer shell are ASTM A240, Type 304 stainless steel. The attaching bolt material is ASTM A193-B6.

# Security-Related Information Figure Withheld Under 10 CFR 2.390.

**Figure 2.5.1-1. Lifting Ear Details**

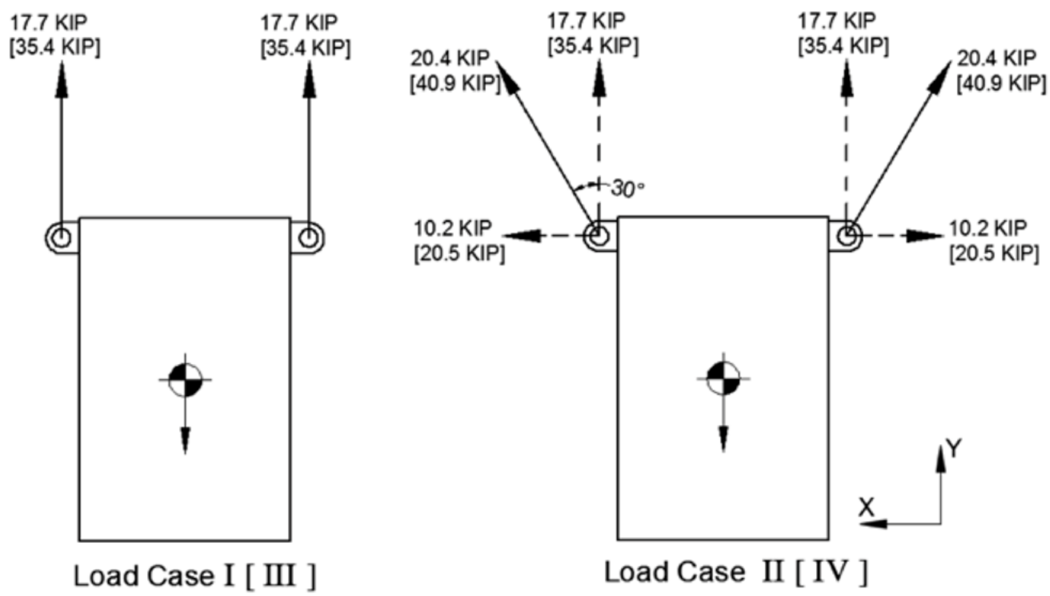


**Figure 2.5.1-2. Magnitude and Direction of Loading in Ear Analysis**

Table 2.5.1-1 provides a summary of the stress evaluation presented in Section 2.12.3. As the table shows, the margin of safety for all components and cases are positive. Therefore, the cask lifting device meets the requirements of 10 CFR 71.45.

**Table 2.5.1-1. Summary of Cask Lifting Device Stresses**

| Condition | Allowable Yield (ksi) | Allowable Ultimate (ksi) | Case I | | | Case II | | | Case III | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Stress (ksi) | MS (y) | MS (U) | Stress (ksi) | MS (y) | MS (U) | Stress (ksi) | MS (y) | MS (U) |
| Shear tearout of lifting hole - Auxiliary | 14.00 | 26.18 | 6.02 | 1.33 | 3.35 | --- | --- | --- | --- | --- | --- |
| Shear tearout of lifting hole - Standard | 14.00 | 26.18 | 8.98 | 0.56 | 1.92 | --- | --- | --- | --- | --- | --- |
| Tensile failure of lifting ear plate - Auxiliary | 23.70 | 68.60 | 4.82 | 3.92 | 13.23 | --- | --- | --- | --- | --- | --- |
| Tensile failure of lifting ear plate - Standard | 23.70 | 68.60 | 17.70 | 0.34 | 2.88 | --- | --- | --- | --- | --- | --- |
| Bearing of shackle pin on ear - Auxiliary | 23.70 | 68.60 | 10.20 | 1.32 | 5.73 | --- | --- | --- | --- | --- | --- |
| Bearing of shackle pin on ear - Standard | 23.70 | 68.60 | 17.70 | 0.34 | 2.88 | --- | --- | --- | 4.72 | 4.02 | 13.53 |
| Tensile stress on weld joint - Auxiliary | 23.70 | 68.60 | 6.50 | 2.65 | 9.55 | --- | --- | --- | --- | --- | --- |
| Tensile stress on base metal - Auxiliary | 23.70 | 68.60 | 9.19 | 1.58 | 6.46 | 9.20 | 1.58 | 6.46 | --- | --- | --- |
| Tensile stress on weld joint - Standard | 23.70 | 68.60 | 8.16 | 1.90 | 7.41 | --- | --- | --- | --- | --- | --- |
| Tensile stress on base metal - Standard | 23.70 | 68.60 | 5.77 | 3.11 | 10.89 | 4.85 | 3.89 | 13.14 | --- | --- | --- |
| Tensile stress on mounting bolt-Standard | 85.00 | 110.00 | 57.80 | 0.47 | 0.90 | --- | --- | --- | --- | --- | --- |
| Shearing of bolt - Standard | 51.00 | --- | 14.60 | 2.49 | --- | --- | --- | --- | --- | --- | --- |
| Shearing of bolt threads-Standard | 51.00 | --- | 11.07 | 3.61 | --- | --- | --- | --- | --- | --- | --- |
| Shearing of tapered threads-Standard | 14.00 | 26.18 | 8.64 | 0.62 | 2.03 | --- | --- | --- | --- | --- | --- |
| Tensile stress on cask outer shell - Standard | 23.70 | 68.60 | 10.95 | 1.16 | 5.26 | --- | --- | --- | --- | --- | --- |

Note:
M(y): Margin of safety based on yield strength
M(U): Margin of safety based on ultimate strength

### 2.5.1.2. Cask Lifting Ear Mounting Bolt Fatigue Evaluation

The fatigue evaluation of the lifting ear mounting bolts per ASME Section III NB indicates that the bolts have an expected life of 12.5 years based on 12 usages per year. Bolts are inspected during the installation of the lifting ears. Damaged or defective bolts are replaced as needed.

### 2.5.1.3. Excessive Load Failure

The lifting devices must be designed such that their failure under excessive load would not impair the ability of the package to meet other requirements of 10 CFR 71.45(a). A review of the above margin of safety from Table 2.5.1-1 indicates that, under excessive loading, the ear attaching bolts will fail before the ear plates, ear welds or cask shell. Failure of the bolts assures that the ability of the package to meet any other regulatory requirements is not impaired.

#### 2.5.1.4. Model 2000 Lid Lifting Lug Analysis

The lid is lifted by a single lifting lug that is composed of a 1-inch diameter stainless steel rod located at the center of the lid top. It is shown by analysis that this lifting device complies with requirements of 10 CFR 71.45(a). The lifting lug is able to support three times the weight of the lid without yielding.

The weakest part of the lifting lug is determined to have a factor of safety of 1.76 when analyzed for lifting three times the weight of the lid. Details of the analysis are documented in Section 2.12.3.

Because the lid lifting lug is covered by the cask overpack during transport the device is rendered inoperable. Therefore, no further evaluation is required.

### 2.5.2. Tie-Down Devices

The Model 2000 Transport Package tie-down components are evaluated structurally in the following sections. The lifting and tie-down requirements are as specified in 10 CFR 71.45(b).

#### 2.5.2.1. Tie-Down Evaluation

The Model 2000 Transport Package is normally shipped by truck. Figure 2.5.2-1 the overall plan for tying the package to the vehicle. Eight wire ropes or chains tie the package to the vehicle: four connect to the upper [[ ]] tie-down ribs of the overpack, and the other four connect to the overpack base [[ ]] tie-down ribs. In addition, the base of the package is wedged to the truck bed to prevent sliding. Evaluation of the tie-down stresses is presented in Table 2.5.2-1. As the table shows all components exhibit a positive margin of safety.

**Table 2.5.2-1. Tie-Down System Stress Analysis Results**

| Condition | Stress (ksi) | Allowable based on Yield (ksi) | MS | Allowable Based on Ultimate Strength (ksi) | MS |
|---|---|---|---|---|---|
| Shear tear-out of rib hole | 20.99 | 0.6 × 45.2 = 27.12 | 0.29 | 96.8/(2 × 1.31) = 36.95 | 0.76 |
| Bearing of shackle pin | 42.46 | 45.2 | 0.06 | 96.8 | 1.28 |
| Shear stress in weld joints | 20.99 | 0.6 × 45.2 = 27.12 | 0.29 | 96.8/(2 × 1.31) = 36.95 | 0.76 |

#### 2.5.2.2. Excessive Load Failure

Tie-down devices must be designed such that their failure under excessive load would not impair the ability of the package to meet other requirements of 10 CFR 71.45(b)(3). A review of the above margin of safety from Table 2.5.2-1 indicates that, under excessive loading, either the rib hole will tear out or the connecting weld will fail in shear. Failure of the rib or connecting weld does not impair the ability of the overpack or other package components from meeting other regulatory requirements

Security-Related Information Figure Withheld Under 10 CFR 2.390.

**Figure 2.5.2-1. Tie-Down of Transport Package to Vehicle**

## 2.6 Normal Conditions of Transport

This section provides the evaluation that shows the Model 2000 Transport Package, with HPI and material basket, meets the standards specified in 10 CFR 71.43 and 71.51, when subjected to the tests and conditions specified in 10 CFR 71.71 (Normal Conditions of Transport). The package is evaluated against each condition individually.

### 2.6.1. Heat

The thermal evaluation for the NCT heat conditions is presented in Section 3.3. The NCT heat condition consists of exposing the cask to direct sunlight and 100°F still air. For routine conditions, solar insolation is neglected. For NCT, solar insolation is applied to the package surface. For both cases, an initial temperature of 100°F and a maximum internal power generation of 3000 W are used for the evaluation.

#### 2.6.1.1. Summary of Pressures and Temperatures

Table 2.6.1-1 provides a summary of temperatures for the Configuration #2 thermal evaluation, which thermally bounds Configuration #1, presented in Chapter 3 of this application. Additionally, internal gasses in the cask and HPI are explicitly modeled in Chapter 3. Evaluation of the maximum pressure at the calculated average gas temperatures, presented in Section 3.1.4, shows that Configuration #2, which thermally bounds Configuration #1, does not exceed the design pressure of 30 psia.

#### 2.6.1.2. Differential Thermal Expansion

The differential thermal expansion of the Model 2000 cask is evaluated as part of the ASME Section III NB stress analysis included in Section 2.6.7 of this application to show compliance with the design criteria presented in Section 2.1.2. Review of the NCT heat conditions shows that a bounding thermal expansion model is possible by applying a 300°F temperature differential from the outside surface to the inside surface of the cask. To maximize thermal expansion, a temperature of 300°F is applied to the outer surface of the cask and 600°F to the inside surface of the cask. For the HPI and material basket thermal expansion and fit during worst-case thermal conditions assuming an initial temperature of 70°F.

***<u>Radial Thermal Expansion</u>***

Figure 2.6.1-1 through Figure 2.6.1-3 shows the HPI [[ ]], material basket, and HPI [[ ]] and cask inner shell diameters. Using the bounding temperature for each component, the change in diameter is calculated as:

$$d_{final} = d_0 (1 + \alpha \Delta T)$$

Where, the initial diameter, $d_0$, is multiplied by the product of the coefficient of thermal expansion, $\alpha$, and change in temperature, $\Delta T$, plus one. Table 2.6.1-2 shows the results of the evaluation. The minimum difference in diameters is calculated to be [[ ]] inches between the HPI [[ ]] and basket alignment disks, which results no radial interference. Therefore, the HPI and material basket can be removed from the cask following shipment.

***Axial Thermal Expansion***

Axial thermal expansion occurs when the material basket is heated by the source material from ambient conditions to NCT steady-state temperatures. Axial thermal expansion also occurs as the HPI heat reaches steady state and the inner shell of the cask expands. Using the bounding temperature for each component, the change in length is calculated as:

$$L_{final} = L_0 (1 + \alpha\Delta T)$$

Where, the initial length, $L_0$, is multiplied by the product of the coefficient of thermal expansion, $\alpha$, and change in temperature, $\Delta T$. Table 2.6.1-3 shows the results of the evaluation. The minimum difference in lengths is calculated to be 0.23 inches between the material basket and HPI inner cavity, which results in no axial interference.

### 2.6.1.3. Stress Calculations

Regulatory Guide 7.8 stress combination results are presented in Section 2.6.7. Individual thermal stresses are summarized in Table 2.6.1-4. For the HPI and material basket, the evaluation of thermal stresses is not required per ASME Code III-NF (NF-3121.11).

### 2.6.1.4. Comparison with Allowable Stresses

This section presents the stress combinations based upon the design criteria presented in Section 2.1.2 for NCT. The cask stresses resulting from NCT are presented in Table 2.6.1-5. Comparison of the calculated stresses to the allowable stresses presented in Section 2.1.2 demonstrates that the Model 2000 cask meets the performance requirements. In addition, the condition of the overpack during NCT is evaluated in Section 2.12.1, Cases 4, 5, and 6.

Evaluation of the HPI for end and side drop orientations calculated stresses in key components including the inner and out [[ ]]. The results show that in all cases the calculated margin of safety is greater than +1. Therefore, the HPI meets the performance requirements specified in Section 2.1.2. The material basket was also evaluated for NCT drop conditions using classic methods. The results of the analysis show that the margin of safety is greater than +1. Therefore, the material basket meets the performance requirements specified in Section 2.1.2.

The NCT analysis results show that the overpack, cask, HPI and material basket meet all performance requirements, which include maintaining containment and geometry.

[[

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**Figure 2.6.1-1.  HPI Support Disk Details**

[[

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**Figure 2.6.1-2.  Material Basket Details**

[[

]]

**Figure 2.6.1-3.  HPI Inside Diameter**

**Table 2.6.1-1. Temperature Results, NCT (in Shade and with Insolation)**

| Component | 100°F Ambient Temperature, in Shade | | | 100°F Ambient Temperature, with Insolation | | |
|---|---|---|---|---|---|---|
| | Max | Min | Avg | Max | Min | Avg |
| Material Basket | 989 | 465 | 801 | 1,001 | 490 | 815 |
| HPI | 581 | 360 | --- | 604 | 388 | --- |
| HPI Shielding (top) | 517 | 506 | 513 | 539 | 529 | 535 |
| HPI Shielding (sides) | 581 | 435 | 544 | 601 | 460 | 565 |
| HPI Shielding (bottom) | 477 | 427 | 451 | 501 | 452 | 475 |
| Cask (bottom, shells, top, lid) | 430 | 309 | --- | 455 | 338 | --- |
| Cask Shielding (lid) | 424 | 408 | 414 | 449 | 433 | 440 |
| Cask Shielding (sides) | 405 | 341 | 385 | 431 | 370 | 412 |
| Cask Lid Seal | 406 | 383 | --- | 432 | 409 | --- |
| Cask Drain Port (bottom) | 342 | 309 | --- | 370 | 338 | --- |
| Cask Test Port (top) | 400 | 383 | --- | 426 | 409 | --- |
| Cask Vent Port (lid) | 416 | 410 | --- | 442 | 435 | --- |
| Overpack Base | 335 | 159 | --- | 364 | 184 | --- |
| Overpack Cover | 272 | 108 | --- | 308 | 174 | --- |
| Overpack Toroidal Shell (top) | 159 | 110 | 125 | 207 | 165 | 179 |
| Overpack Toroidal Shell (bottom) | 215 | 114 | 139 | 249 | 136 | 176 |
| Overpack Honeycomb Impact Limiter (top) | 220 | 205 | 215 | 263 | 249 | 258 |
| Overpack Honeycomb Impact Limiter (bottom) | 330 | 275 | 304 | 359 | 305 | 334 |
| HPI Fill Gas | 971 | 460 | 672 | 983 | 485 | 689 |
| Cask Fill Gas | 574 | 346 | 462 | 594 | 374 | 486 |
| HPI and Cask Fill Gas, Combined | 971 | 346 | 481 | 983 | 374 | 505 |

Note: Data taken from Table 3.3.1-1

**Table 2.6.1-2. Radial Thermal Expansion Evaluation for HPI and Material Basket**

[[

]]

**Table 2.6.1-3. Axial Thermal Expansion Evaluation for HPI and Material Basket**

[[

]]

**Table 2.6.1-4. NCT Thermal Stress Results (psi)**

| Case | Section Number | Thermal Stress (psi) |
|---|---|---|
| NCT End Drop | 1 | 15110 |
| NCT End Drop | 2 | 6404 |
| NCT Side Drop | 3 | 9649 |
| NCT Side Drop | 4 | 15110 |
| NCT Side Drop | 5 | 7039 |

**Table 2.6.1-5. Model 2000 Cask NCT Stress Analysis Summary (psi)**

| Case | Stress Component | Stress Combination | Stress Intensity | Allowable | Margin of Safety |
|---|---|---|---|---|---|
| 1 | $P_m$ | 5411 | 20000 | 20000 | 2.7 |
| | $P_m + P_b$ | 17510 | 20000 | 30000 | 0.7 |
| | Q | 15110 | 20000 | N/A | N/A |
| | $P_m + P_b + Q$ | 32620 | 20000 | 60000 | 0.8 |
| 2 | $P_m$ | 14500 | 20000 | 20000 | 0.4 |
| | $P_m + P_b$ | 25000 | 20000 | 30000 | 0.2 |
| | Q | 6404 | 20000 | N/A | N/A |
| | $P_m + P_b + Q$ | 31404 | 20000 | 60000 | 0.9 |
| 3 | $P_m$ | 2906 | 19300 | 19300 | 5.6 |
| | $P_m + P_b$ | 9699 | 19300 | 28950 | 2.0 |
| | Q | 9649 | 19300 | N/A | N/A |
| | $P_m + P_b + Q$ | 19348 | 19300 | 57900 | 2.0 |
| 4 | $P_m$ | 6023 | 19300 | 19300 | 2.2 |
| | $P_m + P_b$ | 17910 | 19300 | 28950 | 0.6 |
| | Q | 15110 | 19300 | N/A | N/A |
| | $P_m + P_b + Q$ | 33020 | 19300 | 57900 | 0.8 |
| 5 | $P_m$ | 16090 | 19300 | 19300 | 0.2 |
| | $P_m + P_b$ | 25950 | 19300 | 28950 | 0.1 |
| | Q | 7039 | 19300 | N/A | N/A |
| | $P_m + P_b + Q$ | 32989 | 19300 | 57900 | 0.8 |

### 2.6.2. Cold

The Model 2000 Transport Package is analyzed for structural adequacy in accordance with the thermal evaluation of the Model 2000 Transport Package for the temperatures specified in 10 CFR 71.71(c)(2) is presented in Chapter 3. The thermal evaluation demonstrates that the Model 2000 Transport Package component temperatures are maintained within their safe operating ranges for all normal conditions of transport. The bounding methodology for evaluating the thermal stress in the Model 2000 Transport Package is presented in Section 2.6.1 and individual thermal stresses are summarized in Table 2.6.1-4. Thermal stresses are combined with mechanical stresses in Section 2.6.7 and compared to the appropriate ASME Code allowables.

### 2.6.3. Reduced External Pressure

The drop in atmospheric pressure to 24 kPa (3.5 psia) is specified in 10 CFR 71.71(c)(3). This additional differential pressure has a negligible effect on the Model 2000 cask because, in Section 2.6.7, the cask is analyzed for a normal transport conditions internal pressure of 15.3 psig (30 psia). Maximum internal pressure is included in combination with internal loads. Because the margins of safety are all positive, this 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), has a negligible effect on the Model 2000 cask because of the thick outer shell and end closures. 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) are satisfied.

### 2.6.5. Vibration

The Model 2000 Transport Package is evaluated for effects of vibrations that are normally incident to transport, as specified in 10 CFR 71.71(c)(5). The effects of shock and vibration loads associated with this road on transportation on the Model 2000 are negligible as determined in this section. For this evaluation, rather than determining the frequency of vibration of the package to establish the maximum acceleration, the cask has been structurally analyzed using the accelerations associated with NCT. Table 2.6.7-1 provides a summary of the accelerations used to evaluate the cask. The accelerations are applied statically to the ANSYS model described in detail in Section 2.6.7 to produces the maximum stress intensity in the package components. The results of the cask body, HPI and material basket analyses show that the package is capable of experiencing continuous NCT accelerations without degrading the ability of the package to meet the other parts of the regulations. Additionally, the closure system is designed in accordance with NUREG/CR-6007, which determines the bolt preload based on the impact loads experienced during HAC, which bounds the loads experience during transport (Reference 2-15). Further, a fatigue analysis is performed in accordance with ASME Code, Section III, NB-3232.3,

which concluded that after 190 transports, all bolts shall be replaced. Therefore, the requirements of 10 CFR 71.71(c)(5) are satisfied.

### 2.6.6. Water Spray

Water causes negligible corrosion of the stainless shell of the Model 2000 Transport Package. The cask housed in the overpack and the contents are protected in the sealed cask cavity. A water spray as specified in 10 CFR 71.71(c)(6) has no adverse effect on the package. Therefore, the requirements of 10 CFR 71.71(c)(6) are satisfied.

### 2.6.7. Free Drop

The free drop scenario outlined by 10 CFR 71.71(c)(7) requires a demonstration of the structural adequacy of the Model 2000 cask for a 1-ft drop onto a flat, essentially unyielding horizontal surface in the orientation that inflicts the maximum damage to the cask. The Model 2000 Transport Package is shown to meet the free drop requirements through a combination of classic calculations, impact analyses, and static finite element. The evaluations include the qualification of the Model 2000 cask lid 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 (Reference 2-15) (Section 2.12.4). The combined effects of inertial loads, internal pressures, and thermal stress are considered for packaging components. The impact analysis of the package is presented in Section 2.12.1. Section 2.6.7.1 presents the evaluation of the cask body and Section 2.6.7.2 presents the structural evaluation of the HPI and material basket during free drop conditions. The cask body and HPI structural analyses are performed using the finite element program ANSYS (Reference 2-16) and the material basket is analyzed using classic methods.

#### 2.6.7.1. Cask Body Stress Analysis

This section evaluates the structural performances of the Model 2000 cask body analyses and shows that the design meets the requirements of 10 CFR 71.71. Specifically, the evaluation addresses the loads associated with the NCT. The results of the analyses for various load cases are presented pictorially in stress intensity contour plots as well as in table form, with the corresponding safety factors in critical components of the cask body.

##### 2.6.7.1.1. Model Description

Finite element analysis methods are used to perform the stress evaluation of the Model 2000 cask for normal free drop conditions. Each drop condition is analyzed using a three-dimensional finite element model using the computational modeling software ANSYS that were developed in accordance with the certification drawings. Figure 2.6.7-1 shows the major components of the cask represented in the model including the inner and outer shells, flange, top and bottom forgings, lid, and closure bolts.

As shown in Figure 2.6.7-1, the finite element model, which corresponds to half (180°) of the cask body, is generated by de-featuring the AutoDesk Inventor solid model and exporting the model to a .STEP file format. The .STEP file is imported directly into ANSYS where the finite

element model is developed. 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 is 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. Nodal displacements are used to simulate the interaction between the cask and overpack. Weak springs elements (COMBIN14) are inserted automatically during the solution to help stabilize the model. ANSYS assigns low spring stiffness so their presence will not adversely affect the accuracy of the solution.

Boundary conditions are applied to the model simulating the loading conditions the Model 2000 cask experiences during NCT. The 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. ANSYS input files are used to apply boundary conditions and loads to the cask model.

***Closure Lid Bolt Preload***

The required total bolt preload on the cask lid bolts is 32,000 lb (Section 2.12.4). To apply the bolt preload ANSYS pre-tension elements (PRETS179) are used to define the 3D pre-tension section within the meshed bolt. The PRETS179 element uses a single translation degree of freedom to define pretension direction. The pretension section is modeled by a set of pretension elements defined by the bolt shaft. Figure 2.6.7-2 shows the bolt pretension values and locations. As the figure shows, the bolt divided by the symmetry plane of the model is half of the other values presented.

***Internal Pressure Loading***

A pressure of 30 psia is used to envelope the maximum design pressure for all NCT impact loadings considered.

***Inertial Loads***

To evaluate the impact performance of the cask, an LS-DYNA analysis was performed (Section 2.12.1) to determine the maximum acceleration during hot/cold and heavy/light environmental conditions and varying impact limiter shell thicknesses. Table 2.6.7-1 provides a summary of the maximum accelerations that occur during cold/light conditions.

**Table 2.6.7-1. LS-DYNA Results**

| DESCRIPTION | DROP ANGLE (DEGREE) | APPLICABLE BOUNDARY CONDITION | | | | | | ACCELERATION (g) |
|---|---|---|---|---|---|---|---|---|
| | | Temperature | | | Payload | | | |
| | | Amb. | Hot | Cold | Nom. | Heavy | Light | |
| **NCT, End Drop, Cold** | 90 | – | – | ✓ | – | – | ✓ | 15.5 |
| **NCT, Side Drop, Cold** | 0 | – | – | ✓ | – | – | ✓ | 55.1 |
| **NCT, C.G.-Over-Corner Drop, Cold** | 22 | – | – | ✓ | – | – | ✓ | 14.6 |

***Cask Contents Loading—End Drop***

For the end drop analyses, the contents weight is assumed to be uniformly distributed on the cask top end, over an area determined by the inside diameter of the cask lid. Therefore, one half the contents weight of 5,450 lb is applied to the cask inner shell bottom plate as nodal forces. The contents load is multiplied by the appropriate g-load to accurately represent the 1-foot and 30-foot end drop.

***Cask Contents Loading—Side Drop***

For side drop conditions, the contact area between the contents and the cask cavity is approximately 120° (60° on each side of the drop centerline). The inertial load produced by the 5,450 lb contents weight is represented as nodal forces applied on the interior surface of the cask. The force is applied at the HPI [[ ]] locations to concentrate the bearing load and is varied in the circumferential direction as a cosine distribution. The maximum pressure occurs at the impact centerline; the load decreases to zero at locations that are approximately 60° either side of the impact centerline, as illustrated in Figure 2.6.7-3. The actual location is dependent on the actual nodal position. The following formula is used to determine the contents forces for the side drop analyses. This method uses a summation scheme to approximate the integration of the cosine-shaped pressure distribution:

$$F_{total} = \sum_{i=1}^{4} F_{max} \cos(\theta_i) \cos(\theta'_i)$$

$$F_{total} = 5{,}450/2 \text{ lb} \times G$$

where

$F_{max}$ = maximum pressure (at impact centerline)

$\theta_i$ = 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

$\theta'_i$ = normalized angle to peak at 0° and to be zero at 61.2°

G = impact acceleration

Figure 2.6.7-4 shows the applied nodal forces in the four regions for HAC based on the cosine distribution.

***Nodal Displacement***

With the absence of the overpack, nodal displacements are used to simulate the interaction between the overpack and cask body, which treats the cask body as a beam. For the side the nodes are constrained radially at the location where the cask body contacts the overpack. For the end drop, the nodal locations are visible in Figure 2.6.7-2 as a radial band at the top end of the cask. For the side drop, an additional smaller band of nodes located at the bottom end of the cask is used to represent the bottom impact limiter. Nodal displacements are also applied at the center plane of the cask to simulate symmetry. This is accomplished by fixing the out of plane displacement (Y) and the rotations about the other axes (X and Z).

***Thermal***

According to Regulatory Guide 7.8 (Reference 2-2), four credible thermal conditions must be considered.

*Condition 1 – Hot Case 1:*

a. Ambient temperature, 100°F
b. Initial temperature, 100°F
c. Heat transfer to ambient by natural convection, still air
d. Heat transfer to ambient by radiation
e. Solar insolation as a periodic heat flux applied as 12-hr on and 12-hr off
f. Internal heat load of 3000 W

*Condition 2 – Hot Case 2:*

a. Ambient temperature, 100°F
b. Initial temperature, 100°F
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 of 3000 W

*Condition 3 – Cold Case 1:*

a. Ambient temperature, -40°F
b. Initial temperature, -40°F
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 of 500 W (minimum payload case)

*Condition 4 – Cold Case 2:*

a. Ambient temperature, -20°F
b. Initial temperature, -20°F
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 of 3000 W

Review of the four heat conditions shows that a bounding thermal expansion model is possible by applying a 300°F temperature differential from the outside surface to the inside surface of the cask. For the thermal stress evaluation a temperature of 300°F is applied to the outer surface of the cask and 600°F to the inside surface of the cask. Using the higher temperatures maximizes the thermal expansion of the materials. 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. The temperatures are applied as a boundary condition static structural model using the ANSYS BF command. Figure 2.6.7-5 shows the temperature distribution that is imported into the static structural model to solve for the thermal stresses. The resulting thermal stresses (Q) are combined with the inertial and pressure stresses ($P_m$+ $P_b$) to meet the stress requirements presented in Section 2.1.2.

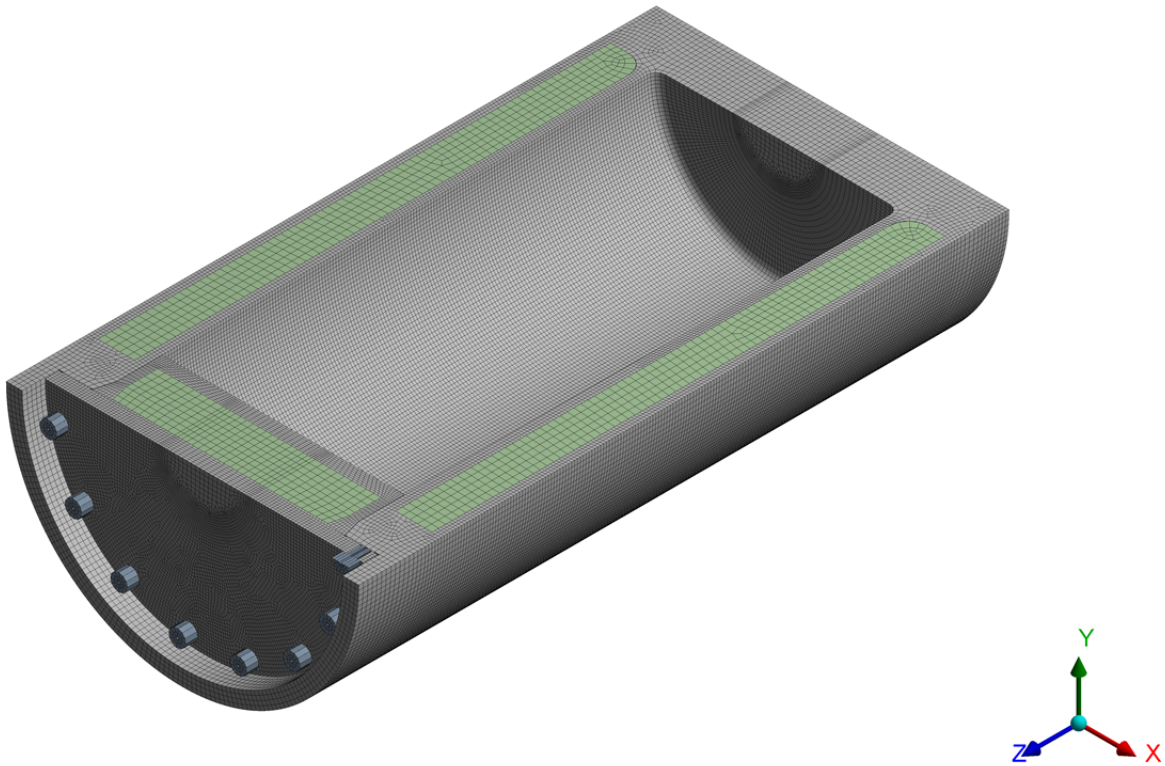


**Figure 2.6.7-1. ANSYS Finite Element Model of the Cask Body**

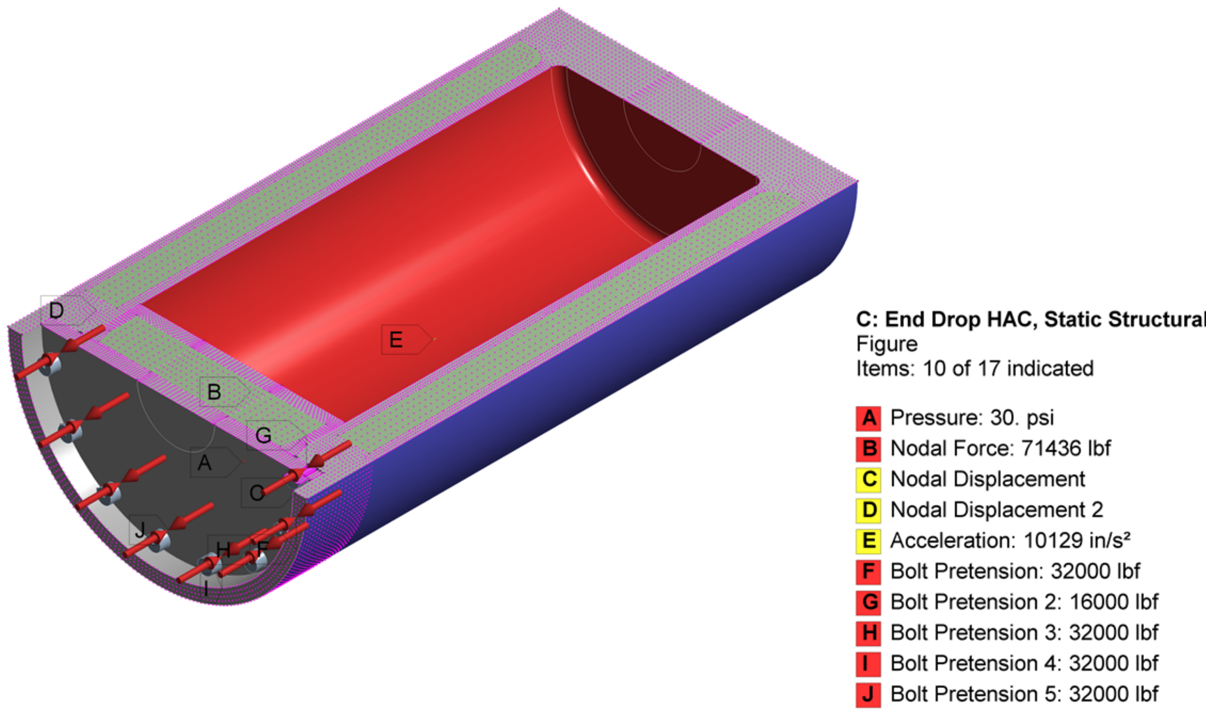


**Figure 2.6.7-2. Applied Boundary Conditions for End Drop Model**

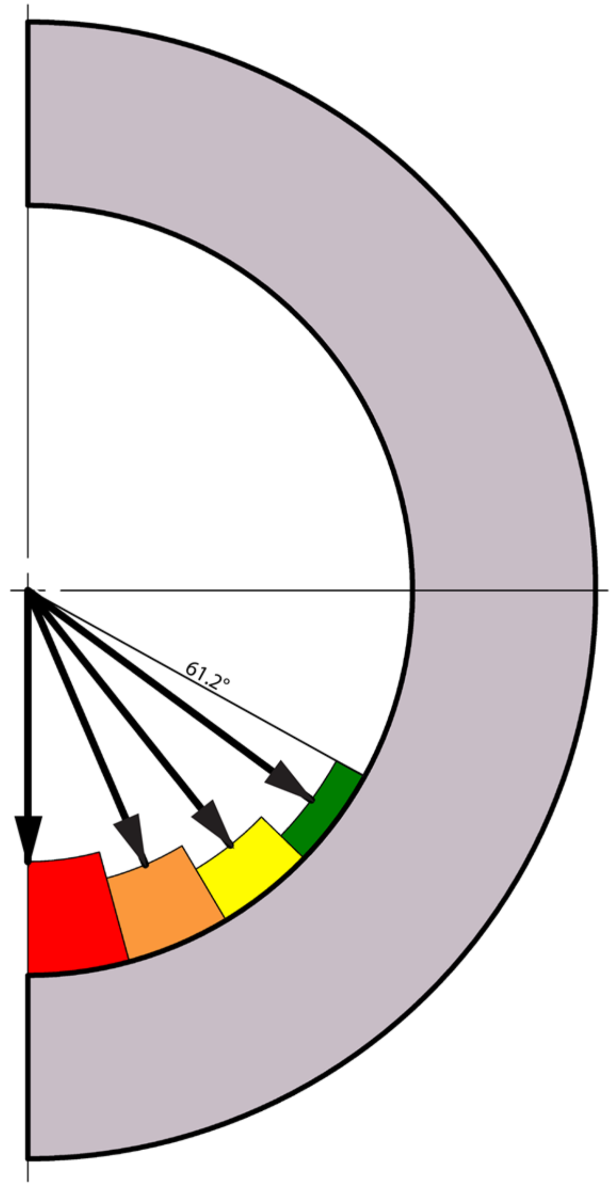


**Figure 2.6.7-3. Cosine Distribution to Simulate Contents Loading During Side Drop**

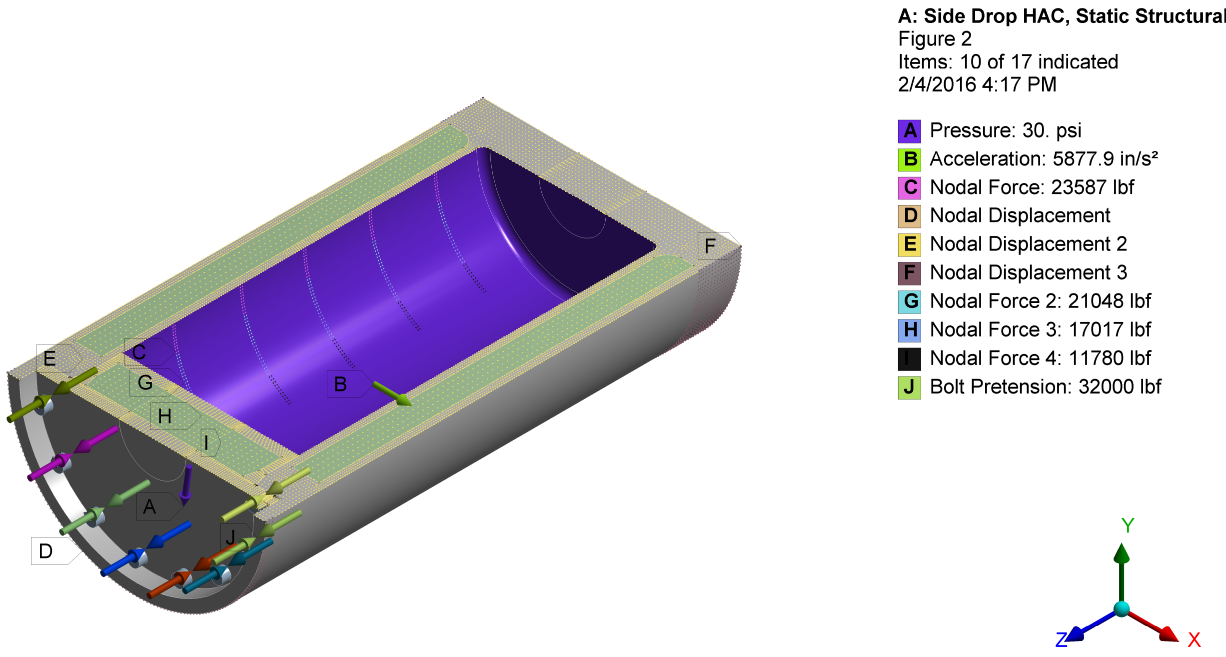


**Figure 2.6.7-4. Applied Boundary Conditions for Side Drop Model**

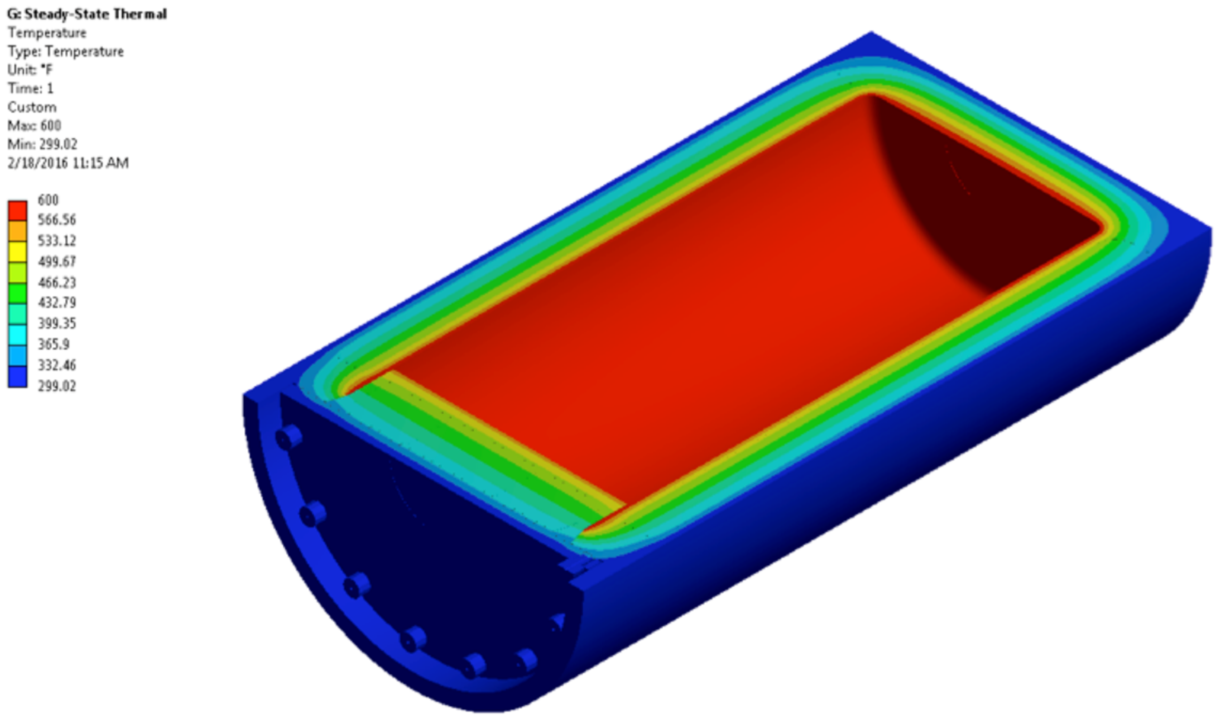


**Figure 2.6.7-5. Temperature Profile for Thermal Stress Evaluation**

#### 2.6.7.1.2. NCT End Drop

In accordance with the requirements of 10 CFR 71.71, the Model 2000 cask is structurally evaluated for the normal condition of transport 1-foot end-drop. In this event, the cask (equipped with an impact limiter over each end) falls a distance of 1-foot onto a flat, unyielding, horizontal surface. The cask strikes the surface in a vertical position; consequently, an end impact on the bottom end or top end of the cask occurs. Because the cask bottom of fabricated from a solid stainless steel forging, the top drop orientation was chosen to maximum damage to the cask containment boundary. Closure bolts are evaluated separately (Section 2.12.4).

The most critically stressed component in the system is the cask flange region, which is due to bending of the flange from the inertial load imposed by the cask lid. The second region of interest is in the cask lid in the closure bolt contact region. To evaluate the stresses in these regions linearized stress are calculated across the thickness of the plate. For the top flange, Figure 2.6.7-6 shows the location of the maximum total stress intensity and Figure 2.6.7-7 indicates the path (Section 1) location where the stresses are calculated. Table 2.6.7-2 is a listing of the Section 1 stresses. Table 2.6.7-3 documents the primary membrane ($P_m$), primary membrane plus primary bending ($P_m$+$P_b$), primary membrane plus primary bending plus secondary stress ($P_m$+$P_b$+Q) in accordance with the criteria presented in Regulatory Guide 7.6 (Reference 2-17). Stresses are compared to the allowable at a bounding temperature of 300°F. The minimum margin of safety is found to be +2.7 for primary membrane, +0.7 for primary membrane plus bending and +0.8 for primary membrane plus bending plus secondary stress intensity.

Figure 2.6.7-8 shows the location of the maximum total stress intensity in the lid and Figure 2.6.7-9 indicates the path (Section 2). Table 2.6.7-4 presents a listing of the Section 2 stresses and Table 2.6.7-5 provides the stress combinations in accordance with the Regulatory Guide 7.6 criteria. The minimum margin of safety is found to be +0.4 for primary membrane, +0.2 for primary membrane plus bending and +0.9 for primary membrane plus bending plus secondary stress intensity. Because all of the margins of safety are positive, the Model 2000 cask meets the end drop requirement of 10 CFR 71.71(c)(7).

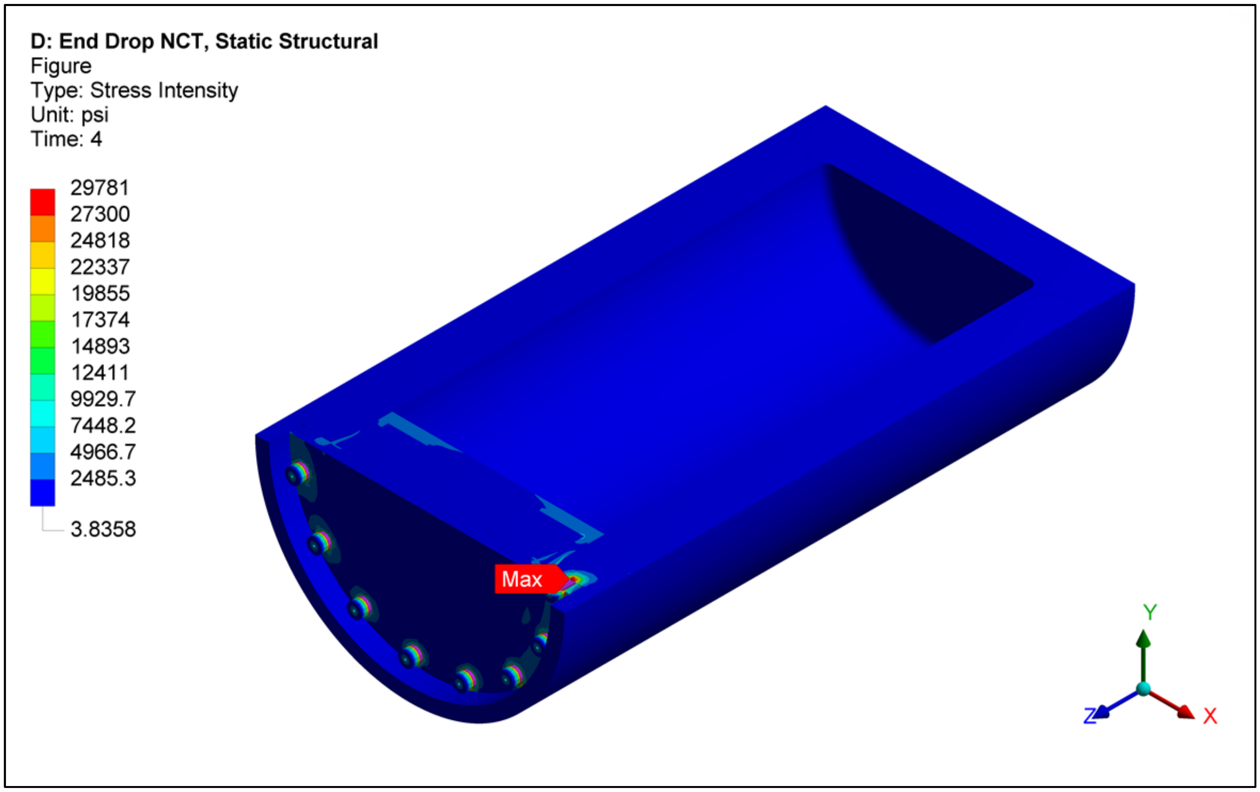


**Figure 2.6.7-6. NCT End Drop Cask Body Stress Intensity (total stress psi)**

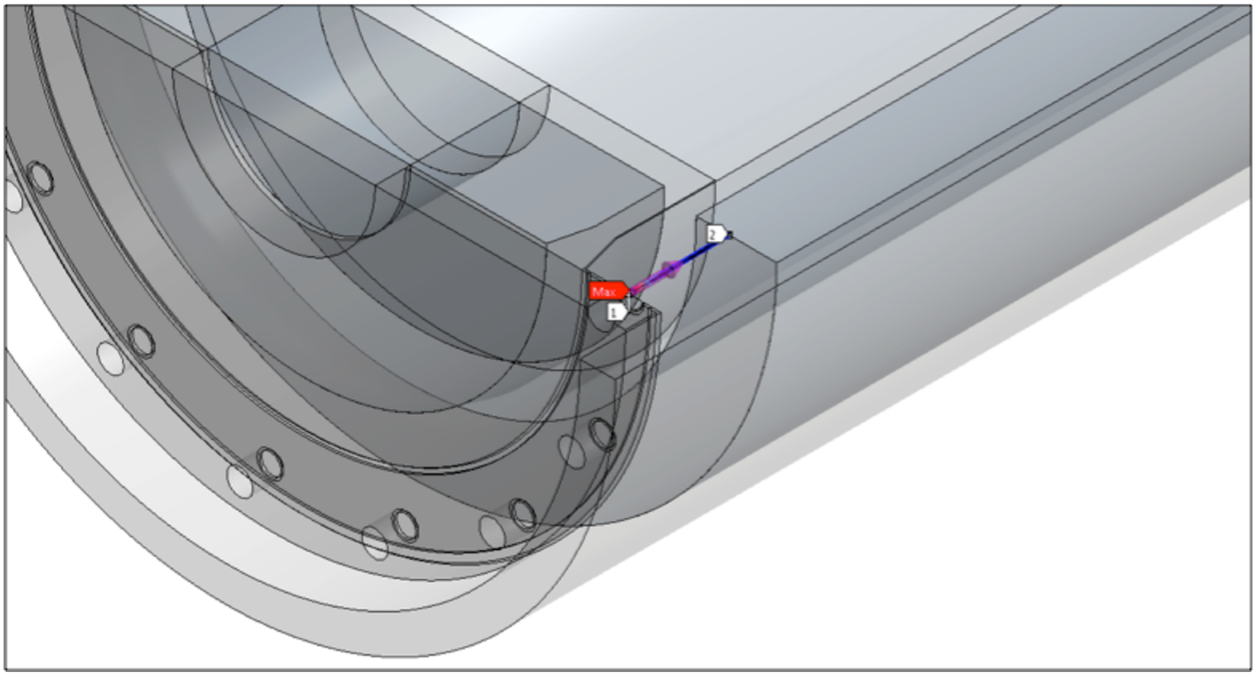


**Figure 2.6.7-7. NCT End Drop Linearized Stress Location (Section 1)**

**Table 2.6.7-2. NCT End Drop Section 1 Stress Results (psi)**

| Stress State | Location | S1 | S2 | S3 | SINT |
|---|---|---|---|---|---|
| MEMBRANE ($P_m$) | — | 5846 | 902 | 435 | 5411 |
| BENDING ($P_b$) | Inside | 14100 | 2053 | 1685 | 12420 |
| | Center | 0 | 0 | 0 | 0 |
| | Outside | -1685 | -2053 | -14100 | 12420 |
| MEMBRANE + BENDING | Inside | 19920 | 2688 | 2411 | 17510 |
| | Center | 5846 | 902 | 435 | 5411 |
| | Outside | -748 | -1599 | -8309 | 7561 |
| PEAK | Inside | 23120 | 13060 | 9779 | 13340 |
| | Center | -626 | -827 | -5431 | 4805 |
| | Outside | 7948 | 1290 | 966 | 6982 |
| TOTAL | Inside | 42540 | 15680 | 12760 | 29781 |
| | Center | 962 | -224 | -438 | 1401 |
| | Outside | 366 | -369 | -449 | 815 |

**Table 2.6.7-3. NCT End Drop Section 1 Stress Results (psi)**

| Stress Component | Stress Combination | Stress Intensity | Allowable | Margin of Safety |
|---|---|---|---|---|
| $P_m$ | 5411 | 20000 | 20000 | 2.7 |
| $P_m + P_b$ | 17510 | 20000 | 30000 | 0.7 |
| Q | 15110 | 20000 | N/A | N/A |
| $P_m + P_b + Q$ | 32620 | 20000 | 60000 | 0.8 |

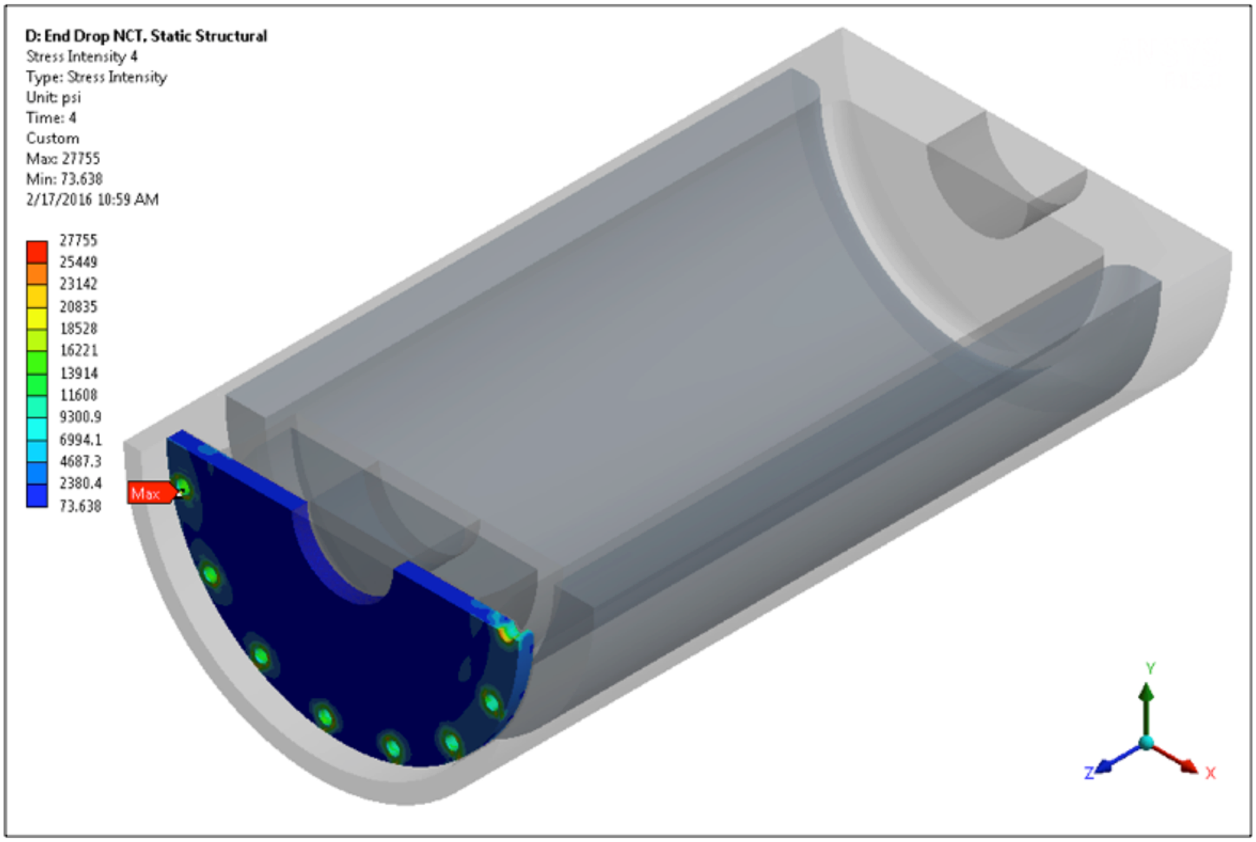


**Figure 2.6.7-8. NCT End Drop Lid Stress Intensity (total stress psi)**

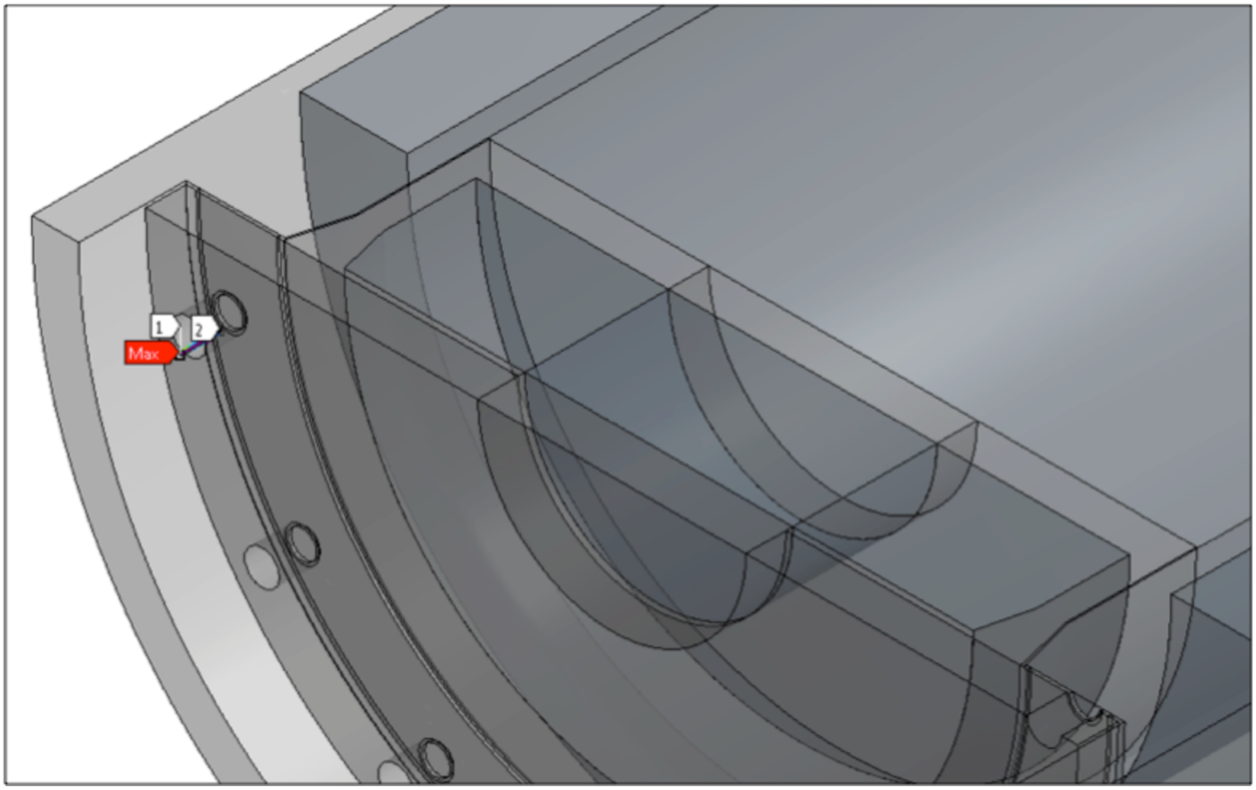


**Figure 2.6.7-9. NCT End Drop Linearized Stress Location (Section 2)**

**Table 2.6.7-4. NCT End Drop Section 2 Stress Results (psi)**

| Stress State | Location | S1 | S2 | S3 | SINT |
|---|---|---|---|---|---|
| MEMBRANE ($P_m$) | — | 285 | -189 | -14210 | 14500 |
| BENDING ($P_b$) | Inside | -2024 | -5455 | -13050 | 11030 |
| | Center | 0 | 0 | 0 | 0 |
| | Outside | 13050 | 5455 | 2024 | 11030 |
| MEMBRANE + BENDING | Inside | -2239 | -5170 | -27240 | 25000 |
| | Center | 285 | -189 | -14210 | 14500 |
| | Outside | 5740 | 2036 | -1360 | 7100 |
| PEAK | Inside | -9130 | -10750 | -14340 | 5215 |
| | Center | 4992 | 2307 | 395 | 4597 |
| | Outside | 235 | -3380 | -6623 | 6858 |
| TOTAL | Inside | -13380 | -14350 | -41140 | 27760 |
| | Center | 2592 | 294 | -9308 | 11900 |
| | Outside | 2789 | 1800 | -7942 | 10730 |

**Table 2.6.7-5. NCT End Drop Section 2 Stress Results (psi)**

| Stress Component | Stress Combination | Stress Intensity | Allowable | Margin of Safety |
|---|---|---|---|---|
| $P_m$ | 14500 | 20000 | 20000 | 0.4 |
| $P_m + P_b$ | 25000 | 20000 | 30000 | 0.2 |
| Q | 6404 | 20000 | N/A | N/A |
| $P_m + P_b + Q$ | 31404 | 20000 | 60000 | 0.9 |

### 2.6.7.1.3. NCT Side Drop

In accordance with the requirements of 10 CFR 71.71, the Model 2000 cask is structurally evaluated for the normal condition of transport 1-foot side-drop. In this event, the cask (equipped with an impact limiter over each end) falls a distance of 1-foot onto a flat, unyielding, horizontal surface. The cask strikes the surface in a horizontal position. Closure bolts are evaluated separately Section 2.12.4.

The most critically stressed component in the system is the cask inner shell at the interface with the bottom forging, the cask flange region, and the cask lid. To evaluate the stresses in these regions linearized stress are calculated across the thickness of the plate. For the cask inner shell, Figure 2.6.7-10 shows the location of the maximum total stress intensity and Figure 2.6.7-11 indicates the path (Section 3) location where the stresses are calculated. Table 2.6.7-6 is a listing of the Section 3 stresses. Table 2.6.7-7 documents the primary membrane ($P_m$), primary membrane plus primary bending ($P_m$+$P_b$), primary membrane plus primary bending plus secondary stress ($P_m$+$P_b$+Q) in accordance with the criteria presented in Regulatory Guide 7.6. Stresses are compared to the allowable at a bounding temperature of 350°F. The minimum margin of safety is found to be +5.6 for primary membrane, +2.0 for primary membrane plus bending and +2.0 for primary membrane plus bending plus secondary stress intensity.

For the top flange, Figure 2.6.7-12 shows the location of the maximum total stress intensity and Figure 2.6.7-13 indicates the path (Section 4) location where the stresses are calculated. Table 2.6.7-8 is a listing of the Section 4 stresses. Table 2.6.7-9 documents the primary membrane ($P_m$), primary membrane plus primary bending ($P_m$+$P_b$), primary membrane plus primary bending plus secondary stress ($P_m$+$P_b$+Q) in accordance with the criteria presented in Regulatory Guide 7.6. The minimum margin of safety is found to be +2.2 for primary membrane, +0.6 for primary membrane plus bending and +0.8 for primary membrane plus bending plus secondary stress intensity.

Figure 2.6.7-14 shows the location of the maximum total stress intensity in the lid and Figure 2.6.7-15 indicates the path (Section 5). Table 2.6.7-10 presents a listing of the Section 5 stresses and Table 2.6.7-11 provides the stress combinations in accordance with the Regulatory Guide 7.6 criteria. The minimum margin of safety is found to be +0.2 for primary membrane, +0.1 for primary membrane plus bending and +0.8 for primary membrane plus bending plus secondary stress intensity. Because all of the margins of safety are positive, the Model 2000 cask meets the end drop requirement of 10 CFR 71.71.

For NCT bearing stresses are also considered in the region where the HPI contacts the cask inner shell. Bearing stress is the total applied load divided by the contact area. Because contact with the HPI is explicitly modeled by applying nodal force at the location of the HPI [[ ]], the bearing stress can be represented as the normal stress in ANSYS. Figure 2.6.7-16 presents the normal stress distribution. As predicted the compressive stress with the largest magnitude, -10,009 psi, occurs at the centerline of the cask. Comparing the absolute value of the compressive stress to the yield strength of the 304 stainless steel at 600°F, 18,400 psi, the margin of safety is +0.84. Therefore, the bearing stress meets the stress criteria presented in Section 2.1.2.

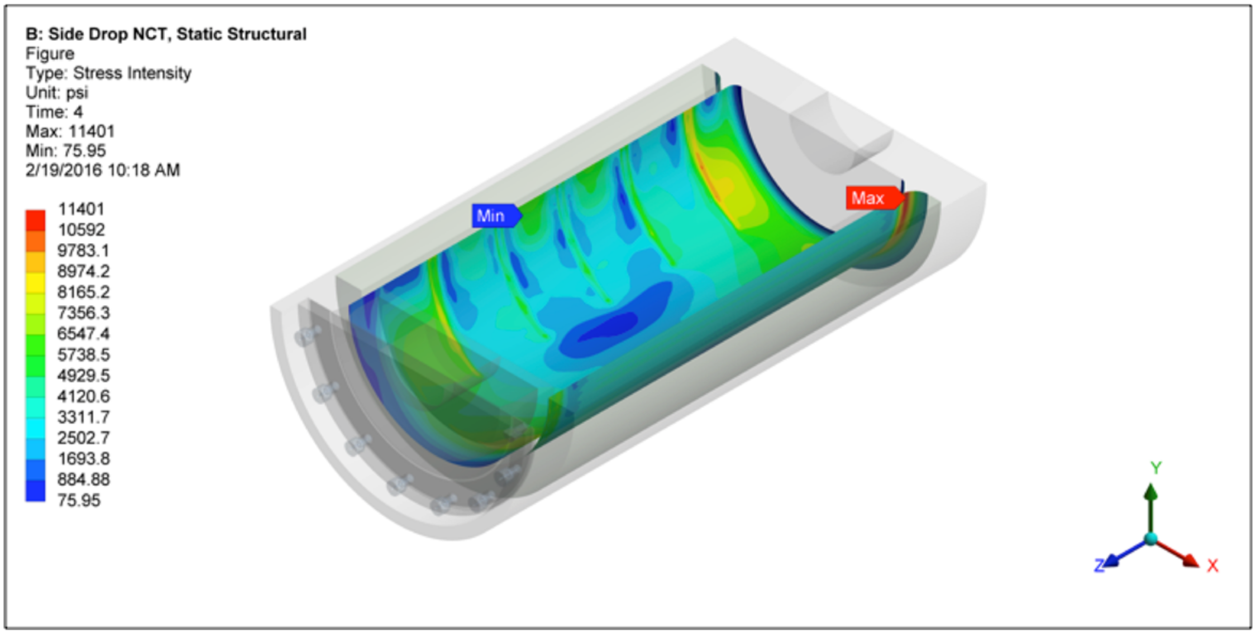


**Figure 2.6.7-10. NCT Side Drop Cask Inner Shell Stress Intensity (total stress psi)**

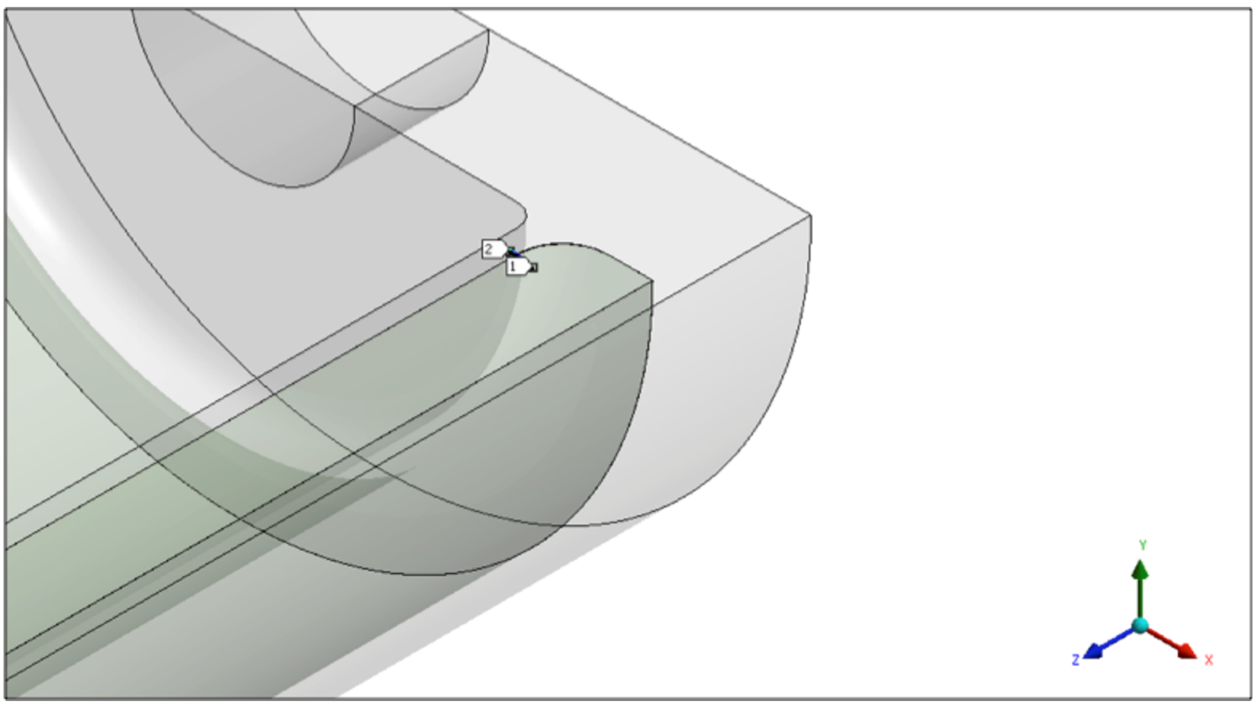


**Figure 2.6.7-11. NCT Side Drop Linearized Stress Location (Section 3)**

**Table 2.6.7-6. NCT Side Drop Section 3 Stress Results (psi)**

| Stress State | Location | S1 | S2 | S3 | SINT |
|---|---|---|---|---|---|
| MEMBRANE ($P_m$) | — | 2685 | 1199 | -221 | 2906 |
| BENDING ($P_b$) | Inside | 7757 | 2447 | 384 | 7373 |
| | Center | 0 | 0 | 0 | 0 |
| | Outside | -384 | -2447 | -7757 | 7373 |
| MEMBRANE + BENDING | Inside | 10150 | 3660 | 447 | 9699 |
| | Center | 2685 | 1199 | -221 | 2906 |
| | Outside | -50 | -1218 | -5656 | 5606 |
| PEAK | Inside | 1466 | 320 | -257 | 1723 |
| | Center | 118 | -40 | -328 | 446 |
| | Outside | 379 | -33 | -363 | 742 |
| TOTAL | Inside | 11600 | 3980 | 200 | 11401 |
| | Center | 2363 | 1155 | -104 | 2468 |
| | Outside | 41 | -1251 | -5731 | 5772 |

**Table 2.6.7-7. NCT Side Drop Section 3 Stress Results (psi)**

| Stress Component | Stress Combination | Stress Intensity | Allowable | Margin of Safety |
|---|---|---|---|---|
| $P_m$ | 2906 | 19300 | 19300 | 5.6 |
| $P_m + P_b$ | 9699 | 19300 | 28950 | 2.0 |
| Q | 9649 | 19300 | N/A | N/A |
| $P_m + P_b + Q$ | 19348 | 19300 | 57900 | 2.0 |

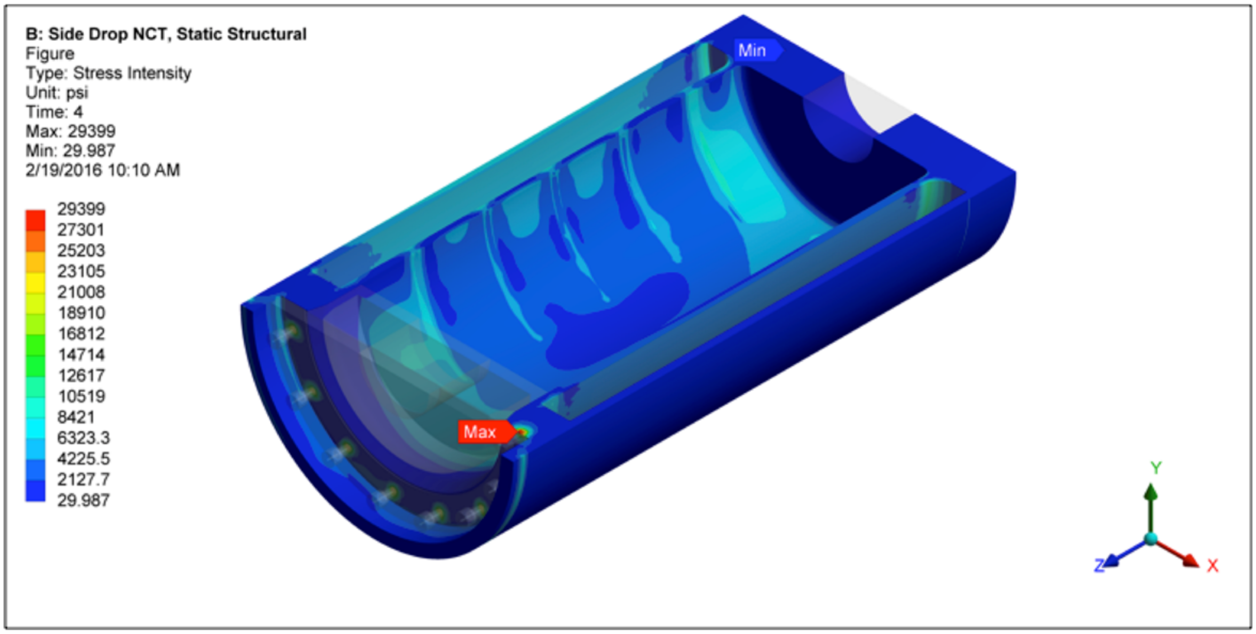


**Figure 2.6.7-12. NCT Side Drop Cask Flange Stress Intensity (total stress psi)**

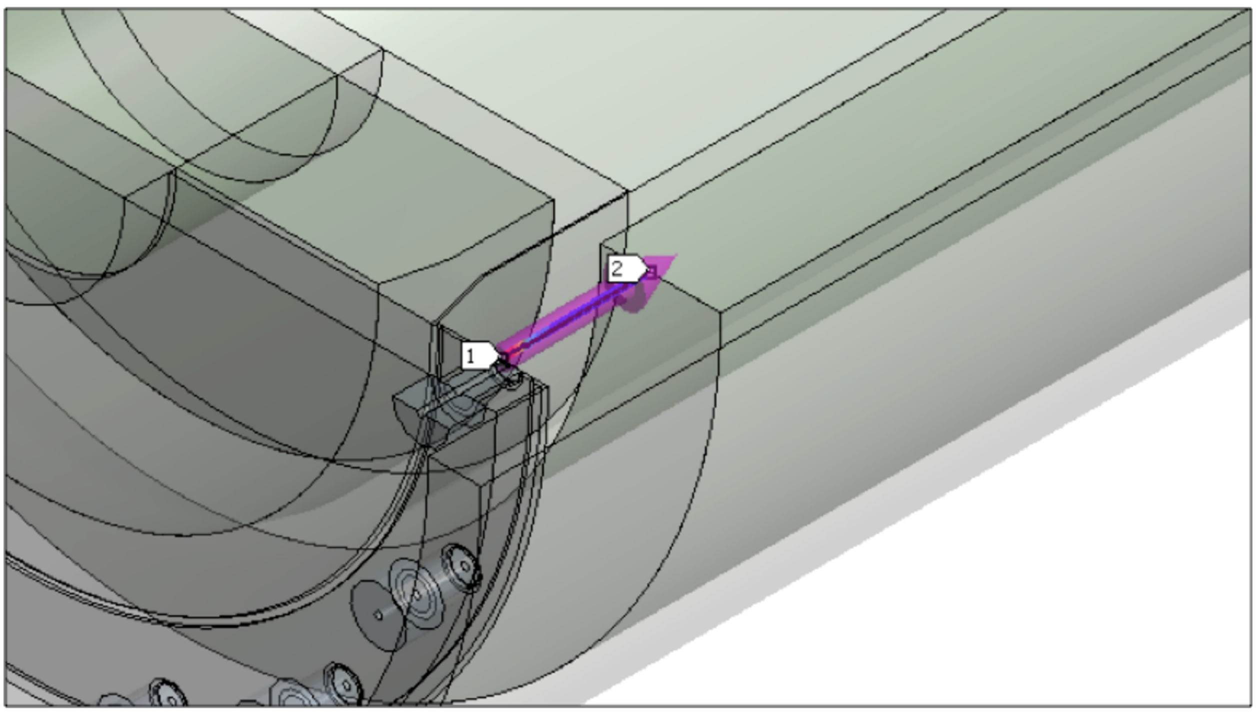


**Figure 2.6.7-13. NCT Side Drop Linearized Stress Location (Section 4)**

**Table 2.6.7-8.  NCT Side Drop Section 4 Stress Results (psi)**

| Stress State | Location | S1 | S2 | S3 | SINT |
|---|---|---|---|---|---|
| MEMBRANE ($P_m$) | — | 6412 | 939 | 389 | 6023 |
| BENDING ($P_b$) | Inside | 13800 | 2527 | 1895 | 11900 |
| | Center | 0 | 0 | 0 | 0 |
| | Outside | -1895 | -2527 | -13800 | 11900 |
| MEMBRANE + BENDING | Inside | 20200 | 3478 | 2287 | 17910 |
| | Center | 6412 | 939 | 389 | 6023 |
| | Outside | -1476 | -1576 | -7429 | 5952 |
| PEAK | Inside | 22380 | 12760 | 10030 | 12350 |
| | Center | -681 | -1027 | -5044 | 4363 |
| | Outside | 7436 | 1432 | 1107 | 6329 |
| TOTAL | Inside | 42240 | 16060 | 12840 | 29400 |
| | Center | 1480 | -190 | -302 | 1782 |
| | Outside | 45 | -120 | -431 | 477 |

**Table 2.6.7-9.  NCT Side Drop Section 4 Stress Results (psi)**

| Stress Component | Stress Combination | Stress Intensity | Allowable | Margin of Safety |
|---|---|---|---|---|
| $P_m$ | 6023 | 19300 | 19300 | 2.2 |
| $P_m + P_b$ | 17910 | 19300 | 28950 | 0.6 |
| Q | 15110 | 19300 | N/A | N/A |
| $P_m + P_b + Q$ | 33020 | 19300 | 57900 | 0.8 |

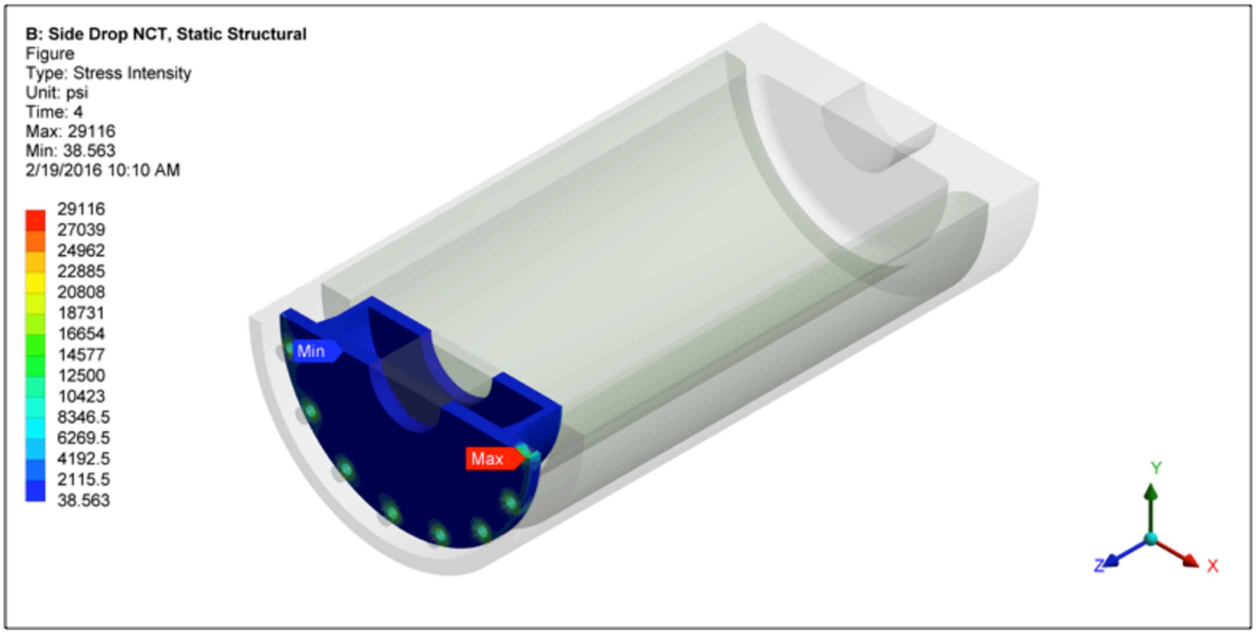


**Figure 2.6.7-14. NCT Side Drop Cask Lid Stress Intensity (total stress psi)**

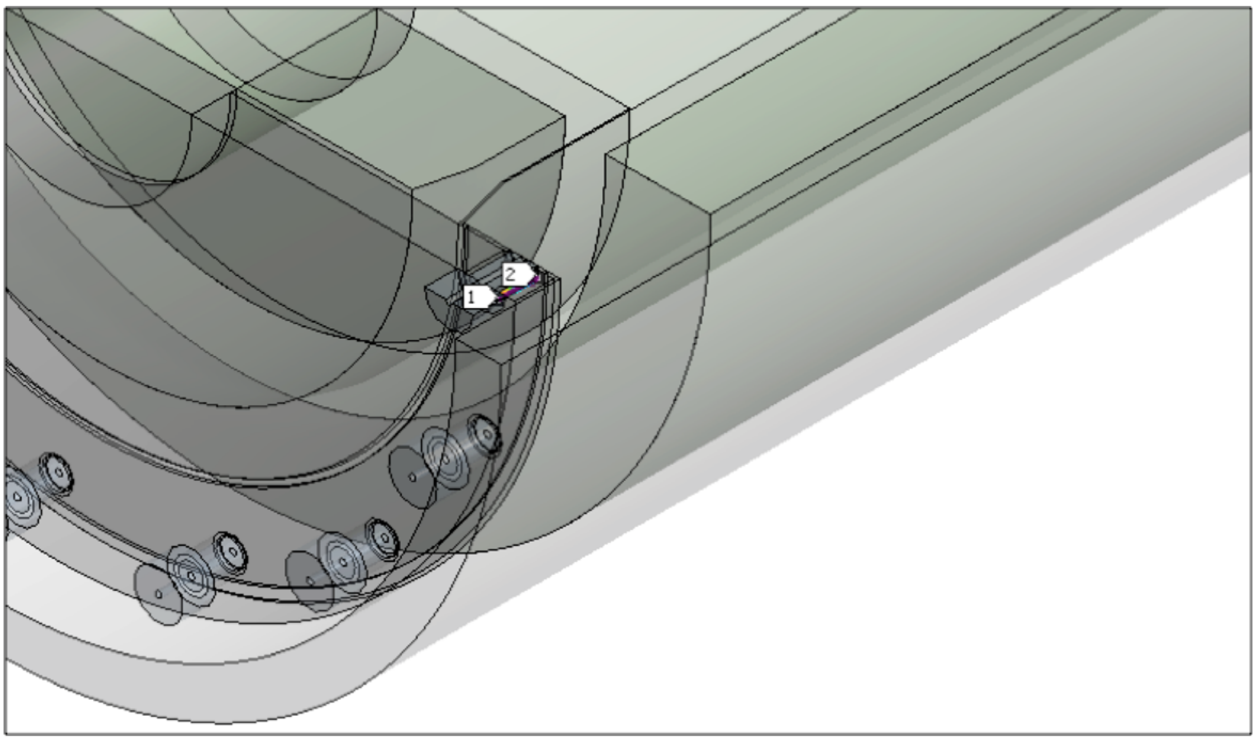


**Figure 2.6.7-15. NCT Side Drop Linearized Stress Location (Section 5)**

**Table 2.6.7-10. NCT Side Drop Section 5 Stress Results (psi)**

| Stress State | Location | S1 | S2 | S3 | SINT |
|---|---|---|---|---|---|
| MEMBRANE ($P_m$) | — | -684 | -4079 | -16770 | 16090 |
| BENDING ($P_b$) | Inside | -343 | -5757 | -10400 | 10060 |
| | Center | 0 | 0 | 0 | 0 |
| | Outside | 10400 | 5757 | 343 | 10060 |
| MEMBRANE + BENDING | Inside | -1106 | -9877 | -27050 | 25950 |
| | Center | -684 | -4079 | -16770 | 16090 |
| | Outside | 1773 | -30 | -6771 | 8544 |
| PEAK | Inside | 117 | -4066 | -6171 | 6288 |
| | Center | 3818 | 2746 | 408 | 3410 |
| | Outside | 640 | -4755 | -5971 | 6611 |
| TOTAL | Inside | -1541 | -15960 | -30660 | 29120 |
| | Center | 10 | -1488 | -13080 | 13090 |
| | Outside | 726 | -3232 | -12610 | 13330 |

**Table 2.6.7-11. NCT Side Drop Section 5 Stress Results (psi)**

| Stress Component | Stress Combination | Stress Intensity | Allowable | Margin of Safety |
|---|---|---|---|---|
| $P_m$ | 16090 | 19300 | 19300 | 0.2 |
| $P_m + P_b$ | 25950 | 19300 | 28950 | 0.1 |
| Q | 7039 | 19300 | N/A | N/A |
| $P_m + P_b + Q$ | 32989 | 19300 | 57900 | 0.8 |

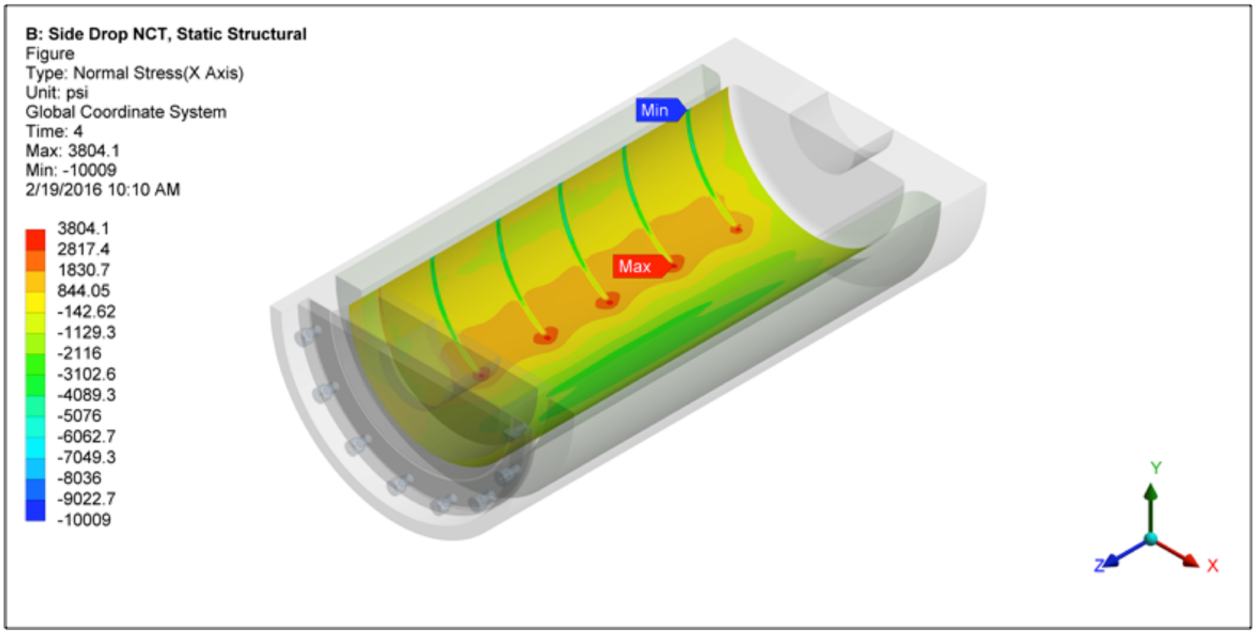


**Figure 2.6.7-16. NCT Side Drop Normal Stress Distribution (psi)**

### 2.6.7.1.4. NCT Corner Drop

The Model 2000 cask is composed of materials other than fiberboard or wood. Also, the weight of the Model 2000 cask exceeds 220 lb. According to 10 CFR 71.71(c)(8), the corner drop test is not applicable to the Model 2000 cask.

### 2.6.7.1.5. Penetration

According to 10 CFR 71.71(c)(10), a penetration test involving a 13-lb penetration cylinder dropped from a height of 40 inches is required for evaluation of packages during normal conditions of transport. However, Regulatory Guide 7.8 states "the penetration test of 10 CFR 71.71 is not considered by the NRC staff to have structural significance for large shipping casks (except for unprotected valves and rupture disks) and is not considered as a general requirement." A penetration evaluation is not performed because the Model 2000 cask has no unprotected valves or rupture disks that could be affected by normal conditions of transport.

### 2.6.7.2. HPI Stress Analysis

The purpose of this section is to document the Model 2000 HPI and material basket analyses that shows the design meets the requirements of 10 CFR 71. Specifically, the evaluation addresses the mechanical loads associated with the NCT.

The results of the analyses for various load cases are presented pictorially as stress intensity contour plots as well as in table form, with the corresponding margin of safety in each component of the cask body.

#### 2.6.7.2.1. HPI Model Description

The HPI design was developed using Autodesk Inventor. To generate the ANSYS compatible solid model, the Inventor model of the HPI is divided in half (180°) along the center plane. The final solid model is exported as a .STEP file and is imported directly into ANSYS where the finite element model is meshed. The solid model of the HPI is shown in Figure 2.6.7-17.

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 HPI [[ ]] and depleted uranium (DU) shielding is modeled using CONTAC174/TARGE170 surface-to-surface contact elements with zero friction, which allows the DU to float between the inner and outer shells. Contact elements are also used to bond dissimilarly meshed components. Spring elements (COMBIN14) are inserted automatically during the solution to help stabilize the model. ANSYS assigns low spring stiffness so their presence will not adversely affect the accuracy of the solution. Welds are modeled using ANSYS contact elements.

#### 2.6.7.2.2. HPI Side Drop Model

The HPI side drop model evaluates the stresses in the [[ ]] and HPI assembly to ensure the HPI maintains structural integrity during NCT. Using the base model, refinements are made in the [[ ]] mesh to ensure accurate results. Figure 2.6.7-18 shows the finite element model of the HPI.

To simulate contact with the cask, the interaction between the HPI and cask inner shell is modeled using CONTAC52 gap elements, 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. Figure 2.6.7-19 shows the distribution of the contact elements used to simulate contact between the HPI and cask inner shell.

#### 2.6.7.2.3. HPI End Drop Model

Of primary concern during a top or bottom end impact event is the inertial loading of the [[ ]] plug. For this case, a top impact is assumed because the HPI bottom [[ ]] is composed of [[ ]] inches of depleted uranium. To evaluate the bottom [[ ]], the [[ ]] subassembly is treated as a separate component. Figure 2.6.7-20 shows the solid model of the bottom [[ ]] assembly. The bottom [[ ]] is bolted to the HPI as a means of lifting the HPI from the cask without the need to remove the material basket. However, no credit is taken for the bolt. Therefore, only the lid assembly is evaluated using a highly refined mesh to accurately predict stresses at the weld seam. Figure 2.6.7-21 shows the finite element model of the bottom [[ ]].

[[

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**Figure 2.6.7-17. HPI Solid Model**

[[

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**Figure 2.6.7-18. HPI Side Drop Finite Element Model**

[[

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**Figure 2.6.7-19. Contact Elements Between HPI and Cask Inner Shell**

[[

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**Figure 2.6.7-20. Solid Model of HPI Bottom [[ ]]**

[[

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**Figure 2.6.7-21. Finite Element Model of HPI Bottom [[ ]]**

### 2.6.7.2.4. Boundary Conditions

Boundary conditions are applied to the model simulating the loading conditions the HPI will experience during NCT. The five categories of cask loading considered in the free drop event are pressure loaded to simulate side drop contents, discrete mass to simulate end drop, thermal conditions, inertial body load and displacement. ANSYS input files are used to apply boundary conditions and loads to the cask model.

***Inertial Load***

To evaluate the impact performance of the HPI, an LS-DYNA analysis was performed (Section 2.12.1) to determine the maximum acceleration during hot/cold and heavy/light environmental conditions and varying impact limiter shell thicknesses. Table 2.6.7-12 provides a summary of the maximum accelerations that occur during cold conditions. With the exception of corner drop case, the accelerations listed in Table 2.6.7-12 are applied to the HPI model using the ANSYS ACEL command equivalent to NCT accelerations corresponding to the 0.3-meter drop case. Equivalent static forces, in accordance with D'Alembert's principle, represent the applied accelerations.

***Pressure Loading Contents - Side Drop***

Two cases are presented to evaluate the performance of the HPI during the side drop. Case 1 is a concentrated pressure distribution at the four [[ ]] locations ("line load"). Case 2 is a uniform pressure distribution ("area load"). The contact area between the material basket and the HPI inner shell is approximately 180° (90° on each side of the drop centerline). The inertial load produced by the 317-lb. content weight is represented as an equivalent static pressure applied on the interior surface of the cask. The pressure is uniformly distributed along the cavity length and is varied in the circumferential direction as a cosine distribution. The maximum pressure occurs at the impact centerline; the pressure decreases to zero at locations that are 90° from either side of the impact centerline. The pressure loading simulating the Case 1 (line load)

is illustrated in Figure 2.6.7-22 and Figure 2.6.7-23 shows the pressure loading for Case 2 (area load). 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:

$$F_{total} = \sum_{i=1}^{180} P_{max} A_i \cos(\theta_i) \cos(\theta'_i)$$

$$F_{total} = 317/2 \text{ kg} \times G$$

where

$P_{max}$ = maximum pressure (at impact centerline)
$\theta_i$ = 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
$\theta'_i$ = normalized angle to peak at 0° and to be zero at 90°
$A_i$ = $i^{th}$ circumferential area over which the pressure is applied
G = side acceleration

Gap elements are defined at both ends of the cask to simulate the pressure applied by the cask inner shell during side drop conditions (see Figure 2.6.7-19). This is accomplished by defining the gap stiffness as a cosine function from a maximum value $1 \times 10^6$ lb/in at the centerline to 87,156 lb/in at 85° from the centerline of impact, and a value 50,000 lb/in from 90° to 180°.

**Table 2.6.7-12. LS-DYNA NCT Impact Results Summary**

| DESCRIPTION | DROP ANGLE (DEGREE) | APPLICABLE BOUNDARY CONDITION | | | | | | ACCELERATION (g) |
|---|---|---|---|---|---|---|---|---|
| | | Temperature | | | Payload | | | |
| | | Amb. | Hot | Cold | Nom. | Heavy | Light | |
| NCT, Cold, End Drop | 90 | — | — | X | — | — | X | 15.5 |
| NCT, Cold, Side Drop | 0 | — | — | X | — | — | X | 55.1 |
| NCT, Cold, Corner Drop | 68 (=90-22) | — | — | X | — | — | X | 14.6 |

[[

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**Figure 2.6.7-22. Cosine Pressure Distribution Simulating Material Basket [[ ]]**

[[

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**Figure 2.6.7-23. Cosine Pressure Distribution Assuming Uniform Contact**

#### 2.6.7.2.5. HPI NCT Side Drop Results

To evaluate the stresses in the HPI body, with a concentrated pressure load at the material basket [[ ]], linearized section stresses are evaluated at the intersection of plates, weld joints and anywhere a stress riser is observed. Stresses are evaluated using the ANSYS APDL macro language to cycle through each location of interest. To provide a thorough understanding of the stress profile, 684 individual sections are evaluated at axial and radial increments. At each section location, the primary membrane ($P_m$) and primary membrane plus primary bending ($P_m$+$P_b$) are calculated and compared to the stress criteria in accordance with the criteria presented in ASME Section III-NF (Reference 2-3). Figure 2.6.7-24 provides a visual representation of the section stress locations. Because of the total number of sections and close proximity, the section numbers are not legible. Separately, an additional seven sections are evaluated in the worst-case [[ ]]. Figure 2.6.7-25 provides a visual representation of the section stress locations for the [[ ]].

#### 2.6.7.2.6. NCT Case 1 Stress Results

The top 30 stress results for the Case 1 NCT HPI body results are presented in Table 2.6.7-13. Figure 2.6.7-26 and Table 2.6.7-14 present the Case 1 NCT [[ ]] stress results. As shown in the tables, the margins of safety when compared to the stress intensity for each category are greater than one.

Bearing loads, per ASME III-NF-3223.1 for Service Level A (NCT) events, are compared to the yield stress at temperature. From the ANSYS output, the maximum bearing stress that results from the total force applied by the material basket [[ ]] to the HPI inner shell is 1690.2 psi. Assuming a maximum temperature of 1000°F the yield stress is 17,000 psi. Therefore, the margin of safety is 9.1.

[[

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**Figure 2.6.7-24. Linearized Section Locations for the HPI Body Evaluation**

[[

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**Figure 2.6.7-25. Linearized Section Locations for the [[ ]] Evaluation**

**Table 2.6.7-13. NCT Case 1 HPI Body Top 30 Results**

[[

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Table Key:

- M = Membrane stress intensity (psi)
- M+B = Membrane + Bending stress intensity (psi)
- In = stress at the inside surface of the element (psi)
- Cen = stress at the center of the element (psi)
- Out = stress at the outer surface of the element (psi)
- Max = maximum of in, cen, and out, which is compared to the allowable stress (psi)
- Allowable = Allowable stress at temperature (psi)
- MS = Margin of safety

[[

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**Figure 2.6.7-26. Case 1, NCT, Stress Intensity Result (psi)**

**Table 2.6.7-14. NCT Support Disk Case 1 Results**

[[

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### 2.6.7.2.7. NCT Case 2 Stress Results

The top 30 stress results for the Case 2 NCT HPI body results are presented in Table 2.6.7-15. Figure 2.6.7-27 and Table 2.6.7-16 present the Case 2 NCT support disk stress results. Review of the stress results shows that there is sufficient positive margin of safety of all cases.

Bearing loads per ASME III-NF-3223.1 for Service Level A (NCT) events are compared to the yield stress at temperature. From the ANSYS output the maximum bearing stress that results from the total force applied by the material basket to the HPI inner shell is 60.0 psi. Assuming a maximum temperature of 1000°F the yield stress is 17,000 psi. Therefore, the margin of safety is +Large.

**Table 2.6.7-15. NCT Case 2 HPI Body Top 30 Results**

[[

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Table Key:

- M = Membrane stress intensity (psi)
- M+B = Membrane + Bending stress intensity (psi)
- In = stress at the inside surface of the element (psi)
- Cen = stress at the center of the element (psi)
- Out = stress at the outer surface of the element (psi)
- Max = maximum of in, cen, and out, which is compared to the allowable stress (psi)
- Allowable = Allowable stress at temperature (psi)
- MS = Margin of safety

[[

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**Figure 2.6.7-27. Case 2, NCT, Stress Intensity Result (psi)**

**Table 2.6 7-16. NCT Support Disk Case 2 Results**

[[

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### 2.6.7.2.8. HPI NCT End Drop Results

Stress results for the NCT end drop discussed previously are documented in Table 2.6.7-17. The table presents the primary membrane ($P_m$) and primary membrane plus primary bending ($P_m$+$P_b$) in accordance with the criteria presented in ASME Section III-NF (Reference 2-3).

As shown in the table, the margins of safety when compared to the stress intensity for each category are positive. The most critically stressed component in the system is the [[

]]. The minimum margin of safety is found to be large. The locations of the critical sections corresponding to the maximum stress location and axial displacement are shown in Figure 2.6.7-28.

**Table 2.6.7-17. NCT End Drop Stress Summary**

[[

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[[

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**Figure 2.6.7-28. HPI NCT End Drop Results – Peak Stress Intensity (psi) and Displacement (inches)**

### 2.6.7.3. Material Basket Evaluation

This section evaluates the material basket for NCT. Factors of safety for the basket are calculated based on the criteria for Service Level 'A' limits from ASME Section III-NF (NF-3221). During the end drop case, the [[ ]] columns are not loaded in the axial direction because the basket contents would either load the HPI [[ ]] or the cask bottom. However, during the side drop the steel [[ ]] provides a close fit with the high performance insert inner shell, which distributes the inertial load as three beam [[ ]] along the length of the basket assembly. The basket is assembled using short [[ ]] at each end of the basket starting at the center location. To provide strength to the basket assembly, [[ ]] are added between the [[ ]] at the outside of the assembly forming a [[ ]] shape. For this evaluation it is assumed that only the outer [[ ]] connected by the [[ ]] carry the load. Additionally, no credit is taken for the [[ ]] shape, which is significantly stiffer than the individual [[ ]]. The basket is analyzed using classical hand calculations for a 55.1 g side drop inertia load and a bounding weight of [[ ]] pounds. Assuming one-third of the inertial load is carried by one of the equivalent beam [[ ]], the bending stress in the basket is:

$$\sigma_b = \frac{Mc}{I_{cc}} = 688.4 \text{ psi}$$

| | | | | | |
|---|---|---|---|---|---|
| where | $P$ | = | $W \times G$ | = [[ ]] lb | Load on 12 [[ ]] section |
| | $W$ | = | [[ ]] | | Bounding basket weight |
| | $G$ | = | 55.1 g | | NCT side drop acceleration |
| | $M$ | = | $\frac{Wa \times l^2}{12}$ | = 7224.4 lb-in | Bending moment |
| | $l$ | = | [[ ]] in | | Length of beam section |
| | $Wa$ | = | 391.02 lb/in | | Uniformly distributed load |
| | $c$ | = | 3.73 in | | Neutral axis to outer fiber |
| | $I_{cc}$ | = | 39.09 $in^4$ | | Moment of inertia (12 [[ ]]) |

The moment of inertia calculation is shown in Table 2.6.7-18.

**Table 2.6.7-18. Moment of Inertia Calculation**

[[

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The pure shear stress, ASME III NF-3223.2, which develops across the composite [[ ]] section during the side drop is:

$$\tau = \frac{P}{2A} \approx 744.8 \text{ psi} < 0.6S_m = 0.6 \times 15900 = 9540 \text{ psi}$$

where

| | | | |
|---|---|---|---|
| $P$ | = | 5822.2 lb | |
| $A$ | = | 3.91 in² | Cross-sectional area (12 [[ ]]) |
| $d_o$ | = | [[ ]] in | Outside diameter of [[ ]] |
| $d_i$ | = | [[ ]] in | Inside diameter of [[ ]] |

The stress intensity in the basket that results from the combination of the bending and shear stresses is

$$\sigma = \sqrt{\sigma_b^2 + 4\tau^2} = 1641.0 \text{ psi}$$

The margin of safety is

$$MS = \frac{1.5S_m}{\sigma} - 1 = \frac{23850}{1641.0} - 1 = +\text{Large}$$

[[ ]] that attach adjoining outer layer of [[ ]] hold the basket together using [[ ]] (ASME III-NF, Class 1). The spacer strips and welds are equivalent in thickness and strength to the adjoining [[ ]]. Therefore, the previous analysis bounds the stresses generated in the welds.

### 2.6.8. Corner Drop

The Model 2000 cask is composed of materials other than fiberboard or wood. Also, the weight of the Model 2000 cask exceeds 220 lb. According to 10 CFR 71.71(c)(8), the corner drop test is not applicable to the Model 2000 cask. Additionally, as can be seen in Table 2.6.7-12, the end drop and side drop NCT accelerations bound the corner drop. Therefore, a stress analysis of the corner drop scenario is not required.

### 2.6.9. Compression

This test does not apply to the Model 2000 Transport Package, because the package weight is in excess of 11,000 lb (5,000 kg).

### 2.6.10. Penetration

According to 10 CFR 71.71(c)(10), a penetration test involving a 13-lb penetration cylinder dropped from a height of 40 inches is required for evaluation of packages during NCT. However, Regulatory Guide 7.8 states "the penetration test of 10 CFR 71.71 is not considered by the NRC staff to have structural significance for large shipping casks (except for unprotected valves and rupture disks) and is not considered as a general requirement." A penetration evaluation is not performed because the Model 2000 cask has no unprotected valves or rupture disks that could be affected by normal conditions of transport.

## 2.7 Hypothetical Accident Conditions

The Model 2000 Transport Package has been demonstrated to meet the performance requirements specified in Subpart E of 10 CFR 71, when subjected to hypothetical accident conditions as specified in 10 CFR 71.73. According to the Regulatory Guide 7.6

(Reference 2-17), for the hypothetical accident conditions the stress intensities resulting from primary membrane and primary bending stresses are to be investigated. The stress intensities from the thermal stresses are presented in this section.

### 2.7.1. Free Drop

The free drop scenario outlined by 10 CFR 71.73(c)(1) requires a demonstration of the structural adequacy of the Model 2000 cask for a 30-ft drop onto a flat, essentially unyielding horizontal surface in the orientation that inflicts the maximum damage to the cask. The Model 2000 Transport Package is shown to meet the free drop requirements through a combination of classic calculations, impact analyses, and static finite element. The evaluations include the qualification of the Model 2000 cask lid 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 (Reference 2-15) (Section 2.12.4). The combined effects of inertial loads, and internal pressures are considered for packaging components. The impact analysis of the package is presented in Section 2.12.1. Section 2.7.1.1 presents the evaluation of the cask body and Section 2.7.1.2 presents the structural evaluation of the HPI and material basket during free drop conditions. The cask body and HPI structural analyses are performed using the finite element program ANSYS (Reference 2-16) and the material basket is analyzed using classic methods. Table 2.7.1-1 provides a summary of the HAC accelerations predicted by the LS-DYNA analysis presented in Section 2.12.1. A lead slump analysis is provided in Section 2.12.2.

**Table 2.7.1-1. LS-DYNA Results**

| DESCRIPTION | DROP ANGLE (DEGREE) | APPLICABLE BOUNDARY CONDITION | | | | | | ACCELERATION (g) |
|---|---|---|---|---|---|---|---|---|
| | | Temperature | | | Payload | | | |
| | | Amb. | Hot | Cold | Nom. | Heavy | Light | |
| **HAC, End Drop, Hot** | 90 | — | ✓ | — | — | ✓ | — | 157.5 |
| **HAC, Side Drop, Cold** | 0 | — | — | ✓ | — | — | ✓ | 161.9 |
| **HAC, Corner Drop, Cold** | 68 (90-22) | — | — | ✓ | — | — | ✓ | 80.3 |
| **HAC, Slap Down** | 5 | ✓ | — | — | ✓ | — | — | 114.4 |
| **HAC, Slap Down** | 10 | ✓ | — | — | ✓ | — | — | 118.0 |

#### 2.7.1.1. Cask Body Stress Analysis

This section evaluates the structural results of the Model 2000 cask body analyses and shows that the design meets the requirements of 10 CFR 71.71. Specifically, the evaluation addresses the loads associated with the HAC. The results of the analyses for various load cases are presented pictorially in stress intensity contour plots as well as in table form, with the corresponding safety factors in critical components of the cask body.

#### 2.7.1.1.1. End Drop

In accordance with the requirements of 10 CFR 71.73(c)(1), the Model 2000 Transport Package is structurally evaluated for the 30-foot end-drop condition. In this hypothetical accident, the cask including the payload and the impact limiters falls 30 feet onto a flat, unyielding, horizontal surface. The cask strikes the surface in a vertical upright position. For the Model 2000 cask, the bottom end drop is bounding. In the bottom down position, the prying load on the closure bolts is maximized. Closure bolts are evaluated separately in Section 2.12.4.

The most critically stressed component in the system is the cask flange region, which is due to bending of the flange from the inertial load imposed by the cask lid. The second region of interest is in the cask lid in the closure bolt contact region. To evaluate the stresses in these regions linearized stress are calculated across the thickness of the plate. For the top flange, Figure 2.7.1-1 shows the location of the maximum total stress intensity and Figure 2.7.1-2 indicates the path (Section 6) location where the stresses are calculated. Table 2.7.1-2 is a listing of the Section 6 stresses. Table 2.7.1-3 documents the primary membrane ($P_m$) and primary membrane plus primary bending ($P_m$+$P_b$) in accordance with the criteria presented in Regulatory Guide 7.6. Stresses are compared to the allowable at a bounding temperature of 300°F. The minimum margin of safety is found to be +3.7 for primary membrane, and +1.8 for primary membrane plus bending.

Figure 2.7.1-3 shows the location of the maximum total stress intensity in the lid and Figure 2.7.1-4 indicates the path (Section 7). Table 2.7.1-4 presents a listing of the Section 2 stresses and Table 2.7.1-5 provides the stress combinations in accordance with the Regulatory Guide 7.6 criteria. The minimum margin of safety is found to be +1.4 for primary membrane and +0.8 for primary membrane plus bending. Because all of the margins of safety are positive, the Model 2000 cask meets the end drop requirement of 10 CFR 71.73.

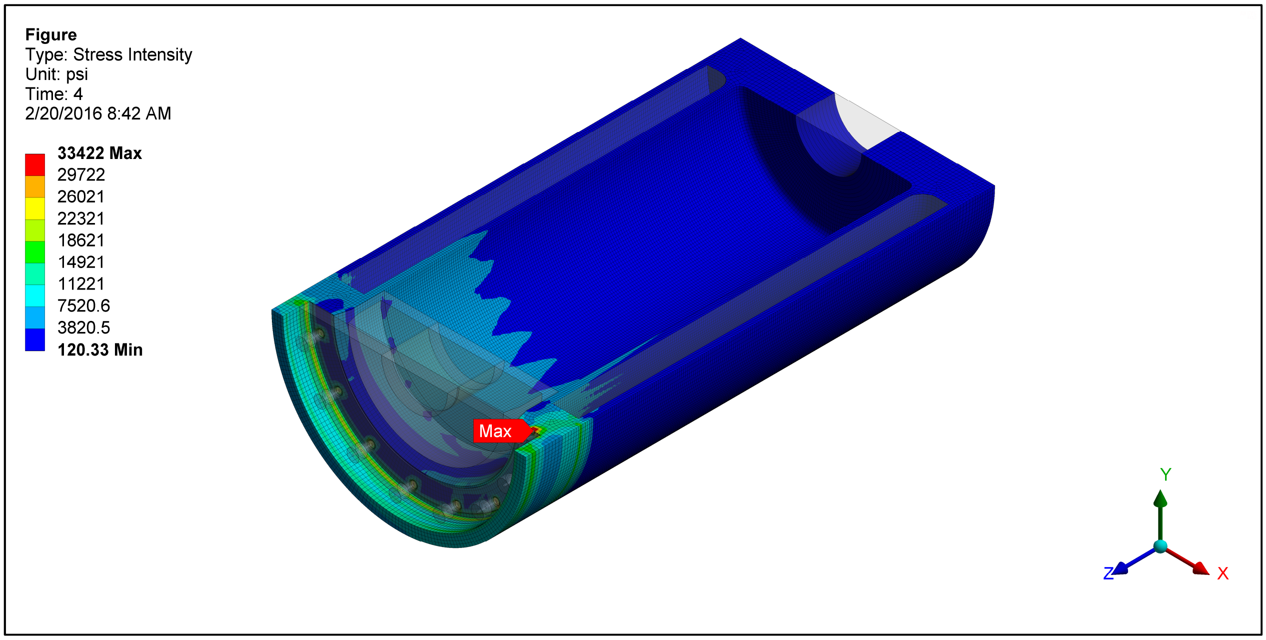



**Figure 2.7.1-1. HAC End Drop Cask Body Stress Intensity (total stress psi)**

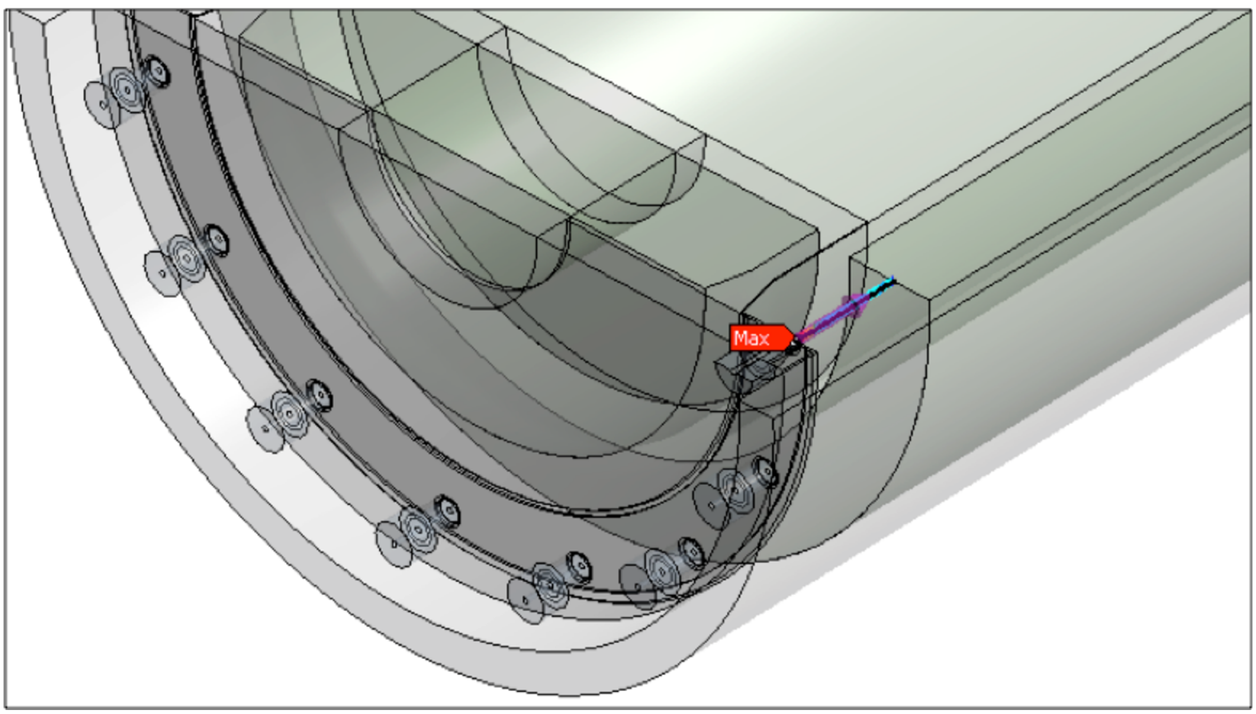



**Figure 2.7.1-2. HAC End Drop Linearized Stress Location (Section 6)**

**Table 2.7.1-2. HAC End Drop Section 6 Stress Results (psi)**

| Stress State | Location | S1 | S2 | S3 | SINT |
|---|---|---|---|---|---|
| MEMBRANE ($P_m$) | — | 6581 | -895 | -3558 | 10140 |
| BENDING ($P_b$) | Inside | 14700 | 1514 | -5075 | 19770 |
| | Center | 0 | 0 | 0 | 0 |
| | Outside | 5075 | -1514 | -14700 | 19770 |
| MEMBRANE + BENDING | Inside | 19290 | 500 | -6531 | 25830 |
| | Center | 6581 | -895 | -3558 | 10140 |
| | Outside | 5773 | -2708 | -12070 | 17840 |
| PEAK | Inside | 23680 | 14560 | 11820 | 11860 |
| | Center | -301 | -939 | -5909 | 5608 |
| | Outside | 7995 | 1326 | 524 | 7471 |
| TOTAL | Inside | 41600 | 13550 | 8174 | 33422 |
| | Center | 4518 | -1942 | -7597 | 12120 |
| | Outside | 6665 | -1547 | -4280 | 10940 |

**Table 2.7.1-3. HAC End Drop Section 6 Stress Results (psi)**

| Stress Component | Stress Combination | Stress Intensity | Allowable | Margin of Safety |
|---|---|---|---|---|
| $P_m$ | 10140 | 20000 | 48000 | 3.7 |
| $P_m + P_b$ | 25830 | 20000 | 72000 | 1.8 |

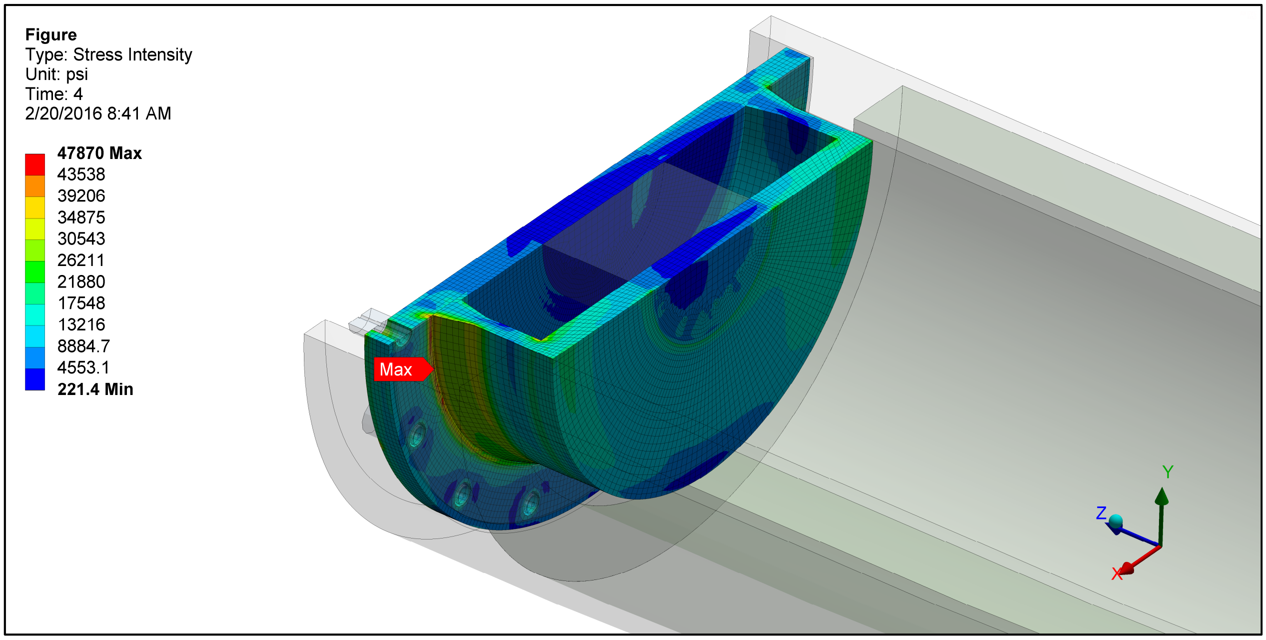



**Figure 2.7.1-3. HAC End Drop Lid Stress Intensity (total stress psi)**

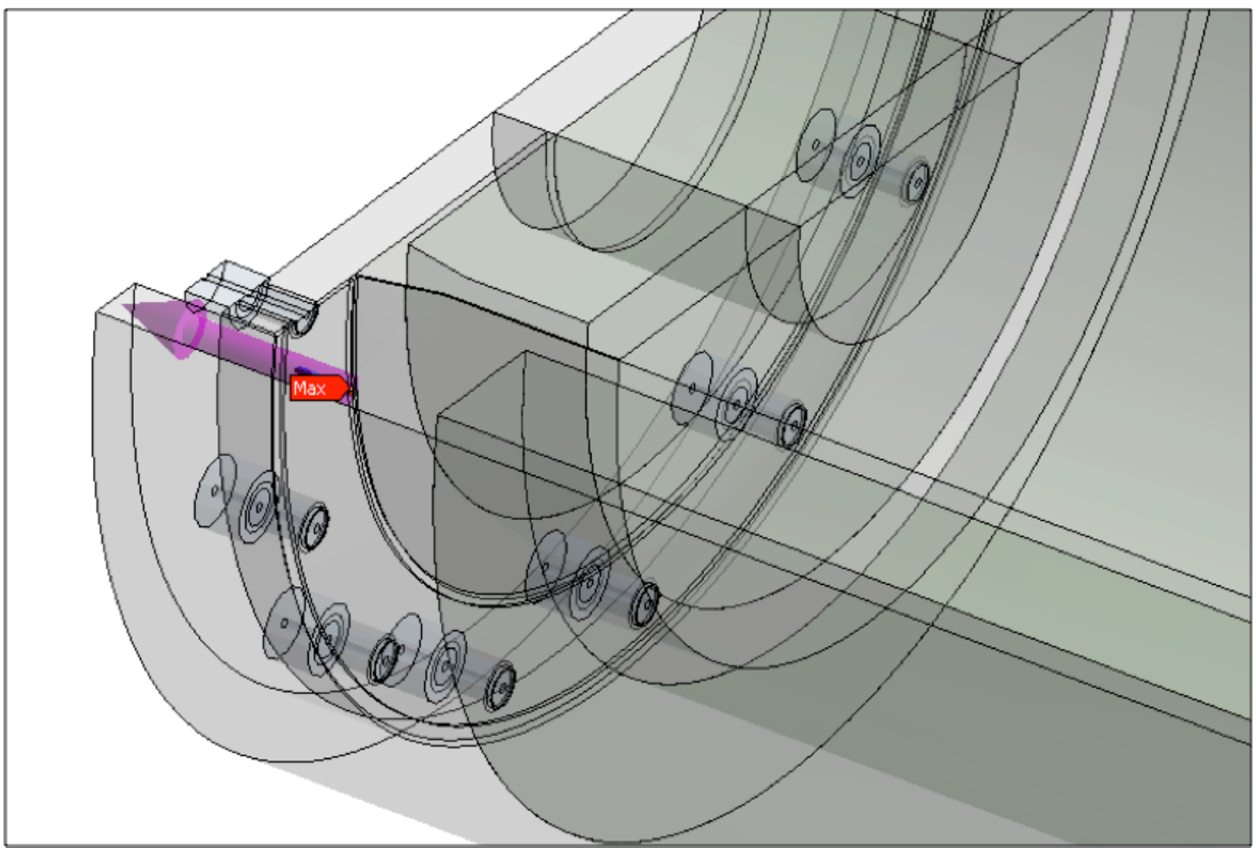



**Figure 2.7.1-4. HAC End Drop Linearized Stress Location (Section 7)**

**Table 2.7.1-4. HAC End Drop Section 7 Stress Results (psi)**

| Stress State | Location | S1 | S2 | S3 | SINT |
|---|---|---|---|---|---|
| MEMBRANE ($P_m$) | — | 4664 | -9598 | -15170 | 19830 |
| BENDING ($P_b$) | Inside | 6095 | -5767 | -15640 | 21730 |
| | Center | 0 | 0 | 0 | 0 |
| | Outside | 15640 | 5767 | -6095 | 21730 |
| MEMBRANE + BENDING | Inside | 10350 | -15400 | -30370 | 40720 |
| | Center | 4664 | -9598 | -15170 | 19830 |
| | Outside | 3790 | -4026 | -4558 | 8348 |
| PEAK | Inside | 6105 | 805 | -4285 | 10390 |
| | Center | 1161 | -449 | -3088 | 4249 |
| | Outside | 3340 | 607 | -925 | 4265 |
| TOTAL | Inside | 14800 | -14510 | -33070 | 47870 |
| | Center | 3087 | -10080 | -15480 | 18570 |
| | Outside | 3323 | -1612 | -3483 | 6806 |

**Table 2.7.1-5. HAC End Drop Section 7 Stress Results (psi)**

| Stress Component | Stress Combination | Stress Intensity | Allowable | Margin of Safety |
|---|---|---|---|---|
| $P_m$ | 19830 | 20000 | 48000 | 1.4 |
| $P_m + P_b$ | 40720 | 20000 | 72000 | 0.8 |

### 2.7.1.1.2. Side Drop

In accordance with the requirements of 10 CFR 71.73(c)(1), the Model 2000 cask is structurally evaluated for the hypothetical accident 30-foot side drop condition. In this event, the cask including the payload and impact limiters falls 30 feet onto a flat, unyielding, horizontal surface. The package strikes the surface in a horizontal position resulting in a side impact. The types of loading involved in a side drop accident are closure lid bolt preload, internal pressure, and inertial body load. Closure bolts are evaluated separately in Section 2.12.4.

The most critically stressed component in the system is the cask inner shell at the interface with the bottom forging, the cask flange region, and the cask lid. To evaluate the stresses in these regions linearized stress are calculated across the thickness of the plate. For the cask inner shell, Figure 2.7.1-5 shows the location of the maximum total stress intensity and Figure 2.7.1-6 indicates the path (Section 8) location where the stresses are calculated. Table 2.7.1-6 is a listing of the Section 8 stresses. Table 2.7.1-7 documents the primary membrane ($P_m$) and primary membrane plus primary bending ($P_m$+$P_b$) in accordance with the criteria presented in Regulatory Guide 7.6. Stresses are compared to the allowable at a bounding temperature of 350°F. The minimum margin of safety is found to be +4.5 for primary membrane and +1.5 for primary membrane plus.

Figure 2.7.1-7 shows the location of the maximum total stress intensity in the lid and Figure 2.7.1-8 indicates the path (Section 9). Table 2.7.1-8 presents a listing of the Section 9 stresses and Table 2.7.1-9 provides the stress combinations in accordance with the Regulatory Guide 7.6 criteria. The minimum margin of safety is found to be +1.6 for primary membrane and +1.2 for primary membrane plus bending. Because all of the margins of safety are positive, the Model 2000 cask meets the end drop requirement of 10 CFR 71.71.

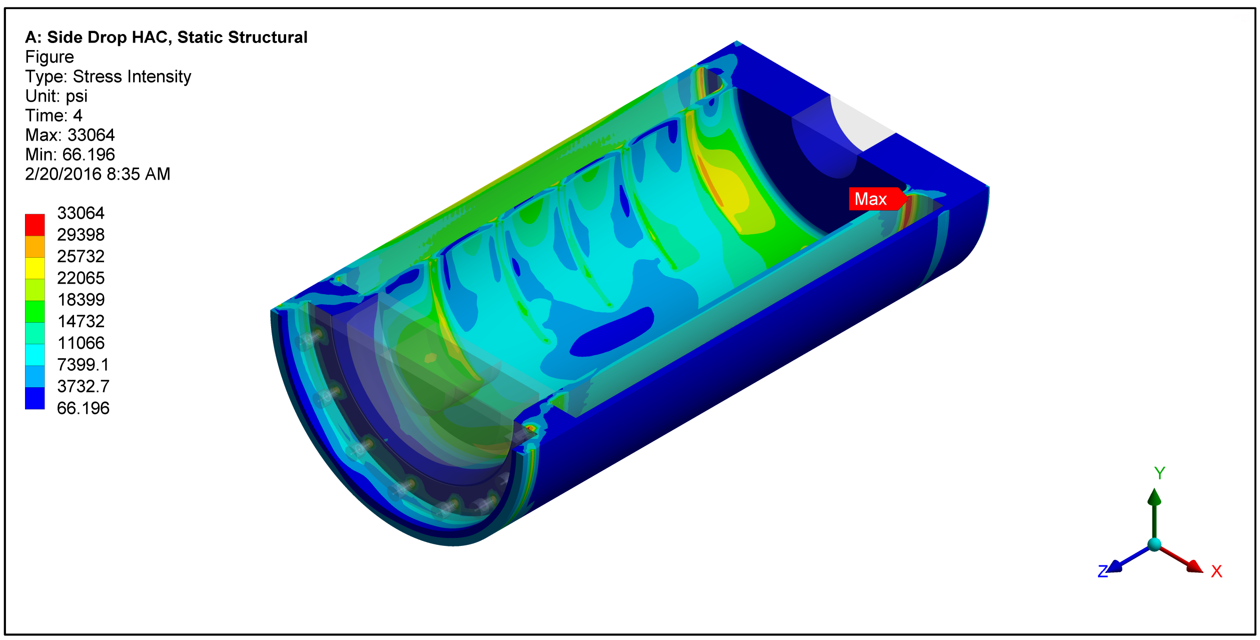



**Figure 2.7.1-5. HAC Side Drop Cask Body Stress Intensity (total stress psi)**

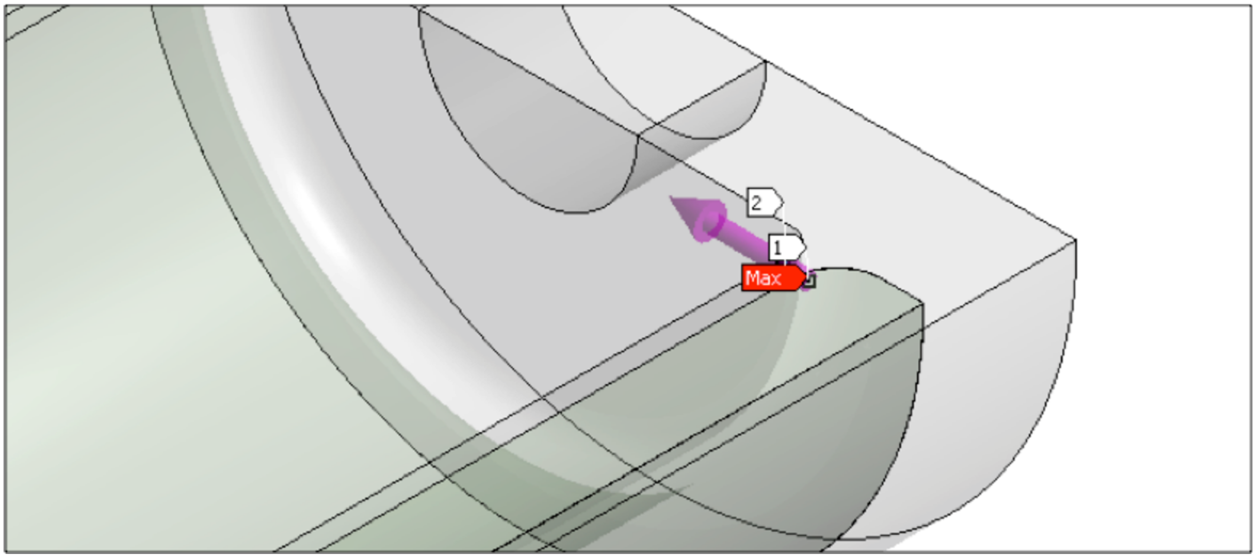



**Figure 2.7.1-6. HAC Side Drop Linearized Stress Location (Section 8)**

**Table 2.7.1-6. HAC Side Drop Section 8 Stress Results (psi)**

| Stress State | Location | S1 | S2 | S3 | SINT |
|---|---|---|---|---|---|
| MEMBRANE ($P_m$) | — | 7919 | 3810 | -536 | 8455 |
| BENDING ($P_b$) | Inside | 22400 | 7025 | 1106 | 21300 |
| | Center | 0 | 0 | 0 | 0 |
| | Outside | -1106 | -7025 | -22400 | 21300 |
| MEMBRANE + BENDING | Inside | 29540 | 10850 | 1339 | 28200 |
| | Center | 7919 | 3810 | -536 | 8455 |
| | Outside | -98 | -3191 | -16050 | 15950 |
| PEAK | Inside | 4194 | 930 | -743 | 4937 |
| | Center | 335 | -133 | -962 | 1297 |
| | Outside | 1120 | -76 | -1042 | 2162 |
| TOTAL | Inside | 33700 | 11780 | 633 | 33060 |
| | Center | 6962 | 3673 | -204 | 7167 |
| | Outside | 175 | -3267 | -16250 | 16420 |

**Table 2.7.1-7. HAC Side Drop Section 8 Stress Results (psi)**

| Stress Component | Stress Combination | Stress Intensity | Allowable | Margin of Safety |
|---|---|---|---|---|
| $P_m$ | 8455 | 19300 | 46320 | 4.5 |
| $P_m + P_b$ | 28200 | 19300 | 69480 | 1.5 |

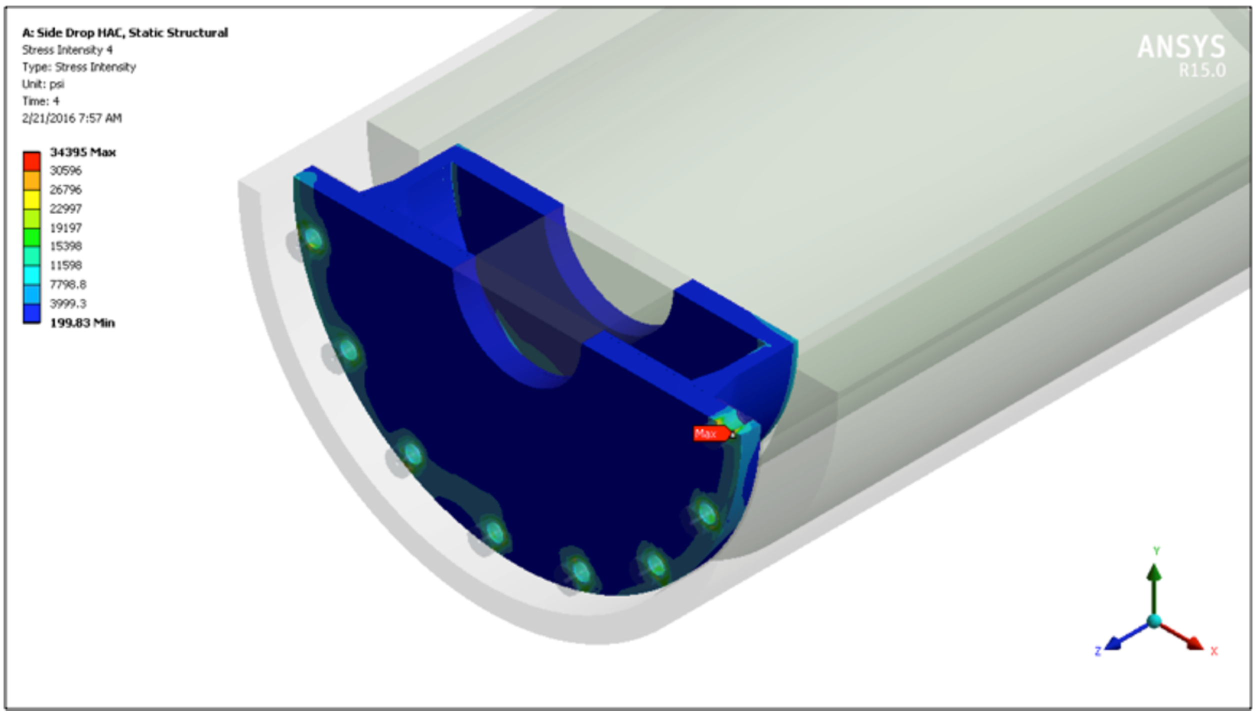



**Figure 2.7.1-7. HAC Side Drop Lid Stress Intensity (total stress psi)**

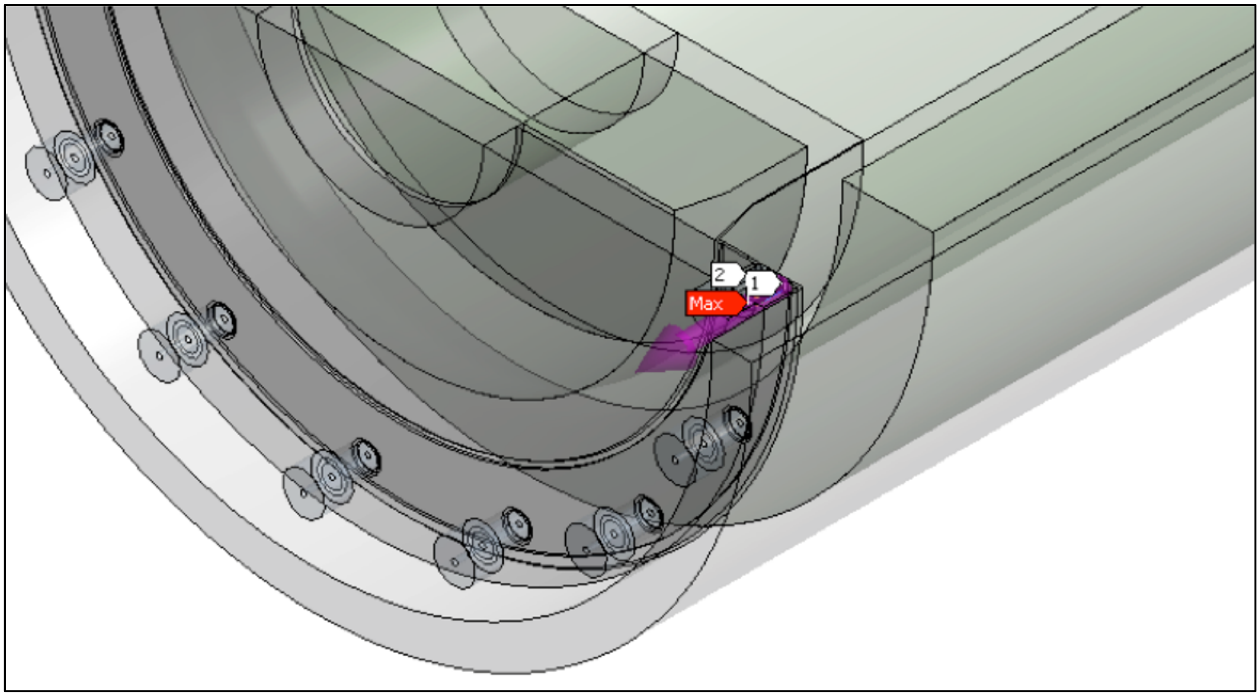



**Figure 2.7.1-8.  HAC Side Drop Linearized Stress Location (Section 9)**

**Table 2.7.1-8. HAC Side Drop Section 9 Stress Results (psi)**

| Stress State | Location | S1 | S2 | S3 | SINT |
|---|---|---|---|---|---|
| MEMBRANE ($P_m$) | — | 191 | -4176 | -17400 | 17590 |
| BENDING ($P_b$) | Inside | 13120 | 4683 | -811 | 13930 |
| | Center | 0 | 0 | 0 | 0 |
| | Outside | 811 | -4683 | -13120 | 13930 |
| MEMBRANE + BENDING | Inside | 1165 | -624 | -4936 | 6102 |
| | Center | 191 | -4176 | -17400 | 17590 |
| | Outside | 993 | -9012 | -30360 | 31350 |
| PEAK | Inside | 945 | -4458 | -6602 | 7547 |
| | Center | 4003 | 2423 | 215 | 3787 |
| | Outside | 1120 | -3506 | -6124 | 7244 |
| TOTAL | Inside | 379 | -4426 | -10460 | 10840 |
| | Center | 1337 | -1978 | -14100 | 15440 |
| | Outside | 1005 | -14500 | -33390 | 34400 |

**Table 2.7.1-9. HAC Side Drop Section 9 Stress Results (psi)**

| Stress Component | Stress Combination | Stress Intensity | Allowable | Margin of Safety |
|---|---|---|---|---|
| $P_m$ | 17590 | 19300 | 46320 | 1.6 |
| $P_m + P_b$ | 31350 | 19300 | 69480 | 1.2 |

### 2.7.1.1.3. Corner Drop

In accordance with the requirements of 10 CFR 71.73(c)(1), the Model 2000 cask is structurally evaluated for the hypothetical accident 30-foot corner drop condition. The impact analysis presented in Section 2.12.1 and the summary of accelerations provided in Table 2.7.1-1 shows that the end and side drop accelerations bound the C.G. over corner drop acceleration. Therefore, the corner drop requirement is satisfied.

#### 2.7.1.1.4. Oblique Drops

In accordance with the requirements of 10 CFR 71.73(c)(1), the Model 2000 cask is structurally evaluated for the hypothetical accident 30-foot oblique drop condition. The impact analysis presented in Section 2.12.1 and the summary of accelerations provided in Table 2.7.1-1 shows that the end and side drop accelerations bound the slap-down/oblique angle drops. Therefore, the oblique drop requirement is satisfied.

### 2.7.1.2. HPI Stress Analysis

The purpose of this section is to document the Model 2000 HPI and material basket analyses that shows the design meets the requirements of 10 CFR 71. Specifically, the evaluation addresses the mechanical loads associated with the HAC.

The results of the analyses for various load cases are presented pictorially as stress intensity contour plots as well as in table form, with the corresponding margin of safety in each component of the cask body.

#### 2.7.1.2.1. End Drop

The HPI is evaluated using the ANSYS finite element model presented in Section 2.6.7. Stress results for the HAC end drop discussed previously are documented in Table 2.7.1-10. The table presents the primary membrane ($P_m$) and primary membrane plus primary bending ($P_m$+$P_b$) in accordance with the criteria presented in ASME Section III, Appendix F (Reference 2-18).

As shown in Table 2.7.1-10, the margins of safety when compared to the stress intensity for each category are positive. The most critically stressed component in the system is the interface between the [[ ]] that surrounds and supports the depleted uranium shield. The minimum margin of safety is +8.0 for primary membrane stress intensity. The locations of the critical sections correspond to the maximum stress location and axial displacement is shown in Figure 2.7.1-9.

[[

]]

**Figure 2.7.1-9. HPI HAC End Drop Results – Peak Stress Intensity (psi) and Displacement (in)**

**Table 2.7.1-10. HAC End Drop Stress Summary**

[[

]]

### 2.7.1.2.2. Side Drop

The HPI is evaluated using the ANSYS finite element model presented in Section 2.6.7. Table 2.7.1-1 provides a summary of the HAC accelerations predicted by the LS-DYNA analysis presented in Section 2.12.1. As with the NCT evaluation, two cases are presented to evaluate the performance of the HPI during the side drop. Case 1 is concentrated pressure distribution at the four [[ ]] locations ("line load"). Case 2 is a uniform pressure distribution ("area load").

Stress results for Case 1 are presented in Tables 2.7.1-11 and 2.7.1-12. Stress results for Case 2 are presented in Table 2.7.1-13 and 2.7.1-14. Figures 2.7.1-10 and 2.7.1-11 illustrate the stresses in the [[ ]] for Case 1 and Case 2, respectively. The tables present the primary membrane ($P_m$) and primary membrane plus primary bending ($P_m$+$P_b$) in accordance with the criteria presented in ASME Section III, Appendix F (Reference 2-18).

As Tables 2.7.1-11 through 2.1.7-14 show, the margins of safety for the HPI [[ ]] when compared to the stress intensity for each category are positive. The minimum margin of safety in the HPI body is found to be +0.8 for primary membrane plus bending stress intensity for both Cases 1 and 2.

**Table 2.7.1-11. HAC Case 1 HPI Body Top 30 Results**

[[

]]

[[

]]

**Figure 2.7.1-10. Case 1, HAC, Stress Intensity Result (psi)**

**Table 2.7.1-12. HAC [[ ]] Case 1 Results**

[[

]]

**Table 2.7.1-13. HAC Case 2 HPI Body Top 30 Results**

[[

]]

[[

]]

**Figure 2.7.1-11. Case 2, HAC, Stress Intensity Result (psi)**

**Table 2.7.1-14. HAC [[ ]] Case 2 Results**

**[[**

**]]**

#### 2.7.1.2.3. Corner Drop

Results of the LS-DYNA analysis presented in Section 2.12.1 shows that the side drop accelerations bound the corner drop.

#### 2.7.1.2.4. Oblique Drops

Results of the LS-DYNA analysis presented in Section 2.12.1 shows that the side drop accelerations bound the oblique drop angles.

### 2.7.1.3. Material Basket Evaluation

This section evaluates the material basket for HAC. Factors of safety for the basket are calculated based on the criteria for Service Level 'D' limits from ASME Section III, Appendix F (F-1332). Assuming one-third of the inertial load is carried by one of the [[ ]], the bending stress in the basket is:

$$\sigma_b = \frac{Mc}{I_{cc}} = 2022.7 \text{ psi}$$

where

| | | | |
|---|---|---|---|
| $P$ | = | $W \times G$ = [[ ]] lb | Load on 12 [[ ]] section |
| $W$ | = | [[ ]] lb | Bounding basket weight |
| $G$ | = | 161.9 g | NCT side drop acceleration |
| $M$ | = | $\frac{Wa \times l^2}{12}$ = 21227.5 lb-in | Bending moment |
| $l$ | = | [[ ]] in | Length of beam section |
| $Wa$ | = | 1148.92 lb/in | Uniformly distributed load |
| $c$ | = | 3.73 in | Neutral axis to outer fiber |
| $I_{cc}$ | = | 39.09 in$^4$ | Moment of inertia (12 [[ ]]) |

The moment of inertia calculation is shown in Table 2.7.1-15.

**Table 2.7.1-15. Moment of Inertia Calculation**

[[

]]

The pure shear stress, ASME Appendix F (F-1332.4), which develops across the section during the side drop is

$$\tau = \frac{P}{2A} \approx 2188.5 \text{ psi} < 0.42S_u = 0.42 \times 70800 = 29736 \text{ psi}$$

where

| | | | |
|---|---|---|---|
| $P$ | = | 17107.4 lb | |
| $A$ | = | 3.91 in² | Cross-sectional area (12 [[ ]]) |
| $d_o$ | = | [[ ]] in | Outside diameter of [[ ]] |
| $d_i$ | = | [[ ]] in | Inside diameter of [[ ]] |

The stress intensity in the basket that results from the combination of the bending and shear stresses is

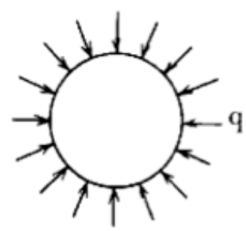
$$\sigma = \sqrt{\sigma_b^2 + 4\tau^2} = 4821.8 \text{ psi}$$

The margin of safety is per ASME Appendix F (F-1332) is

$$MS = \frac{1.5 \times (1.5S_m)}{\sigma} - 1 = \frac{35775}{4821.8} - 1 = +6.4$$

Spacer strips that attach adjoining outer layer of [[ ]] hold the basket together using [[ ]] (ASME III-NF, Class 1). The [[ ]] are equivalent in thickness and strength to the adjoining [[ ]]. Therefore, the previous analysis bounds the stresses generated in the [[ ]].

Because the [[ ]] form a composite section with the addition of [[ ]], contact with the [[ ]]-inch thick [[ ]] is distributed along the face of the disk. Therefore, [[ ]] wall permanent deformation is unlikely to occur. However, assuming the basket [[ ]] are unsupported and uniformly loaded, a lateral external pressure load may be applied along the length of the [[ ]]. Treating the pipe as a thin shell, the elastic stability can be evaluated during HAC side drop event. From Roark's, Table 15.2, Case 19 (Reference 2-19), the elastic stability of a single basket [[ ]] is evaluated by applying the total payload weight times the side drop acceleration that is then applied as an exterior pressure load, q. The critical external pressure, q', is:




$$q' = \frac{1}{4}\frac{E}{1-\nu^2}\frac{t^3}{r^3} = 3180 \text{ psi}$$

| | | | |
|---|---|---|---|
| $E$ | = | $24.1\times10^6$ psi | Modulus at 800°F |
| $\nu$ | = | 0.3 | Poisson's ratio |
| $t$ | = | [[ ]] in | Wall thickness |
| $r$ | = | [[ ]] in | [[ ]] outside radius |

Applying the total contents weight during the HAC side drop to a single [[ ]], the external pressure is:

$$q = \frac{P}{A} = 208.5 \text{ psi}$$

| | | | |
|---|---|---|---|
| G | = | 161.9 g | Side drop acceleration |
| W | = | [[ ]] lb | Bounding loaded basket weight |
| P | = | $W \times G$ = 51322.3 lb | Total load |
| l | = | [[ ]] in | Basket length |
| A | = | $2\pi rl$ = 246.1 in² | Surface area of single [[ ]] |

Comparing the critical external pressure to the external pressure applied to a single [[ ]] during the HAC side drop event, the factor of safety is:

$$FS = \frac{q'}{q} = 15.2$$

Therefore, unsupported basket [[ ]] sections will not collapse during HAC side drop conditions and the Subsection NF, Level A stress acceptance criteria still applies.

#### 2.7.1.4. Summary of Results

Structural analyses are performed for the Model 2000 cask, HPI and material basket for hypothetical accident conditions free drop conditions. To evaluate the Model 2000 Transport Package, ANSYS finite element models and classic calculations are used to analyze the governing drop cases. All structural members have a positive margin of safety under worst case loading conditions. It is concluded that the Model 2000 Transport Package is structurally adequate for the HAC free drop conditions. Therefore, the requirements of 10 CFR 71.73(c)(1) have been satisfied.

### 2.7.2. Crush

In accordance with the requirements of 10 CFR 71.73(c)(2), the Model 2000 Transport Package is to be subjected to a dynamic crush test by evaluating the package on essentially unyielding horizontal surface so as to suffer maximum damage by the drop of an 1,100 pound mass from 30 feet onto the package. The mass must consist of a solid mild steel plate 40 inches × 40 inches and must fall in a horizontal attitude. The crush test is required only when the specimen has a mass not greater than 1,100 pounds, and overall density not greater than 1000 $kg/m^3$ (62.4 $lb/ft^3$) based on external dimension. The crush condition is not applicable because the Model 2000 Transport Package weighs more than 500 kg (1,100 lb.) and overall density is greater than 62.4 $lb/ft^3$.

### 2.7.3. Puncture

This section addresses the second event in the accident design sequence outlined in 10 CFR 71.73(c)(3), the 40-inch drop of the Model 2000 Transport Package onto a mild steel cylindrical punch. The evaluation of this condition is conducted for the package structure and the containment vessel. The demonstration of the puncture capability of the package is presented

in Section 2.12.1 to predict the accumulated damage in support of the thermal analysis. The maximum strain in the outer shell of the cask is 31% and limited to the puncture area. Therefore, no gross deformations of the cask are predicted.

### 2.7.4. Thermal

The fire condition is analyzed in Section 3.4. In this section, maximum values of temperatures and pressures are provided.

#### 2.7.4.1. Summary of Pressures and Temperatures

Table 2.7.1-16 provides summary temperatures for the Model 2000 Transport Package for HAC. During HAC, the average temperature of the cask fill gas (including the gas within the HPI) peaks at 585°F 11 hours after the end of the 30-minute fire. Using the ideal gas law, the cask internal pressure from gas expansion is 29.0 psia, which is less than the design pressure of 30 psia.

**Table 2.7.1-16. Summary Temperatures for HAC**

| Item | Peak Temperature (°F) |
|---|---|
| Material basket | 1,045 |
| HPI shielding (side) | 670 |
| HPI shielding (top) | 599 |
| HPI shielding (bottom) | 618 |
| Cask lid seal | 508 |
| Cask shielding (side) | 570 |
| Cask shielding (top) | 529 |
| Cask shell, puncture location | 782 |
| Cask shell, opposite side to puncture location | 512 |
| Overpack outer shell, puncture location | 1,103 |
| Overpack outer shell, opposite side to puncture location | 1,337 |
| Cask drain port (bottom) | 612 |
| Cask test port (top) | 608 |
| Cask vent port (lid) | 520 |
| HPI fill gas (average) | 740 |
| Cask fill gas (average) | 571 |
| HPI and cask fill gas, combined (average) | 585 |

(Note: Data taken from Table 3.4.3-1)

### 2.7.4.2. Differential Thermal Expansion

Differential thermal expansion resulting from the fire transient has minimal consequence to the Model 2000 Transport Package. All stresses are classified ASME Section III Subsection NB as secondary displacement-limited stresses. Heat conditions that bound both NCT and HAC are presented in Section 2.6.7, which evaluates the thermal expansion of the Model 2000 cask by applying a temperature differential 300°F from the outside surface to the inside surface of the cask. Thermal expansion of the closure bolts are evaluated using the temperatures associated with the HAC fire in Section 2.12.4.

### 2.7.4.3. Stress Calculations

In accordance with the requirements of 10 CFR 71.73(c)(4), the Model 2000 Transport Package is structurally evaluated when subjected to the design pressure of 30 psia. The design pressure is applied in combination with the mechanical loads defined in Section 2.7.1. To obtain stress results, a uniform internal pressure of 30 psia is applied to the ANSYS finite element in combination with the mechanical loading conditions of Section 2.7.1.

### 2.7.4.4. Comparison with Allowable Stresses

The combined HAC pressure and mechanical stresses are presented in Table 2.7.4-1, which documents the primary membrane ($P_m$), primary membrane and plus primary bending ($P_m$+$P_b$) stresses in accordance with the criteria presented in Regulatory Guide 7.6. As Table 2.7.4-1 shows, the margins of safety are positive when the allowable is compared to the stress intensity for each category. Therefore, the requirement of 10 CFR 71.73(c)(4) is satisfied.

**Table 2.7.4-1. Summary of HAC Stress Results**

| Case | Component | Stress Component | Stress Combination | Stress Intensity | Allowable | Margin of Safety |
|---|---|---|---|---|---|---|
| End Drop | Cask body | $P_m$ | 10140 | 20000 | 48000 | +3.7 |
| | | $P_m + P_b$ | 25830 | 20000 | 72000 | +1.8 |
| | Cask Lid | $P_m$ | 19830 | 20000 | 48000 | +1.4 |
| | | $P_m + P_b$ | 40720 | 20000 | 72000 | +0.8 |
| Side Drop | Cask body | $P_m$ | 8455 | 19300 | 46320 | +4.5 |
| | | $P_m + P_b$ | 28200 | 19300 | 69480 | +1.5 |
| | Cask Lid | $P_m$ | 17590 | 19300 | 46320 | +1.6 |
| | | $P_m + P_b$ | 31350 | 19300 | 69480 | +1.2 |

### 2.7.5. Immersion - Fissile Material

According to the requirements of 10 CFR 71.73(c)(5), the Model 2000 Transport Package does not contain fissile material subject to the requirements of 10 CFR 71.55. The impact stress analysis (Section 2.12.1), presented in this section and scale model testing (Section 2.12.5) demonstrates that the geometric form of the package contents is not substantially altered during the sequence of HAC events. The criticality evaluation in Chapter 6 assumes water inleakage within the cask cavity to determine the $k_{eff}$. Therefore, the immersion requirement of 10 CFR 71.73(c)(5) is satisfied.

### 2.7.6. Immersion - All Packages

According to the requirements of 10 CFR 71.73(c)(6), a package must be subjected to water pressure equivalent to immersion under a head of water of at least 15 meters (50 feet) for a period of 8 hours, which is equivalent to 21.7 psig. The cask closure including the lid and bolts are designed to survive puncture loads, which exceed the load experienced during immersion (Sections 2.12.1 and 2.12.4). From ASME Section III-NB, A-2221, when subjected to 21.7 psig the 1.0-inch thick outer shell of the cask with a mean radius of 18.75 inches, produces a primary membrane stress intensity 418 psi that is much less than the material yield strength. Therefore, the Model 2000 Transport Package satisfies all of the immersion requirements for a package that is used for the international shipment of radioactive materials.

### 2.7.7. Deep Water Immersion Test (for Type B Packages Containing More than $10^5$ $A_2$)

The contents specified in this application is less than $10^5$ $A_2$. Therefore, this is not applicable for the Model 2000 Transport Package with HPI and material basket.

### 2.7.8. Summary of Damage

The analytical results reported in Sections 2.7.1 through 2.7.7 indicate that the damage incurred by the Model 2000 Transport Package during the hypothetical accident is minimal, and such damage does not diminish the cask ability to maintain the containment boundary. A 30-foot side drop followed by the 40-inch pin puncture accident may damage the overpack and inflict local damage on the outer shell of the cask. However, the shielding remains intact and satisfies the accident shielding criteria. Additionally the HPI and material baskets maintain structural integrity during all postulated HAC events, which supports the criticality analysis assumptions. Based on the analyses of Sections 2.7.1 through 2.7.7, the Model 2000 Transport Package fulfills the structural and shielding requirements of 10 CFR 71.73 for all of the hypothetical accident conditions.

## 2.8 Accident Conditions for Air Transport of Plutonium

This section does not apply for the Model 2000 Transport Package with HPI and material basket.

## 2.9 Accident Conditions for Fissile Material Packages for Air Transport

This section does not apply for the Model 2000 Transport Package with HPI and material basket.

## 2.10 Special Form

Special form capsules specifically designed for carrying isotope source materials are permitted in the Model 2000 Transport Package. Each special form capsule shall show compliance with the requirements of 10 CFR 71.75 when subjected to the applicable test conditions of 10 CFR 71.77 and independently certified. Special form capsules are not a requirement of this application, because containment is provided by the cask.

## 2.11 Fuel Rods

This section does not apply for the Model 2000 Transport Package, because containment is provided by the cask.

## 2.12 Appendix

### 2.12.1. LS-DYNA Evaluation of the Model 2000 Transport Package

This section summarizes the results of impact evaluation of the Model 2000 Transport Package during NCT of 10 CFR 71.71 and HAC of 10 CFR 71.73 (Reference 2-1) and supplements the test data documented in Section 2.12.5. The primary purpose of this section is to report accelerations for the HPI cask contents and provide realistic damage predictions for the thermal evaluation presented in Chapter 3.

#### 2.12.1.1. Introduction

The NCT and HAC impact analyses presented in this section evaluate the performance of the Model 2000 Transport Package using LS-DYNA Version 971 finite element code (Reference 2-20). Benchmarks of the analysis methodology are first performed using 3-drop orientations to compare with the actual drop tests of a quarter-scale model (see Section 2.12.5). The benchmark results are presented in detail in Section 2.12.1.11.1 through Section 2.12.1.11.3 as Drop Cases 1 through 3, respectively. The benchmark performed confirmed that the LS-DYNA program and dynamic analysis methodology are conservative and bounding.

The accident conditions are conservatively simulated using material properties corresponding to temperatures ranging from -40°F to 300°F for stainless steel and 400°F for aluminum honeycomb. Also considered are variations of the payload weight that is up to 10% of the maximum weight. The overpack toroidal shell thickness is also varied between two thicknesses of 0.50 inches and 0.76 inches. The overall variations include the following configurations,

1. NCT and HAC (2 variations of initial velocities)
2. Hot and cold temperature conditions. (2 variations of material properties)
3. Payload weight of ±10% of the maximum weight. (3 variations of payload weights)
4. Two different toroidal shell thicknesses of 0.50 inches and 0.76 inches. (2 variations of shell thicknesses)
5. Four-drop orientations including two end drops, side drop, and C.G. over corner drops. (4 variations of drop geometries)

There are 96 (=2×2×3×2×4) possible drop configurations. Evaluating the bounding cases reduces the total number of drop configurations. This simplification resulted in performing nine (9) bounding drop configurations. The bounding drop configurations are designated as Drop Cases 4 through 12. The summary of results for the 9 bounding drop cases is presented in Table 2.12.1-1. The worst-case HAC accelerations occur during the cold/thick/light side drop and the hot/thin/heavy bottom end drop. For the bottom end drop, the acceleration trend showed that the accelerations dropped until the honeycomb temperature was increased to 400°F and the honeycomb fully compresses. Because the average temperature of the honeycomb is less than 350°F, the honeycomb has sufficient capacity to protect the package during hot conditions.

Two shallow angle drop simulations are also performed. The drop configurations include nominal payload at ambient temperature with thick toroidal shell thickness (t=0.76 inches) to

compare with the side-drop test performed for the benchmarking test. The results for the two shallow angle drop cases are presented in Table 2.12.1-1. The two shallow angles are 5° and 10° slapdown drops that are designated as Drop Case 13 and 14. The results of shallow angle drops for the 0° (Drop Case 2, side drop), 5° (Drop Case 13) and 10° (Drop Case 14) conclude that the side drop bounds the shallow angle cases with an acceleration of 157 g.

Besides the 30-foot drop configurations, two HAC drop configurations (side drop and end drop) are selected to perform the code-required pin puncture test, where the cask is dropped 30 feet and then followed by a drop height of 40 inches onto a rigid pin 6 inches in diameter. The maximum strain in the cask outer shell is 31% and limited to the puncture location. No gross deformations of the cask are predicted and the structural integrity of the containment boundary is maintained. Additionally, results for the combined 30-foot impact and pin puncture are used as input for the HAC thermal evaluation.

**Table 2.12.1-1. Summary of Drop Cases and Results**

| Case No. | Description | Drop Angle degree | Drop Height (ft) | Shell thickness | Applicable Boundary Condition | | | | | | Acceleration Results (g) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Temperature | | | Payload | | | |
| | | | | | Amb | Hot | Cold | Normal | Heavy | light | |
| 1 | Benchmark HAC End Drop | 90 | 30 | Thick | X | | | X | | | 130.0 |
| 2 | Benchmark HAC Side Drop | 0 | 30 | Thick | X | | | X | | | 157.0 |
| 3 | Benchmark HAC Corner Drop | 68 (=90-22) | 30 | Thick | X | | | X | | | 73.8 |
| 4 | NCT, Cold, End Drop | 90 | 1 | Thick | | | X | | | X | 15.5 |
| 5 | NCT, Cold, Side Drop | 0 | 1 | Thick | | | X | | | X | 55.1 |
| 6 | NCT, Cold, Corner Drop | 68 (=90-22) | 1 | Thick | | | X | | | X | 14.6 |
| 7 | HAC, Cold, End Drop | 90 | 30 | Thick | | | X | | | X | 129.8 |
| 8 | HAC, Hot, End Drop | 90 | 30 | Thin | | X | | | X | | 157.5 |
| 9 | HAC, Cold, Side Drop | 0 | 30 | Thick | | | X | | | X | 161.9 |
| 10 | HAC, Hot, Side Drop | 0 | 30 | Thin | | X | | | X | | 110.7 |
| 11 | HAC, Cold, Corner Drop | 68 (=90-22) | 30 | Thick | | | X | | | X | 80.3 |
| 12 | HAC, Hot, Corner Drop, | 68 (=90-22) | 30 | Thin | | X | | | X | | 52.8 |
| 13 | HAC, Ambient, Slap down | 5 | 30 | Thick | X | | | X | | | 114.4 |
| 14 | HAC, Ambient, Slap down | 10 | 30 | Thick | X | | | X | | | 118.0 |
| 15 | HAC, Hot, End Drop + Puncture | 90 | 30 ft + 40 in. | Thin | | X | | | X | | Same as Case No. 8 |
| 16 | HAC, Hot, Side Drop + Puncture | 0 | 30 ft + 40 in | Thin | | X | | | X | | Same as Case No. 10 |

Multiple LS-DYNA dynamic finite element analyses are performed to determine the structural response of the Model 2000 cask during the impacts onto unyielding surface following NCT and HAC accident events. For each drop case the acceleration of the payload and inner containment enclosure is calculated. Three full 3D half-symmetry models are used to account for the asymmetry of the cask configuration. The three finite element models consist of the same node numbers, elements, material properties and control cards. The only differences are the nodal geometry and the direction of initial velocity. A representative finite element solid model is shown in Figure 2.12.1-1.

Security-Related Information Figure Withheld Under 10 CFR 2.390.

**Figure 2.12.1-1. Model 2000 Solid Model**

The three drop orientations are shown in Figure 2.12.1-2.

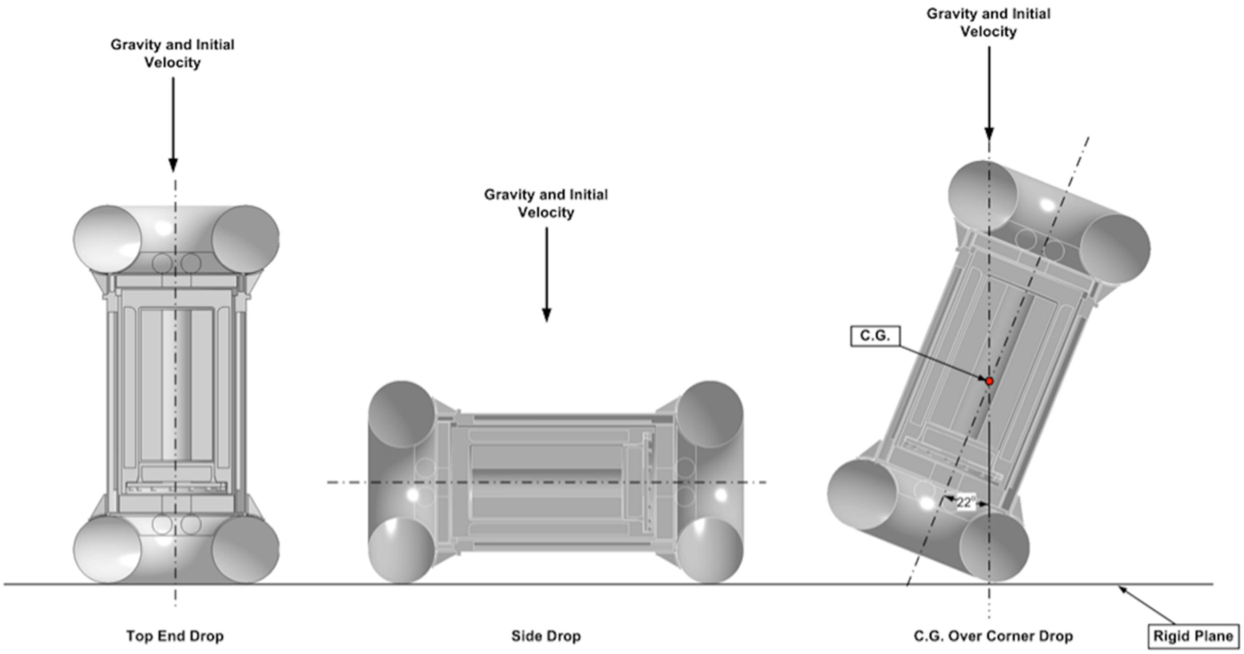



**Figure 2.12.1-2. Drop Orientations**

### 2.12.1.2. Benchmarking Runs

The selection of the drop cases are described in this section. Section 2.12.1.12.1 contains the benchmark results. Benchmarks of the analysis methodology are performed using the 3-drop orientations shown in Figure 2.12.1-2 to compare with the actual drop tests performed on a quarter-scale model. The benchmark runs are designated as Drop Cases 1 through 3. The actual drop tests were performed under at ambient temperature. The nominal payload weight is 5,450 pounds. The thickness in the toroidal shell is 0.76 inches. The drop height is 30 feet. The parameters of the benchmarking runs are listed in Table 2.12.1-2.

**Table 2.12.1-2. Benchmark Runs and the Drop Parameters**

| Case No. | Description | Drop Angle degree | Drop Height, (ft) | Toroid Thickness (in) | Applicable Boundary Condition | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Temperature | | | Payload | | |
| | | | | | Amb. | Hot | Cold | Normal | Heavy | light |
| 1 | End Drop | 90 | 30 | 0.76 | X | — | — | X | — | — |
| 2 | Side Drop | 0 | 30 | 0.76 | X | — | — | X | — | — |
| 3 | C.G. Over Corner Drop | 22 | 30 | 0.76 | X | — | — | X | — | — |

### 2.12.1.3. Normal Condition of Transport

The purpose of the drop simulation is to determine the peak acceleration of the payload and contents during the drop. The bounding acceleration occurs when the toroidal shell is thick so a stiffer response will result. At cold temperature, the material properties have greater elasticity

and yield strength, therefore results in a stiffer response. Finally, a lighter payload will result in lower total cask weight, which in turn causes greater acceleration during impact. The bounding three drops are simulated with thick toroidal shell, reduced-weight payload, and material properties at cold temperature. The drop cases are designated as Drop Case 4 through Drop Case 6, as listed in Table 2.12.1-3.

**Table 2.12.1-3. Normal Condition of Transport Runs and the Drop Parameters**

| Case No. | Description | Drop Angle degree | Drop Height, (ft) | Shell Thickness (in) | Applicable Boundary Condition | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Temperature | | | Payload | | |
| | | | | | Amb. | Hot | Cold | Normal | Heavy | light |
| **4** | NCT Cold, End Drop | 90 | 1.0 | 0.76 | — | — | X | — | — | X |
| **5** | NCT Cold, Side Drop | 0 | 1.0 | 0.76 | — | — | X | — | — | X |
| **6** | NCT Cold, Corner Drop | 68 (=90-22) | 1.0 | 0.76 | — | — | X | — | — | X |

### 2.12.1.4. Hypothetical Accident Condition

The purpose of the drop simulation is to determine the peak acceleration of the payload and/or the maximum damage during the drop.

The bounding acceleration occurs when the toroidal shell is thick so a stiffer response will result. At cold temperatures, the material properties have greater elasticity and yield strength, which results in a stiffer response. Finally, a lighter payload will result in lowered total cask weight, which in turn causes greater acceleration during impact. The three drops with bounding accelerations are simulated with thick toroidal shell, reduced payload, and material properties at cold temperature. For the end drop, the maximum force on the closure lid bolts occurs when the container lid is oriented towards to the rigid plane. The drop cases are designated as Drop Cases 7, 9, and 11 for the end drop, side drop and C.G. over corner drop, respectively.

The maximum damage of the cask occurs when the toroidal shell is thin and has less structural strength. At warmer temperature, comparing with the material strength at ambient temperature, the material has lower elasticity and yield strength therefore resulted in greater damage to the cask. The heavier payload will also result in greater deformation of the toroidal shell. The drop cases with the bounding damage are designated as Drop Cases 8, 10, and 12 for the end drop, side drop and C.G. over corner drop, respectively. The six bounding drop cases for the HAC are listed in Table 2.12.1-4.

**Table 2.12.1-4. Hypothetical Accident Condition of Transport Runs and the Drop Parameters**

| Case No. | Description | Drop Angle degree | Drop Height, (ft) | Shell Thickness (in) | Applicable Boundary Condition | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Temperature | | | Payload | | |
| | | | | | Amb. | Hot | Cold | Normal | Heavy | light |
| **7** | HAC, Cold, End Drop | 90 | 30.0 | 0.76 | — | — | X | — | — | X |
| **8** | HAC, Hot, End Drop | 90 | 30.0 | 0.50 | — | X | — | — | X | — |
| **9** | HAC, Cold, Side Drop | 0 | 30.0 | 0.76 | — | — | X | — | — | X |
| **10** | HAC, Hot, Side Drop | 0 | 30.0 | 0.5 | — | X | — | — | X | — |
| **11** | HAC, Cold, Corner Drop | 68 (=90-22) | 30.0 | 0.76 | — | — | X | — | — | X |
| **12** | HAC, Hot, Corner Drop | 68 (=90-22) | 30.0 | 0.50 | — | X | — | — | X | — |

### 2.12.1.5. Shallow Angle Drops

Two shallow angle drops (5° and 10° from horizontal) with the drop configuration shown in Figure 2.12.1.5-1 are performed to compare the acceleration with the result of the side drop benchmark run. With the same material parameters as the benchmark run, the shallow angle drop parameters consist of the nominal payload weight, material properties at ambient temperature, and thick toroidal shell thickness. The drop cases are designated as Drop Cases 13 and 14 as listed in Table 2.12.1-5.

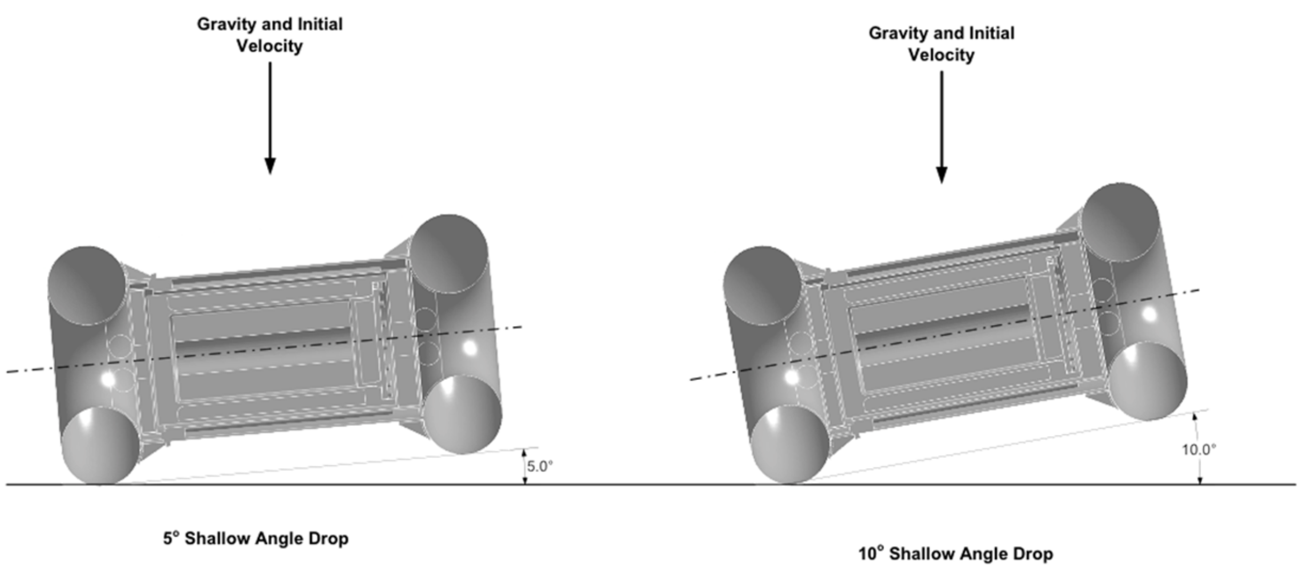



**Figure 2.12.1.5-1. Shallow Angle Drops**

**Table 2.12.1-5. Shallow Angle Drop Runs and the Drop Parameters**

| Case No. | Description | Drop Angle degree | Drop Height, (ft) | Shell Thickness (in) | Applicable Boundary Condition | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Temperature | | | Payload | | |
| | | | | | Amb. | Hot | Cold | Normal | Heavy | light |
| **13** | HAC, Ambient, Slap Down | 5 | 30.0 | 0.76 | X | — | — | X | — | — |
| **14** | HAC, Ambient, Slap Down | 10 | 30.0 | 0.76 | X | — | — | X | — | — |

## 2.12.1.6. Pin Puncture

10 CFR 71.73 requires that a free drop of the specimen through a distance of 1 meter (40 inches) in a position for which maximum damage is expected, onto the upper end of a solid, vertical, cylindrical, mild steel bar mounted on an essentially unyielding, horizontal surface. The bar must be 15 cm (6 inches) in diameter, with the top horizontal and its edge rounded to a radius of not more than 6 mm (0.25 inches), and of a length as to cause maximum damage to the package, but not less than 20 cm (8 inches) long. The long axis of the bar must be vertical.

To simulate the sequential drops, a rigid plane and a rigid pin 6 inches in diameter and 8 inches long are created, for the end drop and side drop respectively. During the pin puncture, the model is allowed to pass through the rigid plane; therefore the puncture is independent of the pin length. Two-drop configurations are selected, that will be subjected to maximum damage. The drop configurations selected for the pin puncture drop are listed in Table 2.12.1-6. The drop cases are designated as Drop Cases 15 and 16 as listed in Table 2.12.1-6.

**Table 2.12.1-6. HAC Drop Cases with Pin Puncture**

| Case No. | Description | Drop Angle degree | Drop Height (ft) | Pin Puncture Height in) | Shell Thickness (in) | Applicable Boundary Condition | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Temperature | | | Payload | | |
| | | | | | | Amb. | Hot | Cold | Normal | Heavy | light |
| **15** | HAC, Hot, End Drop + Pin Puncture | 90 | 30.0 | 40 | 0.50 | — | X | — | — | X | — |
| **16** | HAC, Hot, Side Drop + Pin Puncture | 0 | 30.0 | 40 | 0.50 | — | X | — | — | X | — |

## 2.12.1.7. Material Properties

### 2.12.1.7.1. 304 Stainless Steel

This material is used in the cask inner shell, over pack outer shell, gussets, and toroidal shell (impact limiter). The mechanical properties of the 304 SS at three different temperatures of interest in this calculation are tabulated in Table 2.12.1-7.

**Table 2.12.1-7. Mechanical Properties of SS304 at Temperature of Interest**

| Temperature | -40°F | 70°F | 300°F |
|---|---|---|---|
| Ultimate Tensile Strength, ksi | 75.0 | 75.0 | 66.2 |
| Yield Strength, ksi | 30.0 | 30.0 | 22.4 |
| Modulus of Elasticity, E ($10^6$ psi) | 28.8 | 28.3 | 27.0 |
| Poisson's Ratio | 0.31 | 0.31 | 0.31 |
| Density, lb/in$^3$ | 0.29 | 0.29 | 0.29 |

The stress strain curves for SS304, taken from References 2-7 and 2-21, and are presented in Tables 2.12.1-8 through 2.12.1-10. The graphical representations of the stress strain curves of the SS304 are displayed in Figures 2.12.1.7-1 through 2.12.1.7-3.

**Table 2.12.1-8. Stress Strain Curve of SS304 at -40°F**

| Strain | Stress, psi |
|---|---|
| 0.0020 | 27,000 |
| 0.0034 | 30,000 |
| 0.0074 | 34,868 |
| 0.0182 | 39,736 |
| 0.0395 | 44,604 |
| 0.0625 | 49,472 |
| 0.0816 | 54,340 |
| 0.0998 | 59,208 |
| 0.1189 | 64,076 |
| 0.1398 | 68,944 |
| 0.1624 | 73,812 |
| 0.1870 | 78,680 |
| 0.2134 | 83,548 |
| 0.2418 | 88,416 |
| 0.2722 | 93,284 |
| 0.3045 | 98,152 |
| 0.3389 | 103,020 |
| 0.3753 | 107,888 |
| 0.4137 | 112,755 |
| 0.4542 | 117,623 |
| 0.5542 | 117,623 |
| 0.6542 | 117,623 |
| 0.7542 | 117,623 |

**Table 2.12.1-9. Stress Strain Curve of SS304 at Ambient Temperature**

| Strain | Stress, psi |
|---|---|
| 0.0020 | 27,000 |
| 0.0035 | 30,000 |
| 0.0075 | 34,868 |
| 0.0183 | 39,736 |
| 0.0396 | 44,604 |
| 0.0626 | 49,472 |
| 0.0817 | 54,340 |
| 0.0999 | 59,208 |
| 0.1191 | 64,076 |
| 0.1399 | 68,944 |
| 0.1626 | 73,812 |
| 0.1871 | 78,680 |
| 0.2136 | 83,548 |
| 0.2420 | 88,416 |
| 0.2723 | 93,284 |
| 0.3047 | 98,152 |
| 0.3391 | 103,020 |
| 0.3755 | 107,888 |
| 0.4139 | 112,755 |
| 0.4544 | 117,623 |
| 0.5544 | 117,623 |
| 0.6544 | 117,623 |
| 0.7544 | 117,623 |

**Table 2.12.1-10. Stress Strain Curve of SS304 at 300°F**

| Strain | Stress, psi |
|---|---|
| 0.0022 | 22,500 |
| 0.0033 | 25,000 |
| 0.0076 | 29,477 |
| 0.0198 | 33,953 |
| 0.0431 | 38,430 |
| 0.0659 | 42,906 |
| 0.0849 | 47,383 |
| 0.1036 | 51,859 |
| 0.1236 | 56,336 |
| 0.1454 | 60,812 |
| 0.1691 | 65,289 |
| 0.1947 | 69,765 |
| 0.2223 | 74,242 |
| 0.2518 | 78,719 |
| 0.2832 | 83,195 |
| 0.3167 | 87,672 |
| 0.3522 | 92,148 |
| 0.3896 | 96,625 |
| 0.4291 | 101,101 |
| 0.4707 | 105,578 |
| 0.5707 | 105,578 |
| 0.6707 | 105,578 |

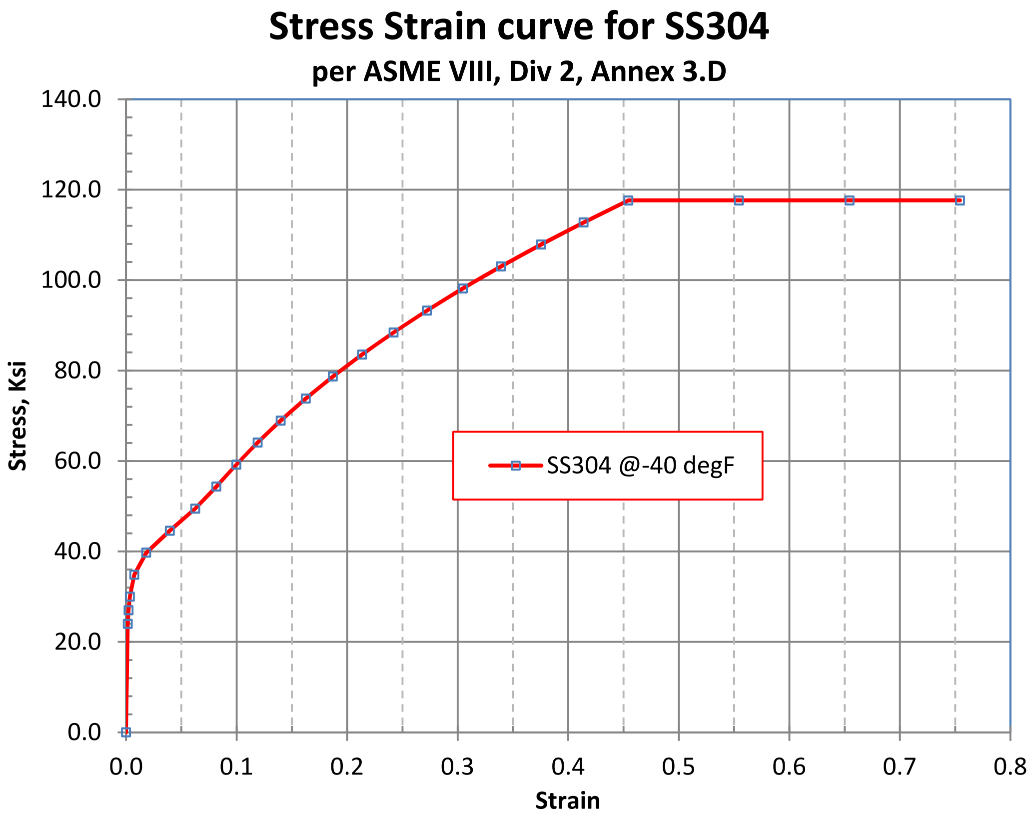



**Figure 2.12.1.7-1. Stress-Strain Curve of SS304 at -40°F**

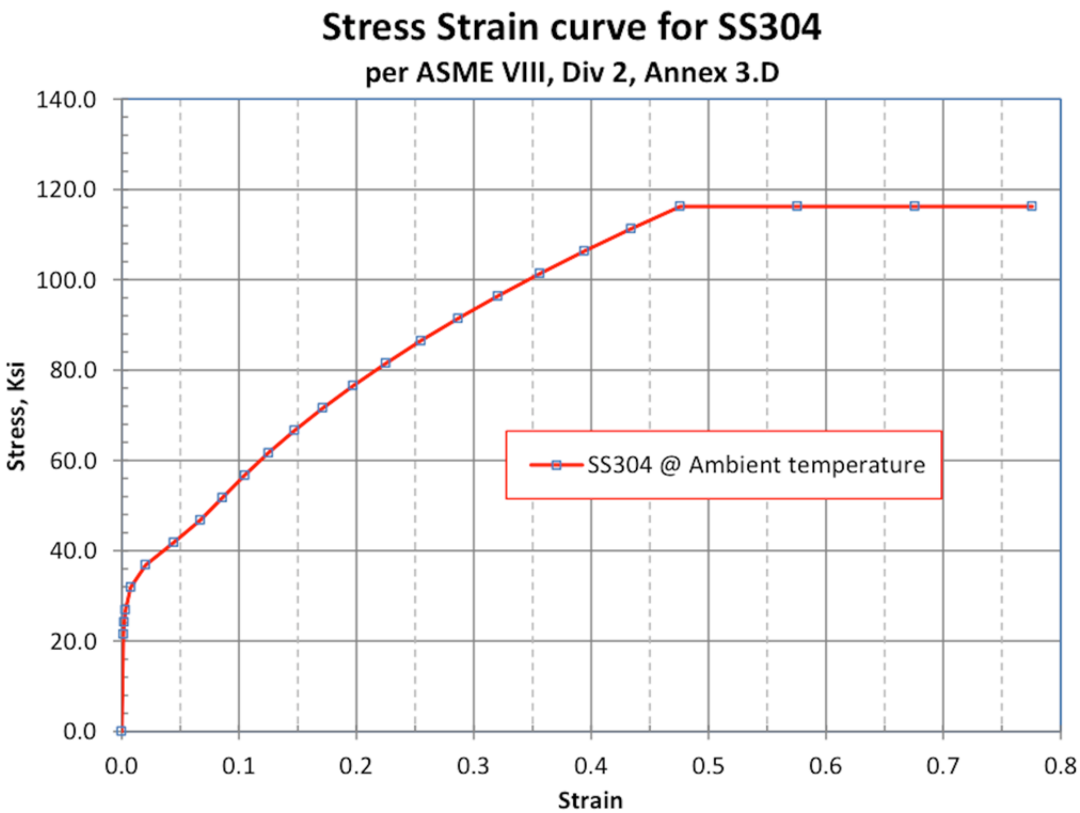



**Figure 2.12.1.7-2. Stress-Strain Curve of SS304 at Ambient Temperature**

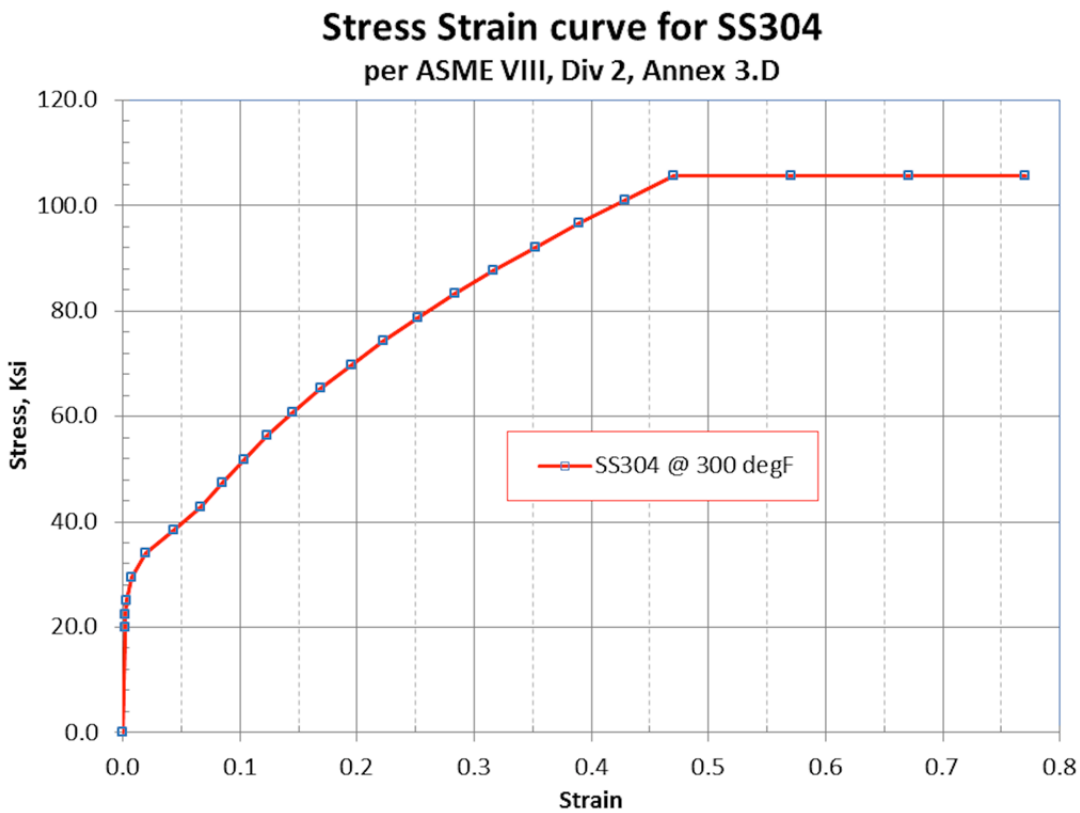



**Figure 2.12.1.7-3. Stress-Strain Curve of SS304 at 300°F**

### 2.12.1.7.2. Lead

Chemical lead is used in the cask as shielding material. The mechanical property of the chemical lead is presented in Table 2.12.1-11.

**Table 2.12.1-11. Lead Temperature Dependent Properties**

| Temperature, (°F) | Modulus of Elasticity, $\times 10^6$ (psi) | Density ($lb_m/in^3$) | Yield Strength, (psi) |
|---|---|---|---|
| -40 | 2.58 | 0.41 | 795 |
| 75 | 2.41 | 0.41 | 620 |
| 100 | 2.38 | 0.41 | 580 |
| 150 | 2.30 | 0.41 | 550 |
| 300 | 2.04 | 0.41 | 390 |

### 2.12.1.7.3. Strain-Rate Sensitive Material Properties of SS304

The factors that elevate true stress-strain curves for SS304 at various strain rates and temperatures were generated by Reference 2-22 (pp. 84-87) and reproduced in Table 2.12.1-12.

**Table 2.12.1-12. Strain-Rate Factors that elevated the Stress-Strain Curves of SS304**

| Strain Rate (in/in/sec) | -20°F | 70°F | 300°F | 600°F |
|---|---|---|---|---|
| 5 | 1.333 | 1.235 | 1.166 | 1.043 |
| 10 | 1.361 | 1.278 | 1.210 | 1.094 |
| 22 | 1.428 | 1.381 | 1.316 | 1.217 |
| 25 | 1.445 | 1.407 | 1.342 | 1.247 |

The data from the above table are used to generate the strain-rate multiplication factors for the current analyses at temperatures of -40°F, ambient temperature and 300°F.

### 2.12.1.7.4. Honeycomb Material Property

The crush strength of the honeycomb material is 750 psi. The material property at temperature of -20°F is assigned a value of 10% greater to account for the increase of rigidity due to cold temperature. Based on the HPI thermal analyses presented in Section 3, the temperature of the honeycomb material is bounded by 400°F. For the crush strength of honeycomb material at 400°F, a reduction of the crush strength of 40% is conservatively assigned. This is based on the thermal tests from Reference 2-23, p. 9. The temperature test result is presented in Figure 2.12.1.7-4.

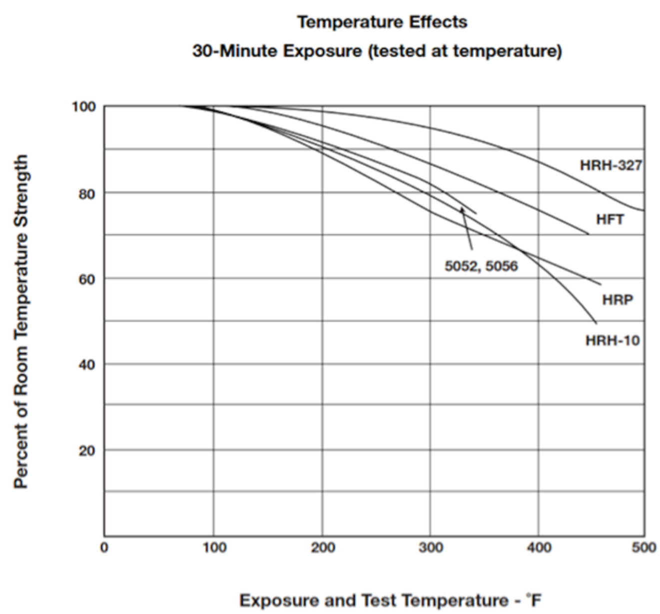



**Figure 2.12.1.7-4. Temperature Effect of Honeycomb Material**

#### 2.12.1.7.5. Temperature Range for Material Properties

The component temperature range and justification for the applied temperature is discussed in Table 2.12.1-13.

**Table 2.12.1-13. Component Temperature Range and Justification**

| Component, Material | Predicted Temperature Range | Applied Temperature | Justification for Use of Non-Bounding Peak Temperature |
|---|---|---|---|
| Overpack Toroids, 304 SS | -20 to 110-250 | -20 to 300 | Bounding. Provides primary impact protection |
| Cask Shell, 304 SS | -20 to 300-460 | -20 to 300 | Cask does not provide primary impact protection. Temperature range selected to best represent the performance of the cask during impact. |
| Cask Shielding, Lead | -20 to 330-450 | -20 to 300 | Lead does not provide primary impact protection. Therefore, temperature range considered acceptable for analyses. |
| Overpack Cover and Base, 304 SS | -20 to 170-370 | -20 to 300 | Overpack cover not included in model. The base does not provide primary impact protection. Therefore, range considered acceptable for analyses. |
| Overpack Honeycomb, Aluminum | -20 to 200-360 | -20 to 400 | 40% compressive strength reduction bounds temperature of 400F. 10% compressive strength increase bounds temperature of -20F. |

### 2.12.1.8. LS-DYNA Model Description

#### 2.12.1.8.1. Finite Element Model

In accordance with the Model 2000 licensing drawings, an LS-DYNA finite element model was generated to evaluate the structural performance of the cask when loaded with the maximum content weight. The model includes the overpack and the Model 2000 cask body with lead shield and lid. The contents of the cask are modeled as a rigid body.

The 3D (half-symmetry) solid model of the Model 2000 cask and overpack was generated using Autodesk Inventor, which was imported into ANSYS Workbench Design Modeler (Reference 2-16). The finite element mesh was generated using the ANSYS Workbench Mechanical interface. The completed FEA model was then saved as a text input file to perform the analyses. Figure 2.12.1.8-1 shows the finite element model.

The finite element model is comprised of 3D brick elements (fully integrated selective-reduced solid) that represent the main body of cask components. Contact between components is modeled as surfaces using contact pairs. Boundary conditions such as symmetry are applied to the symmetry plane of the model. The final model includes 790,526 elements and 1,355,593 nodes.

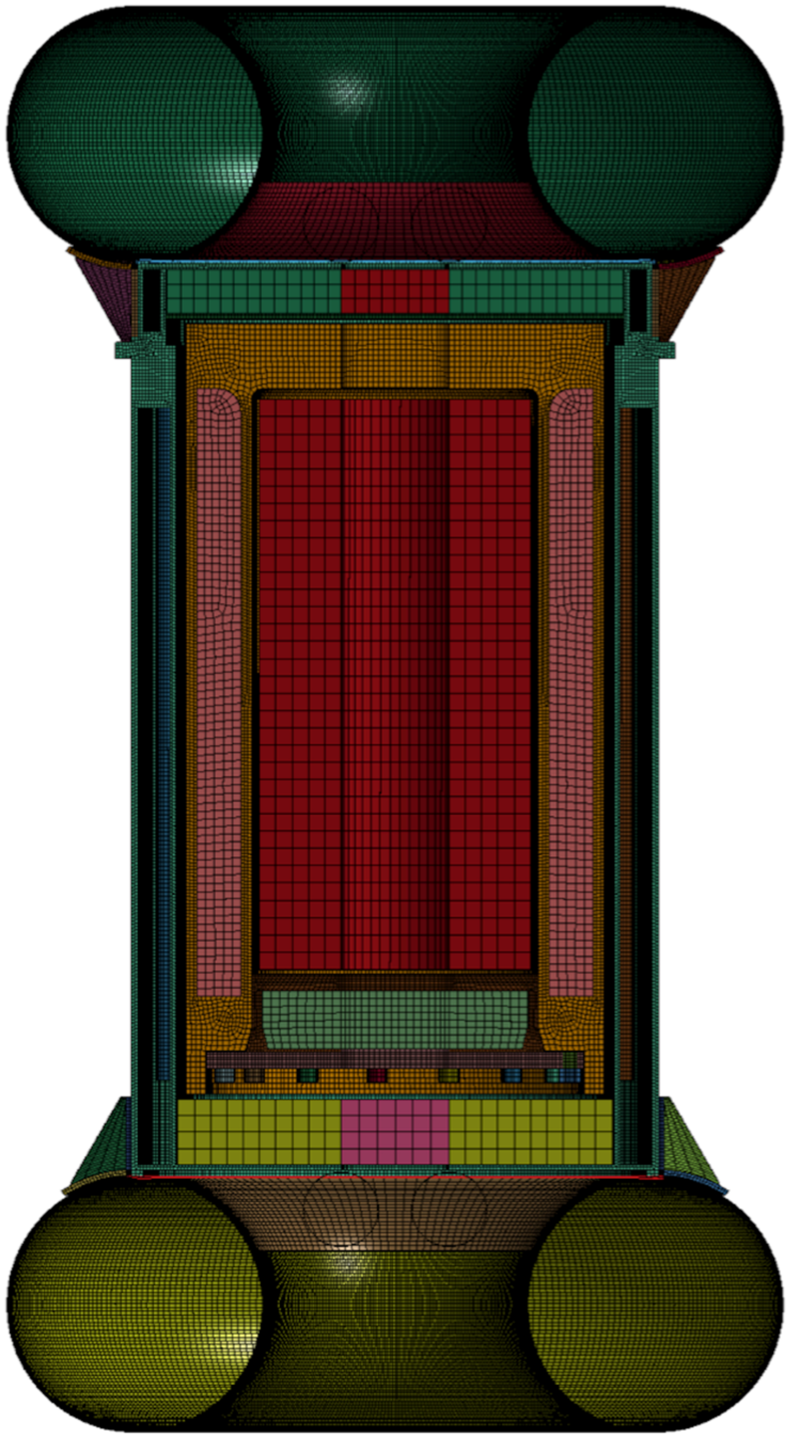


**Figure 2.12.1.8-1. Model 2000 Overpack and Cask Finite Element Model**

### 2.12.1.8.2. Pin Puncture Analysis Methodology

The accident sequence presented in 10 CFR 71.73 requires that the cask, after a 30-foot drop, be dropped onto 6-inch diameter pin. To simulate the sequential drops, a rigid plane and a rigid pin with a 6-inch diameter and 8-inch length are created as shown in Figures 2.12.1.8-2 and 2.12.1.8-3 for the end drop and side drop, respectively.

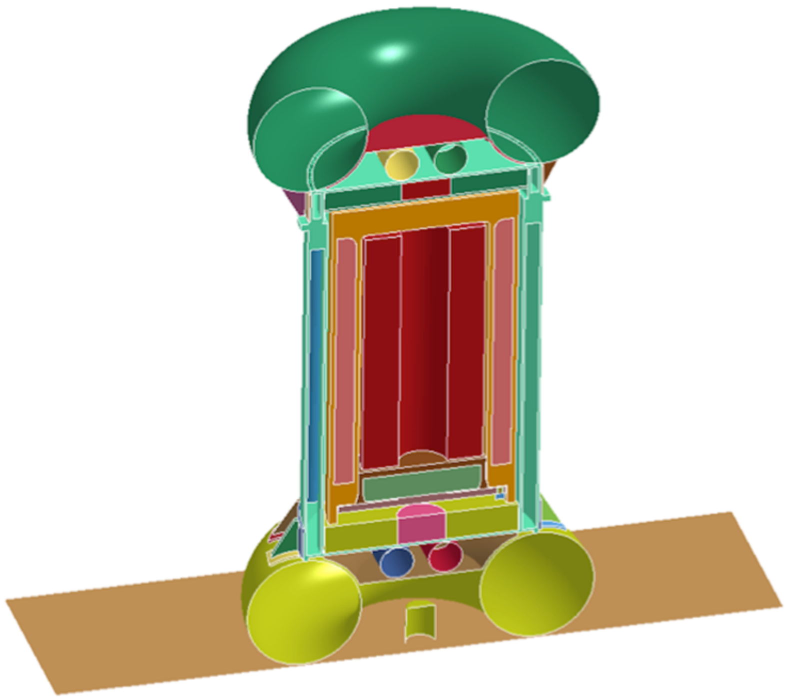


**Figure 2.12.1.8-2. Rigid Plane and Pin Model for the End Drop Configuration**

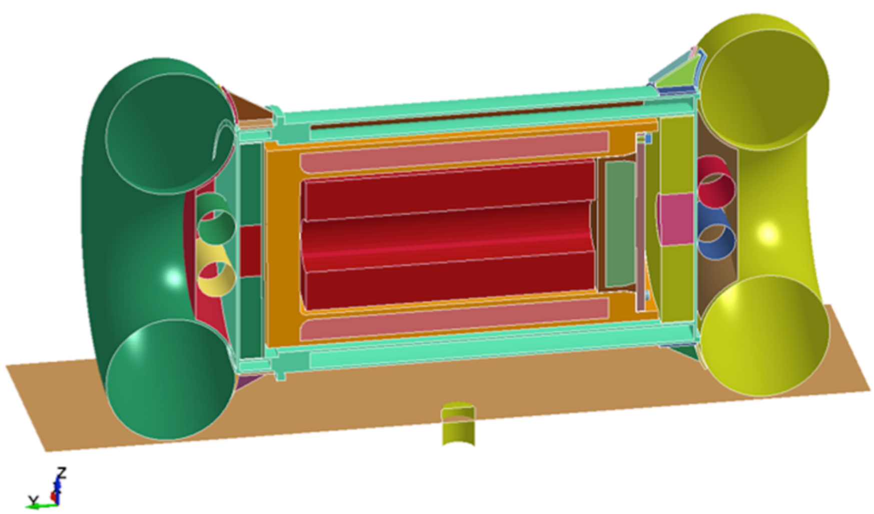


**Figure 2.12.1.8-3. Rigid Plane and Pin Model for the Side Drop Configuration**

The dynamic simulation for this 30-foot drop onto an unyielding surface followed by a 40-inch drop onto a pin is performed using a two steps drop sequence. For the first sequence, the impact velocity of the 30-foot drop is 527.5 in/sec. For the second sequence, the initial velocity for a 40-inch drop is 175.8 in/sec.

During the first drop sequence at the beginning of the 30-foot drop accident, the cask travels in the downward direction with an initial velocity of 703.3 in/sec (=527.5+175.8). The rigid plane and the pin travel at an initial velocity of 175.8 in/sec and the contact interface is activated between the cask and the rigid plane while the contact interface between the cask and the pin is not activated. Therefore, the relative velocity between the cask and the rigid plane is 527.5 in/sec, which is equivalent to a drop height of 30 feet. During this sequence, the distance between the cask the pin is reduced as time progresses. The kinetic energy of the cask dissipates to zero at time = 35 milliseconds. This is the time at which the puncture impact starts.

At the beginning of the second sequence, the distance between the pin and the cask is reduced to a minimum gap but not touching. At this point, the absolute velocity of the cask and pin is 175.8 in/sec. At this time, the contact interface between the pin and the cask is activated while the contact interface between the rigid plane and the cask is deactivated, which allows the damaged impact limiters to pass through the rigid plane. Additionally, the velocity of the pin is set to zero, which results in relative velocity between the cask and the pin of 175.8 in/sec. Figure 2.12.1.8-4 shows the cumulative damage following the 30-foot top end drop and 40-inch pin puncture.

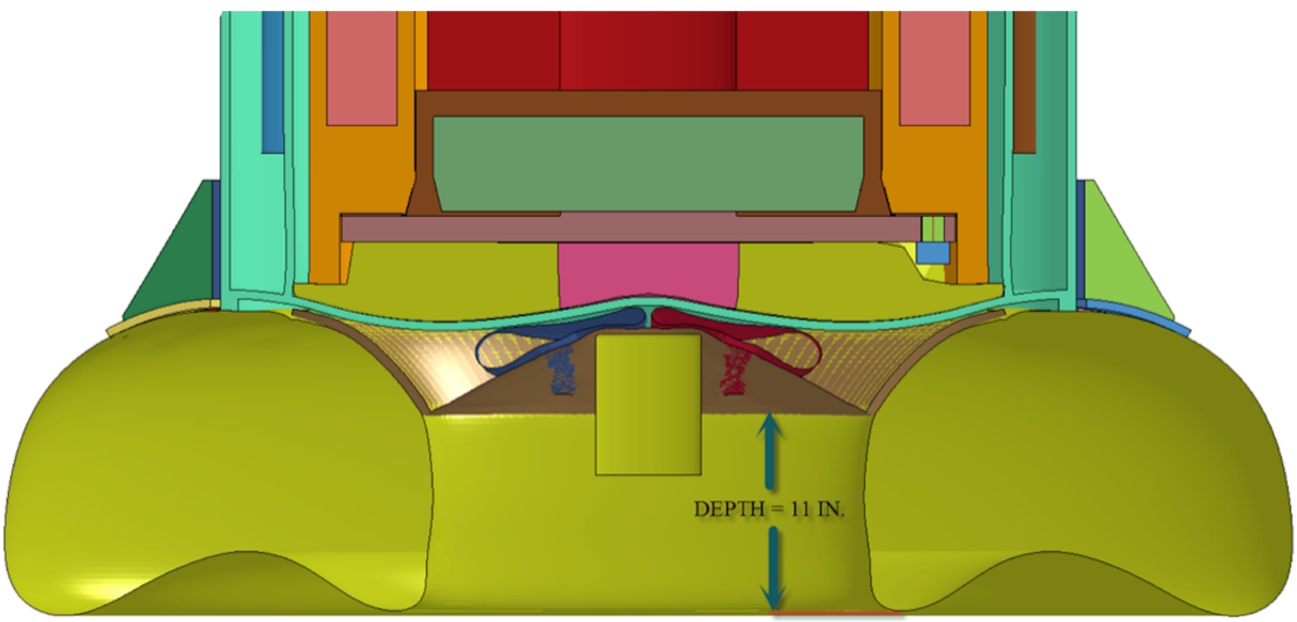



**Figure 2.12.1.8-4. Deformed Geometry of the Overpack after a 30 foot End Drop**

Figure 2.12.1.8-5 shows the cumulative damage for the side drop and pin puncture sequence. For the side drop, the depth of the unexposed cavity below the toroidal shell is less than 2.3 inches (taken from the result of Drop Case 10). Therefore, the modeled pin length of 8 inches is sufficient to sustain maximum damage.

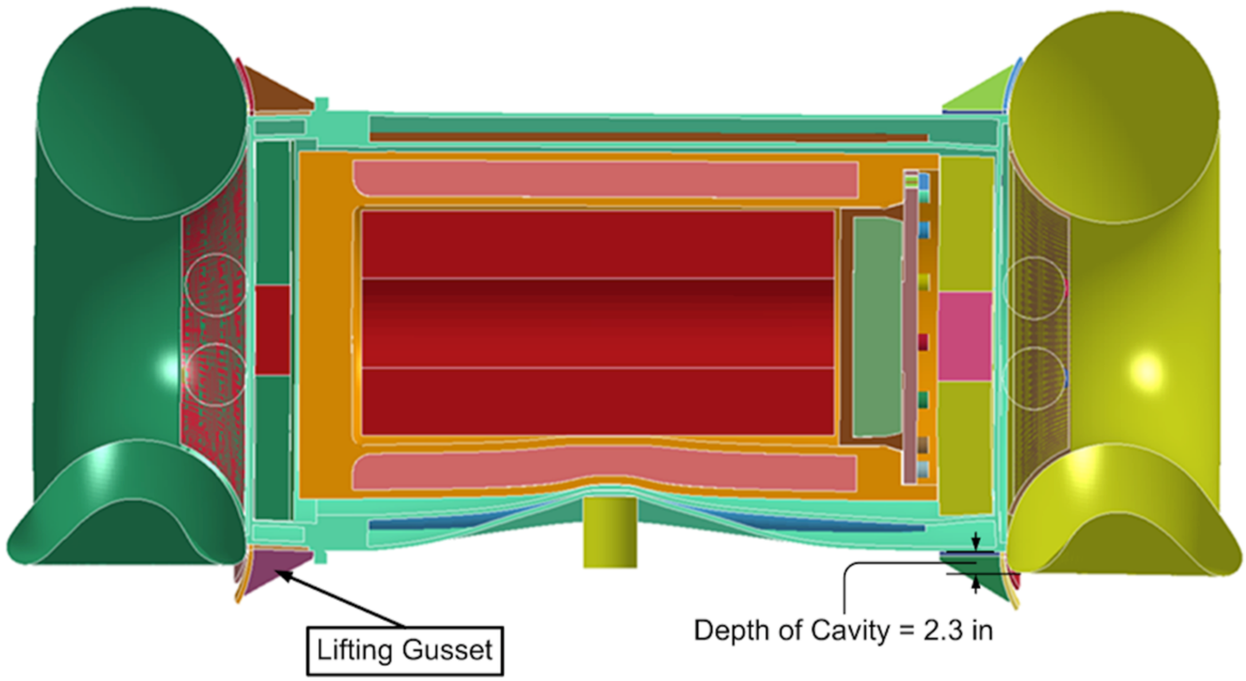



**Figure 2.12.1.8-5. Deformed Geometry of the Overpack after a 30 foot Side Drop**

### 2.12.1.9. Weight

The Model 2000 Transport Package components consist of the closure lid, cask body and overpack. The dimensions used in the calculations are taken from the Model 2000 Transport Package fabrication drawings. The total weight of the Model 2000 Transport Package empty is calculated to be 28,100 lb. From the finite element model, the center of gravity is located 1.5 inches below the centerline of the overpack, 64.25 inches from the bottom line. Table 2.1-3 presents the breakdown of the components weights used for the dynamic analyses.

#### 2.12.1.9.1. Material Model

The LS-DYNA material models used in the analyses are described below:

- The stainless steel shells are modeled using *MAT_PIECEWISE_LINEAR_PLASTICITY.
- The honeycomb impact limiters are modeled using *MAT_CRUSHABLE_FOAM.
- The payload is modeled as *MAT_RIGID.
- The closure lid bolts of the inner shell are modeled as *MAT_ELASTIC.

#### 2.12.1.9.2. Contact Interfaces

The control card *CONTACT_TIED_SURFACE_TO_SURFACE is used to fasten the welded components. For the components within the cask and the overpack, the control card *CONTACT_AUTOMATIC_SINGLE_SURFACE is used to provide global contact control. The honeycomb material has significant stiffness difference between the adjacent part, therefore the control card *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE is used to control and prevent penetration between parts.

### 2.12.1.10. Boundary Conditions

#### 2.12.1.10.1. Symmetry Plane

The half-symmetry finite element model utilizes symmetry boundary conditions that are applied to the cut plane of the half-model in the Z-direction.

#### 2.12.1.10.2. Initial Velocity

The drop height, H, is converted to kinetic energy using the formula below.

$$V = \sqrt{2 \times g \times H}$$

where

V = the initial velocity at the threshold of impact, in/s

g = gravity constant = 386.4 in/s².

H = drop height, in

Therefore, the drop height of H=30 ft is converted to initial velocity, V360-in, as

$$V_{360\text{-in}} = \sqrt{2 \times g \times 360} = 527.45 \text{ in/s}$$

And the drop height of H=40-in is converted to initial velocity, V40-in, as

$$V_{40\text{-in}} = \sqrt{2 \times g \times 40} = 175.8 \text{ in/s}$$

#### 2.12.1.10.3. Gravity

The gravity of 386.4 in/s is applied to all components in the global Z-direction with an initial ramp up period of 0.05 seconds.

### 2.12.1.11. Dynamic Analysis Results HAC 30-foot Drops

The results of the impact analyses of the Model 2000 cask model in the forms of acceleration of the payload and plastic strain of the toroid shell are presented in Sections 2.12.1.11.1 through 2.12.1.11.14. Further, each section contains four plots, which include a plot for the deformed overpack shape, the cask acceleration time history, energy time histories and interface sliding energy time history (Figures 2.12.1.11-1 through 2.12.1.11-58). Section 2.12.1.11.15 presents the results of the 30-foot drop followed by pin puncture drop. The significance of the accelerations and energy time histories (kinetic energy, internal energy, hourglass energy, and sliding energy) of the simulations are described below.

**Accelerations** – Accelerations are extracted from the LS-DYNA MATSUM file. Using the MATSUM data allows for the reporting of the maximum acceleration in any part and at any point in the model.

**Kinetic Energy** - The kinetic energy time history is used to confirm that the kinetic energy of the cask assembly is completely dissipated during the impact and the acceleration has peaked. For a normal and completed drop impact scenario, the kinetic energy must be decreasing to a minimum value as close to zero as possible and starts to increase (due to gravity loading). At the moment of minimum kinetic energy, the primary impact event is over.

**Internal Energy** - The internal energy plot is a measure of how much of the kinetic energy is converted into strain energy, either elastic or inelastic. Most likely, the internal energy is a measure of inelastic strain energy corresponding to the permanent deformation of the energy absorber material. The accumulated internal energy is a measure of how well the impact limiter is working as designed. Internal energy that is significantly smaller than the initial kinetic energy is an indication that the impact limiter is not dissipating the impact energy.

**Hourglass Energy** - The hourglass energy and the sliding energy are numerical terms that are produced by the mathematic solver but not derived from kinetic energy. The hourglass energy is strain energy numerically produced and proportional to the energy used to control the distortion of brick finite elements (solid element). As recommended by the LS-DYNA user manual, the brick elements perform best during the solution when the hourglass energy is limited to less than 10% of the internal energy.

**Sliding Energy** - The sliding energy plots represent the efficiency of the contact interface and the level of penetration between adjacent parts. A negative sliding energy indicates that the contact interface is not working well with a high degree of part penetrations. The contact interface control parameters must be revised to allow the use of different contact algorithms to prevent parts penetrations and pass-through. A positive sliding energy indicates the contact interface is working well and no penetrations are present.

### 2.12.1.11.1. Case 1 End Drop Benchmark

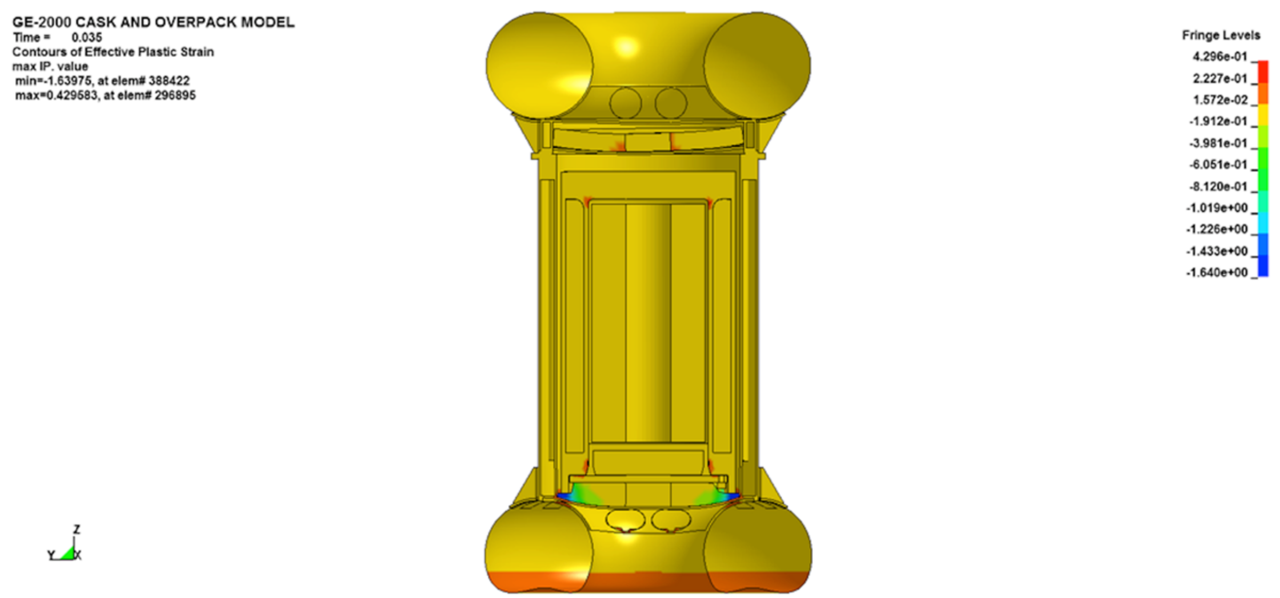



**Figure 2.12.1.11-1. Case 1 Deformed Overpack Shape (Effective Plastic Strain)**

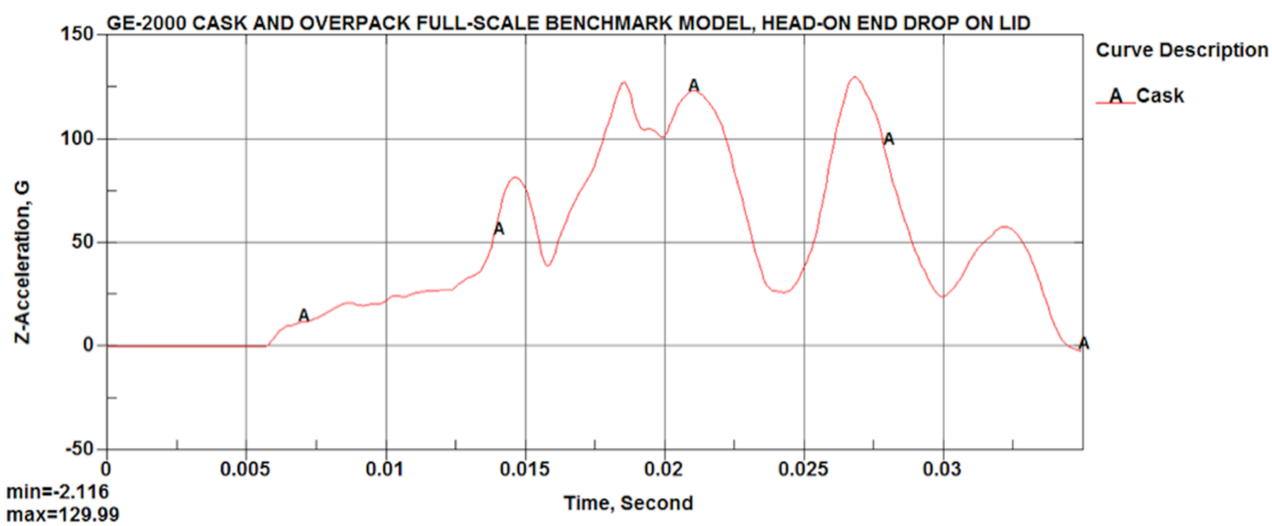
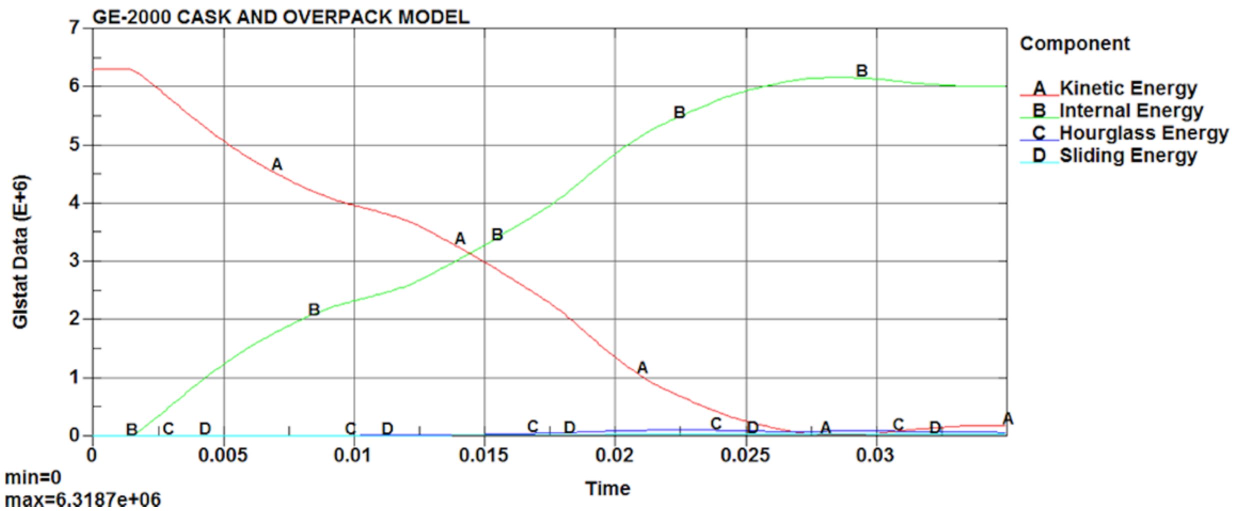
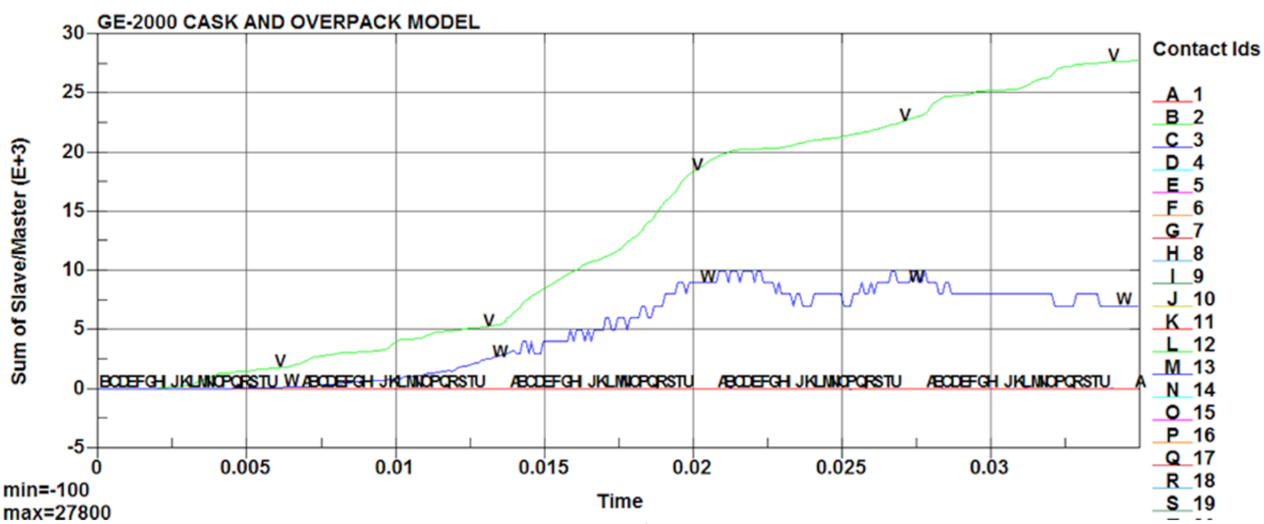



**Figure 2.12.1.11-2. Case 1 Payload Acceleration Time History**




Note: time in Seconds

**Figure 2.12.1.11-3.  Case 1 Impact Energy Plot**




Note: time in Seconds

**Figure 2.12.1.11-4.  Case 1 Interface Sliding Energy Time History**

### 2.12.1.11.2. Case 2 Side Drop Benchmark

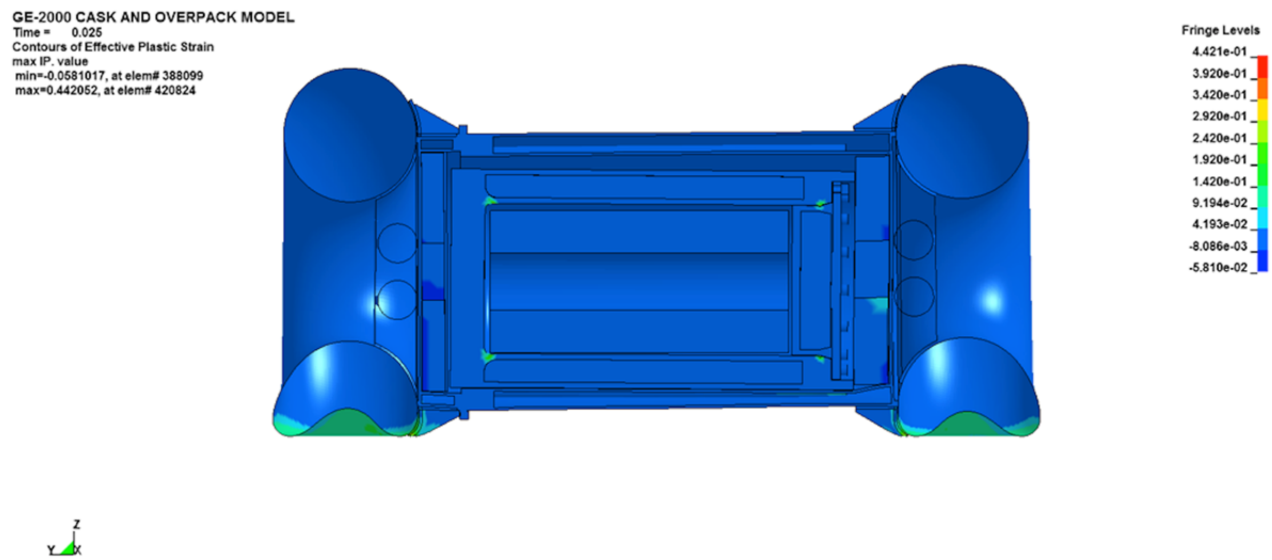



**Figure 2.12.1.11-5. Case 2 Deformed Overpack Shape (Effective Plastic Strain)**

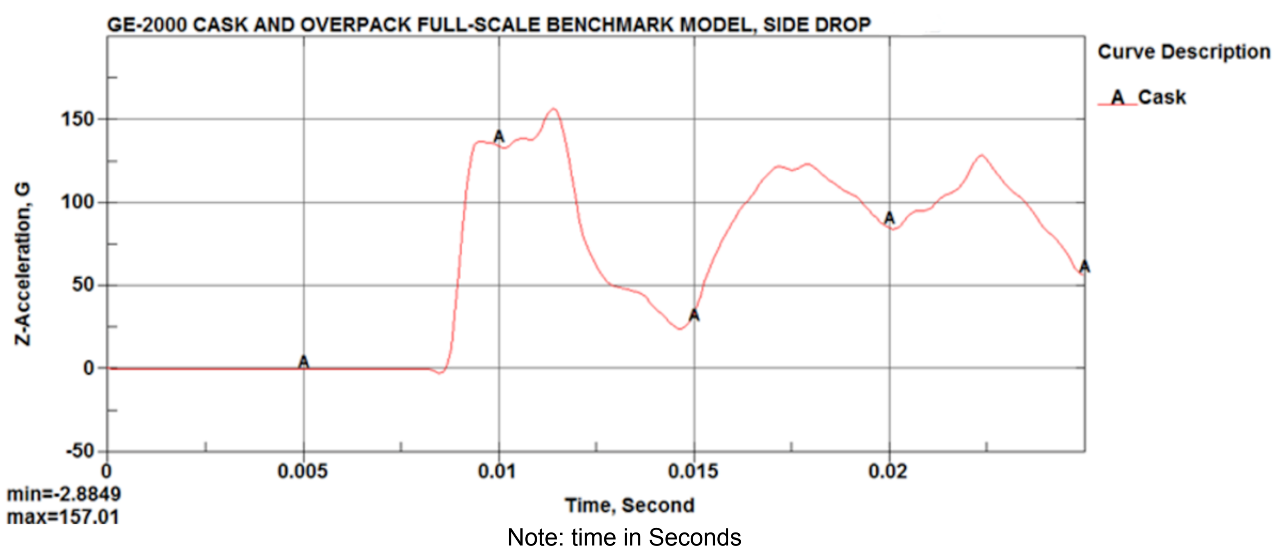



**Figure 2.12.1.11-6. Case 2 Payload Acceleration Time History**

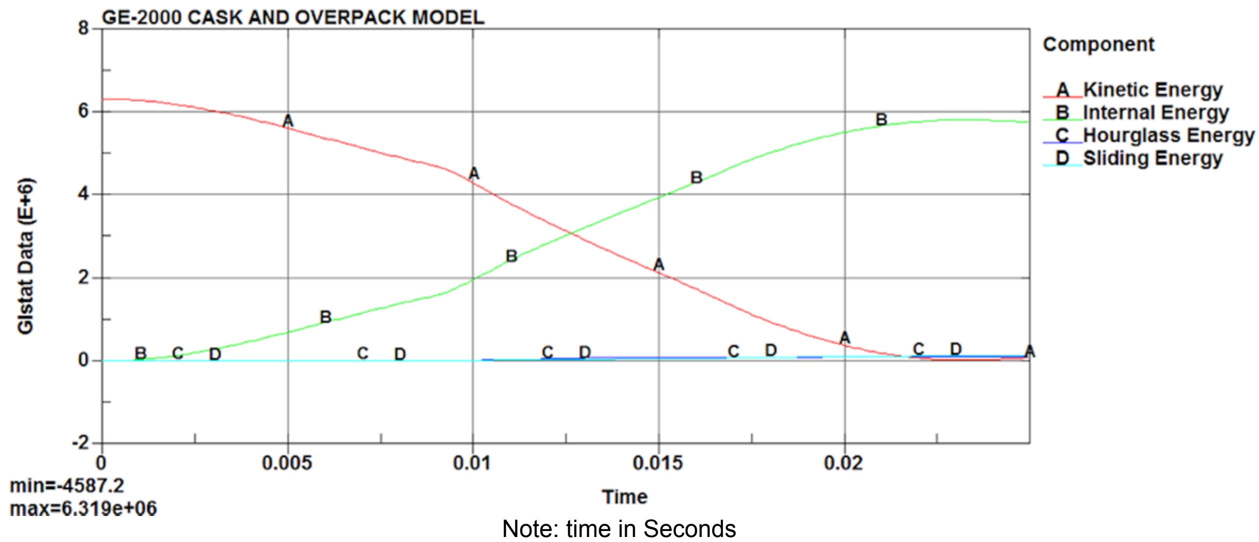



**Figure 2.12.1.11-7. Case 2 Impact Energy Plot**

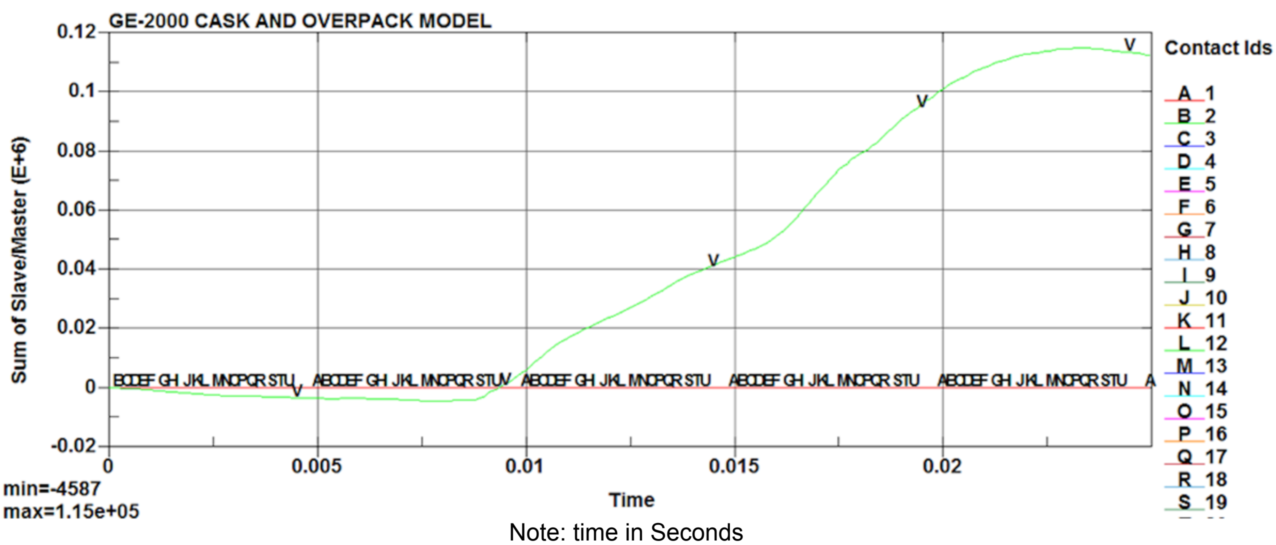



**Figure 2.12.1.11-8. Case 2 Interface Sliding Energy Time History**

### 2.12.1.11.3. Case 3 C.G. over Corner Drop Benchmark

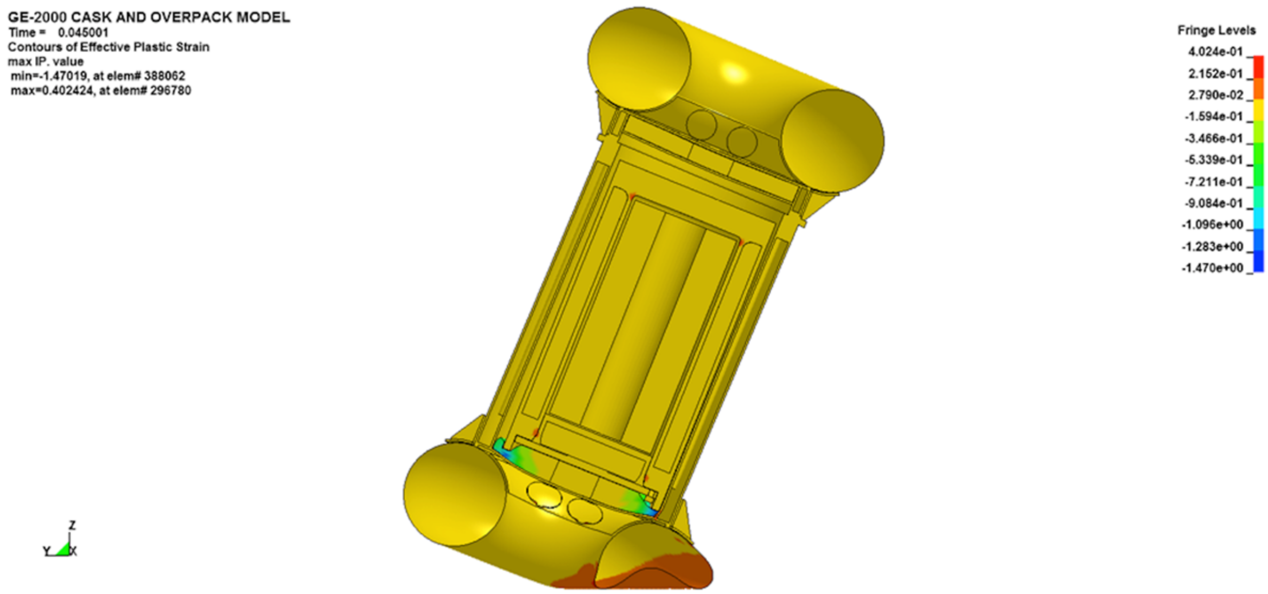
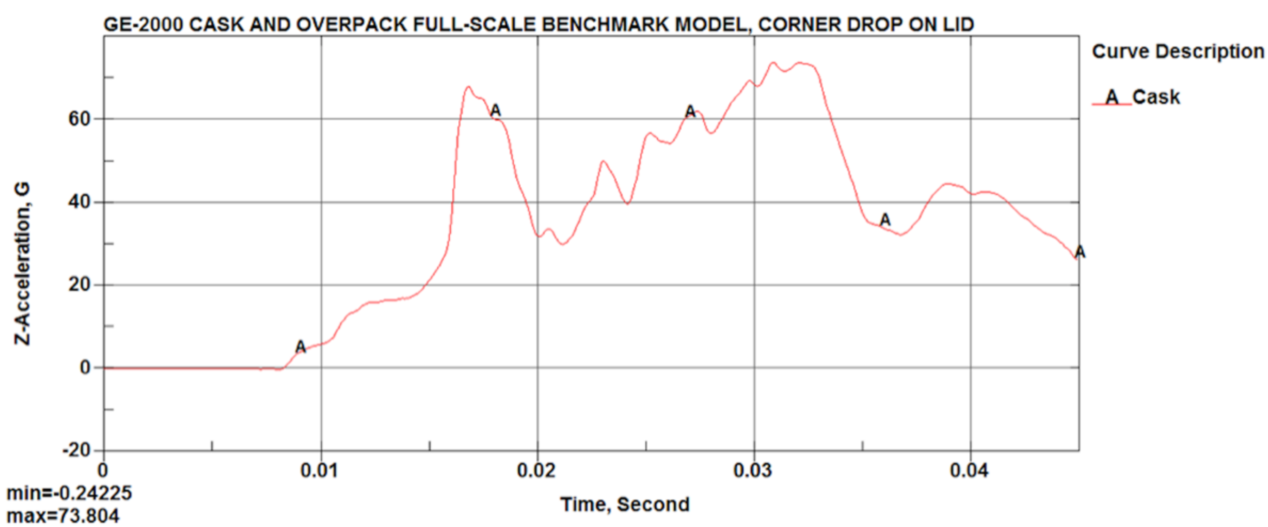



**Figure 2.12.1.11-9. Case 3 Deformed Overpack Shape (Effective Plastic Strain)**




Note: time in Seconds

**Figure 2.12.1.11-10. Case 3 Payload Acceleration Time History**

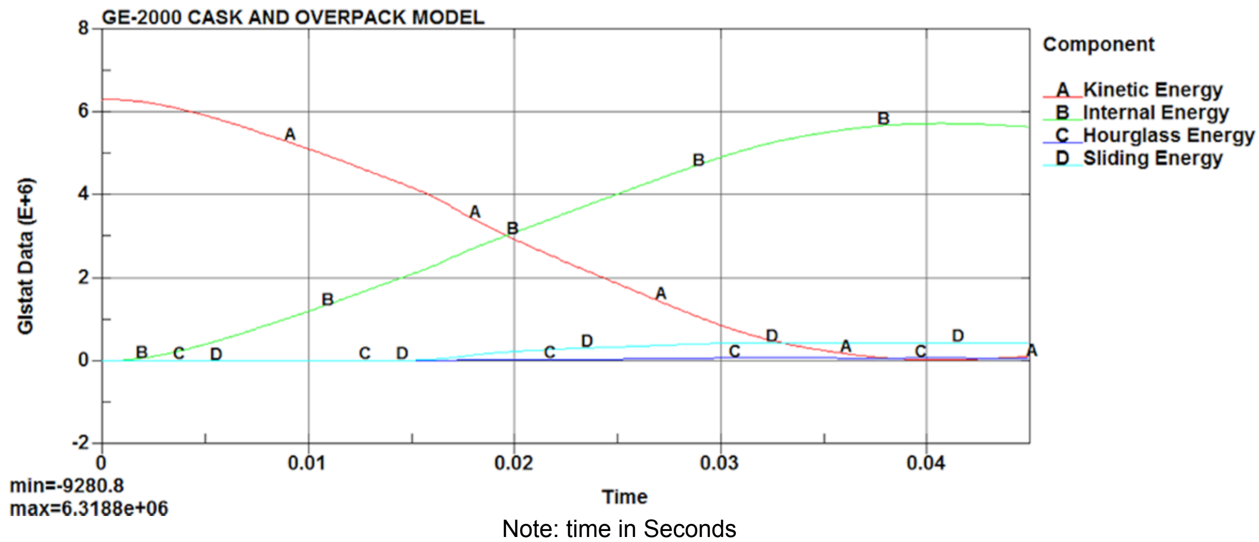



**Figure 2.12.1.11-11. Case 3 Impact Energy Plot**

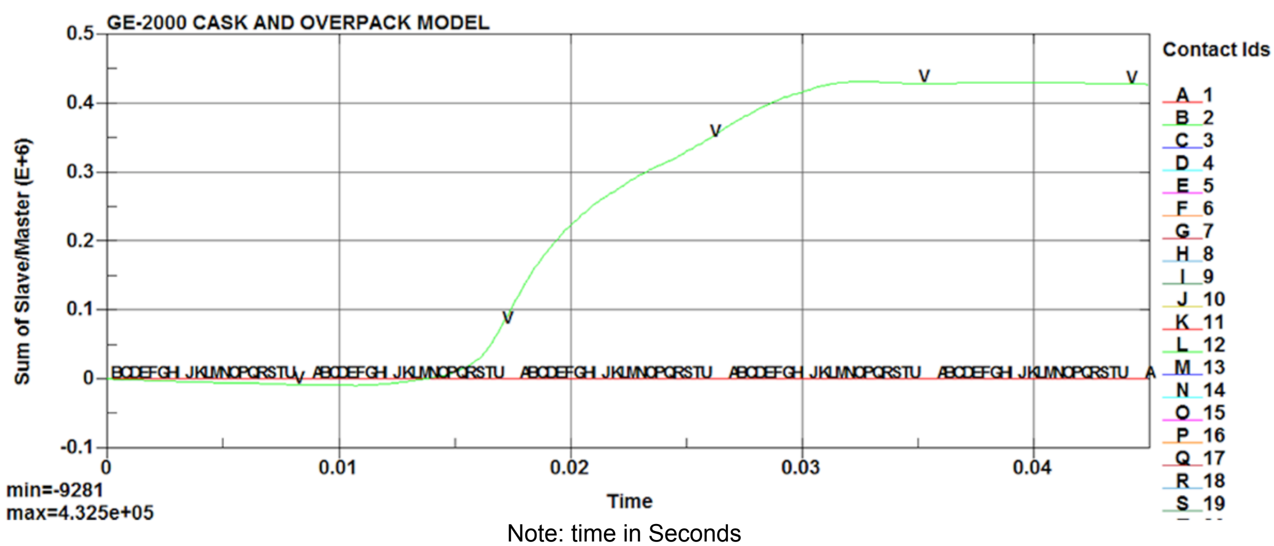



**Figure 2.12.1.11-12. Case 3 Interface Sliding Energy Time History**

### 2.12.1.11.4. Case 4 NCT End Drop with Thick Shell, Cold Condition and Light Payload

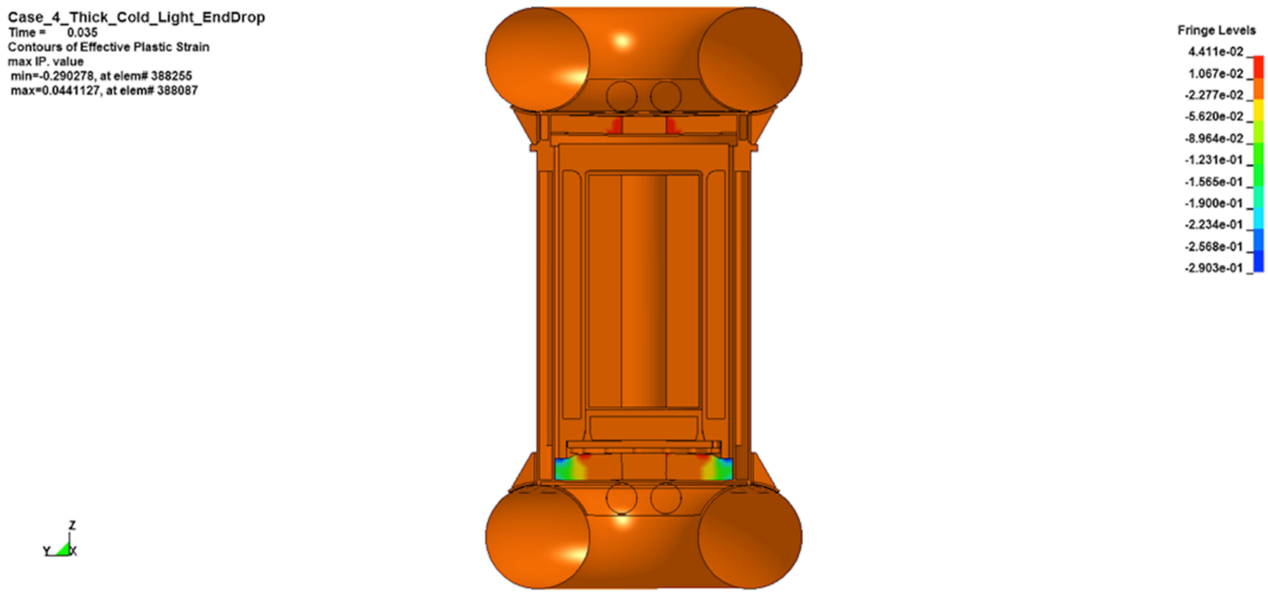



**Figure 2.12.1.11-13. Case 4 Deformed Overpack Shape (Effective Plastic Strain)**

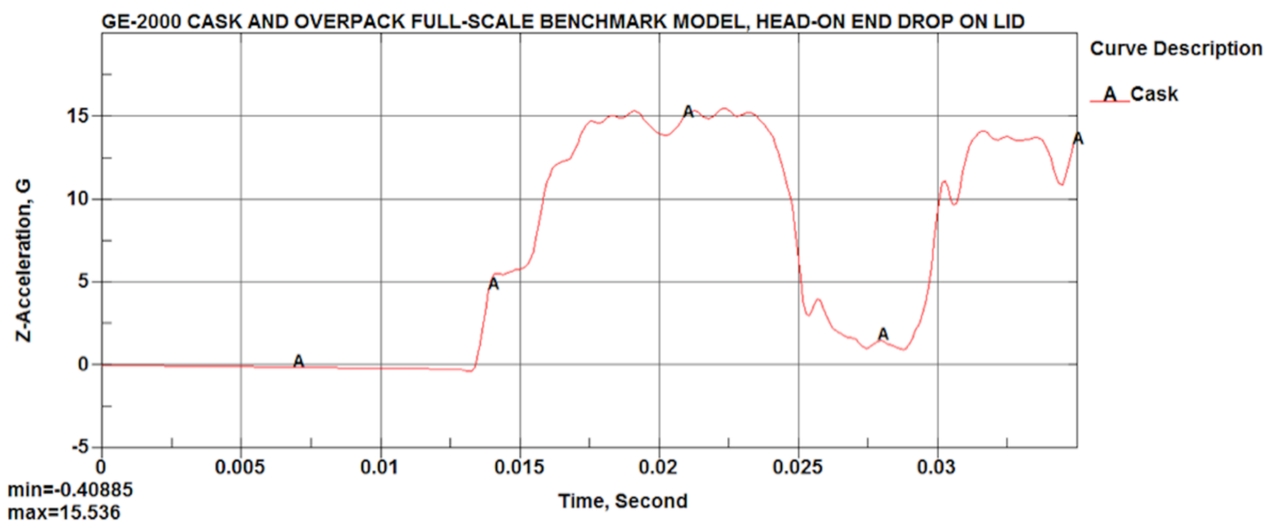
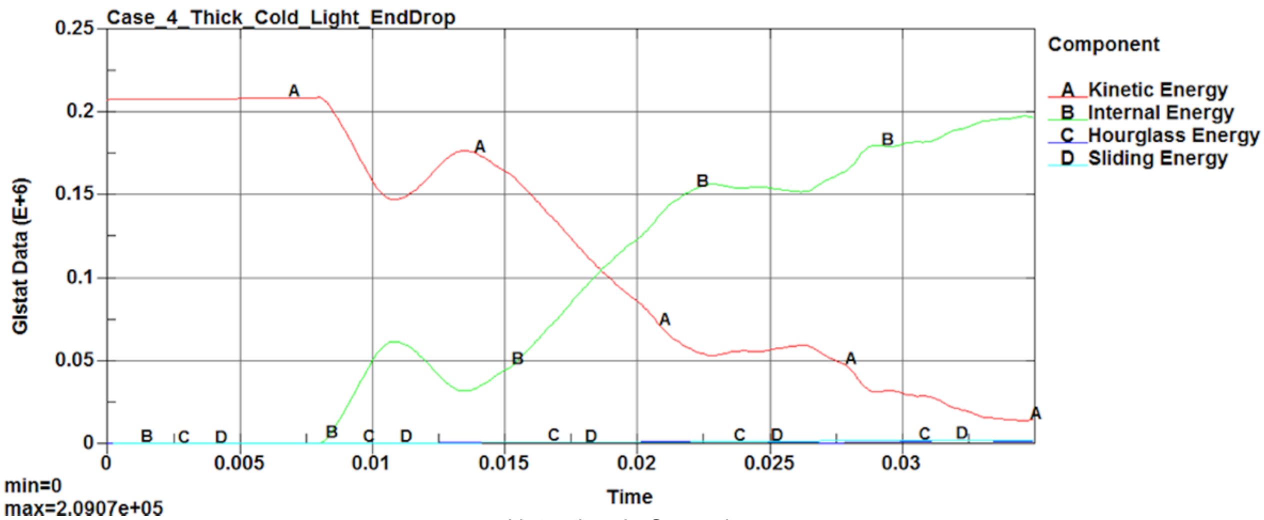
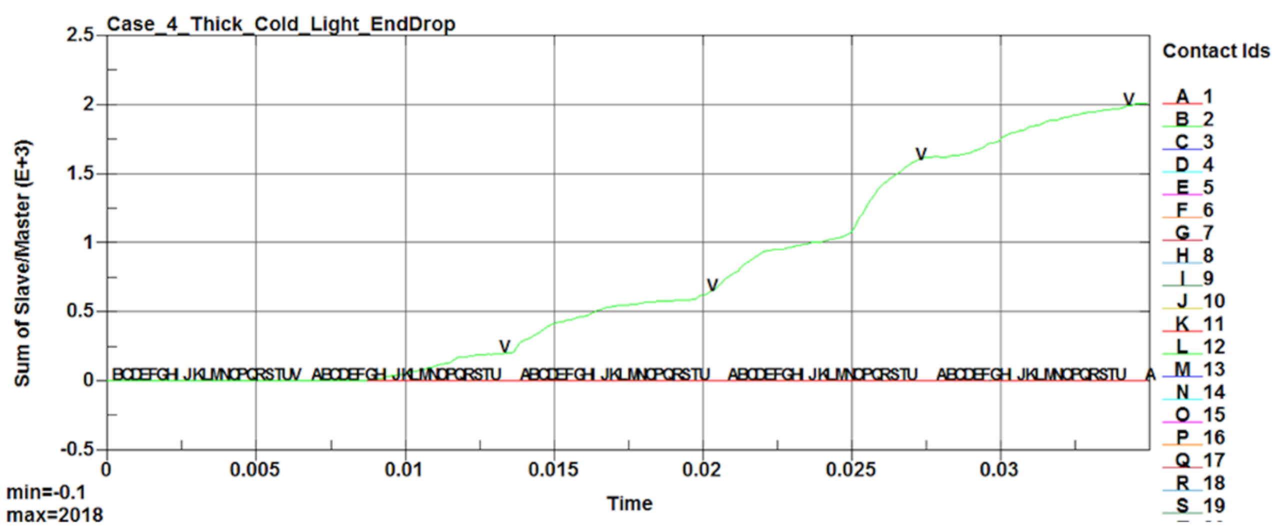



**Figure 2.12.1.11-14. Case 4 Payload Acceleration Time History**




Note: time in Seconds

**Figure 2.12.1.11-15. Case 4 Impact Energy Plot**




Note: time in Seconds

**Figure 2.12.1.11-16. Case 4 Interface Sliding Energy Time History**

### 2.12.1.11.5. Case 5 NCT Side Drop with Thick Shell, Cold Condition and Light Payload

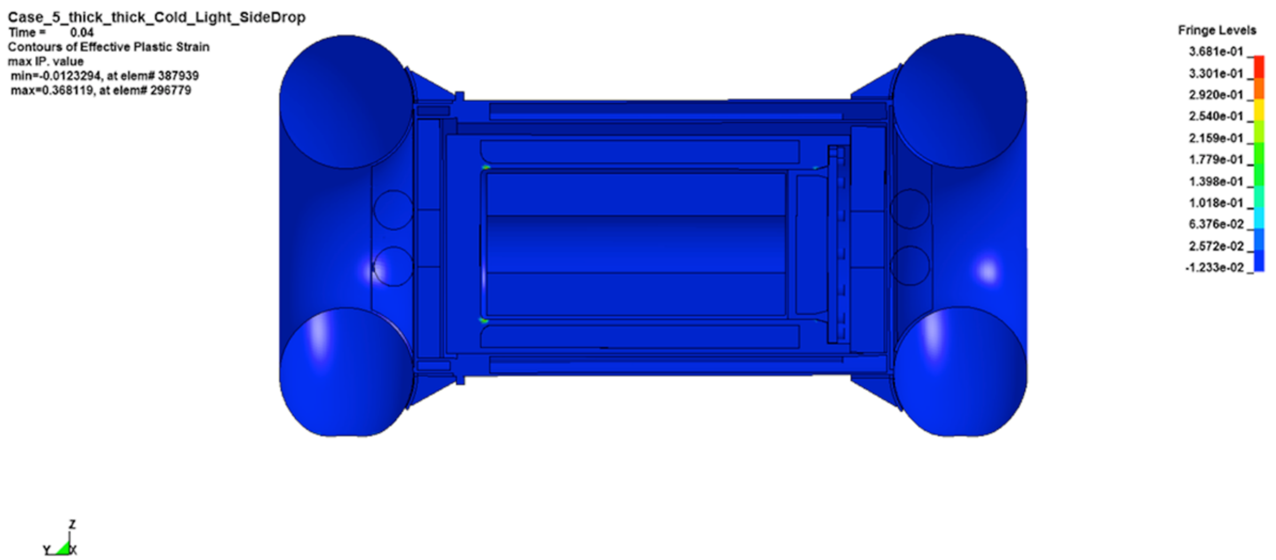



**Figure 2.12.1.11-17. Case 5 Deformed Overpack Shape (Effective Plastic Strain)**

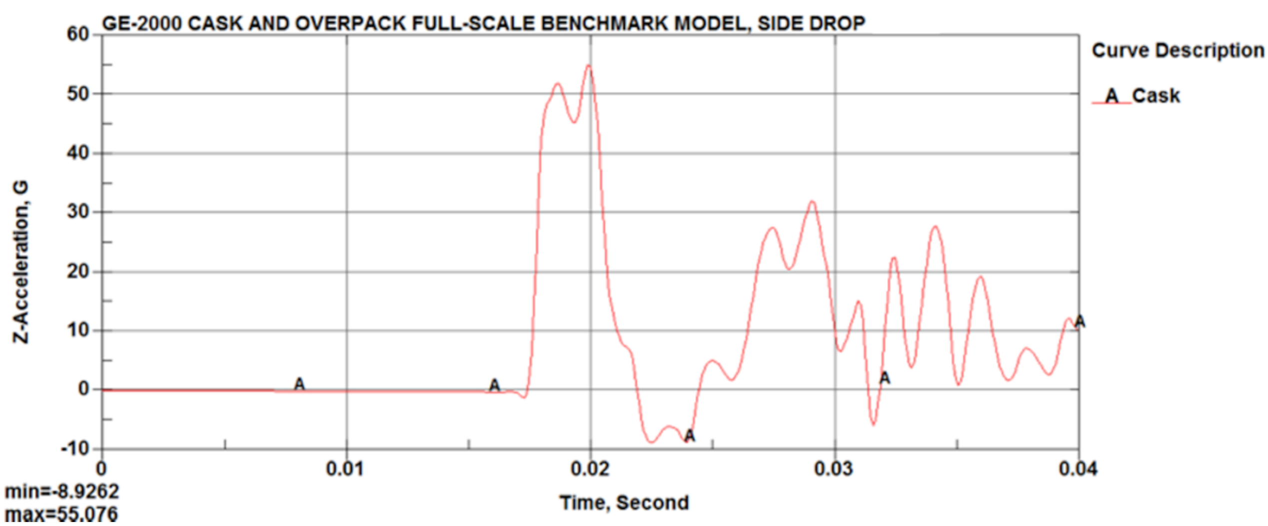
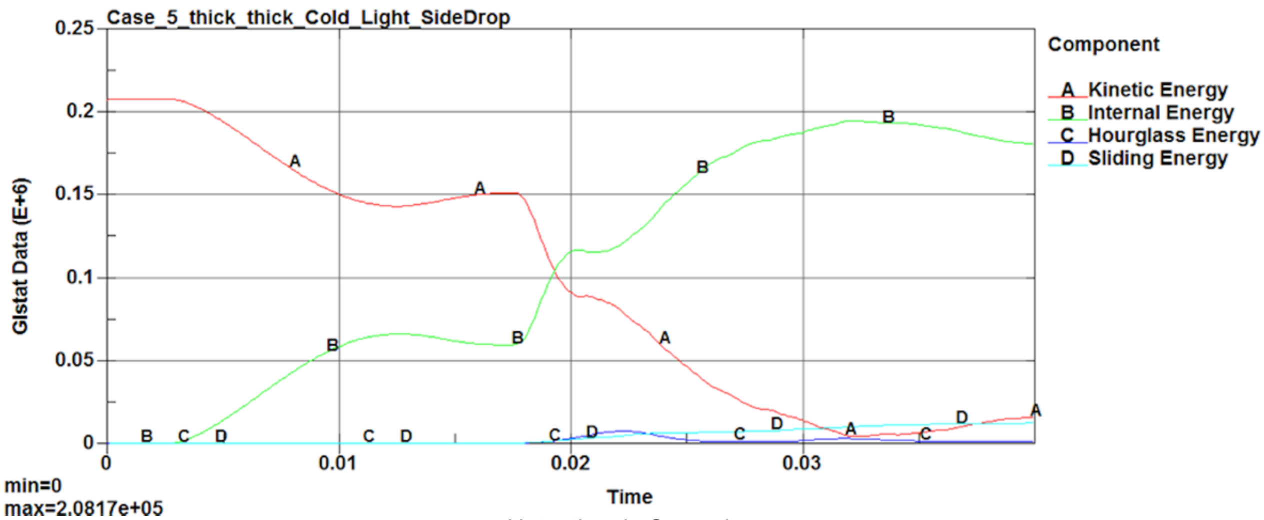
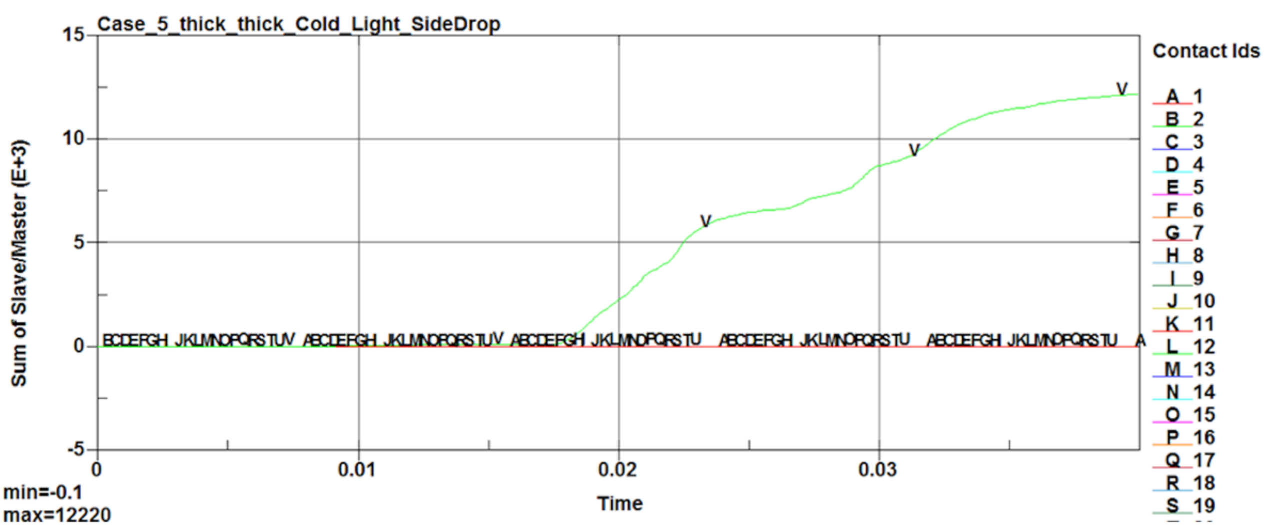



**Figure 2.12.1.11-18. Case 5 Payload Acceleration Time History**




Note: time in Seconds

**Figure 2.12.1.11-19. Case 5 Impact Energy Plot**




Note: time in Seconds

**Figure 2.12.1.11-20. Case 5 Interface Sliding Energy Time History**

#### 2.12.1.11.6. Case 6 NCT Corner Drop with Thick Shell, Cold Condition and Light Payload

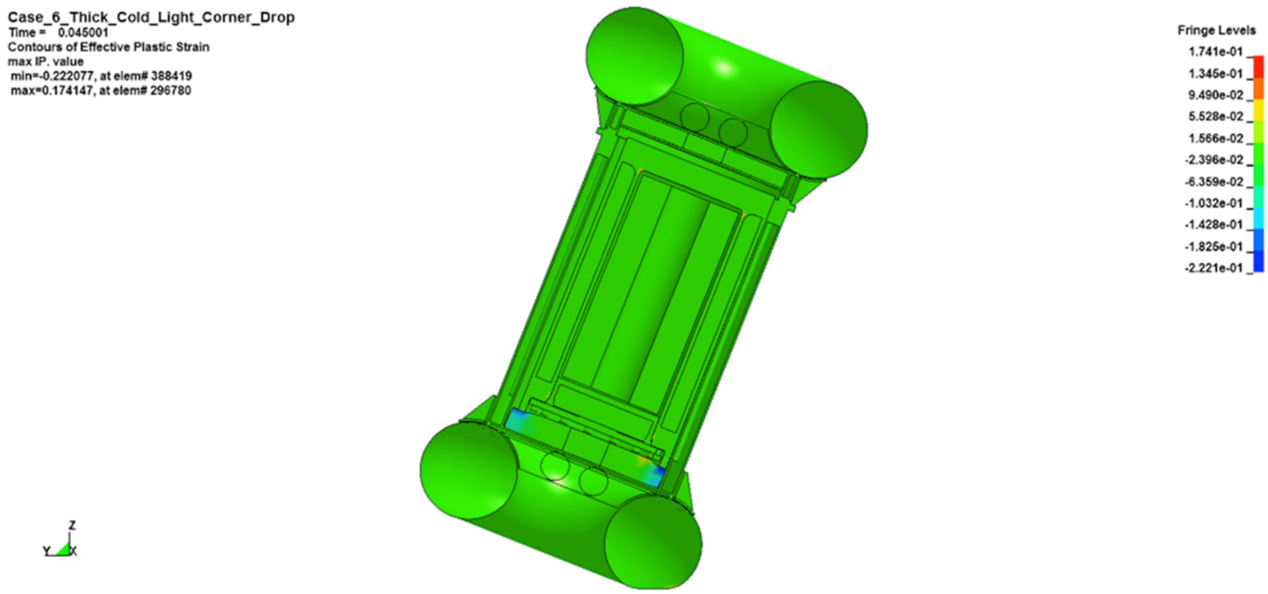



**Figure 2.12.1.11-21. Case 6 Deformed Overpack Shape (Effective Plastic Strain)**

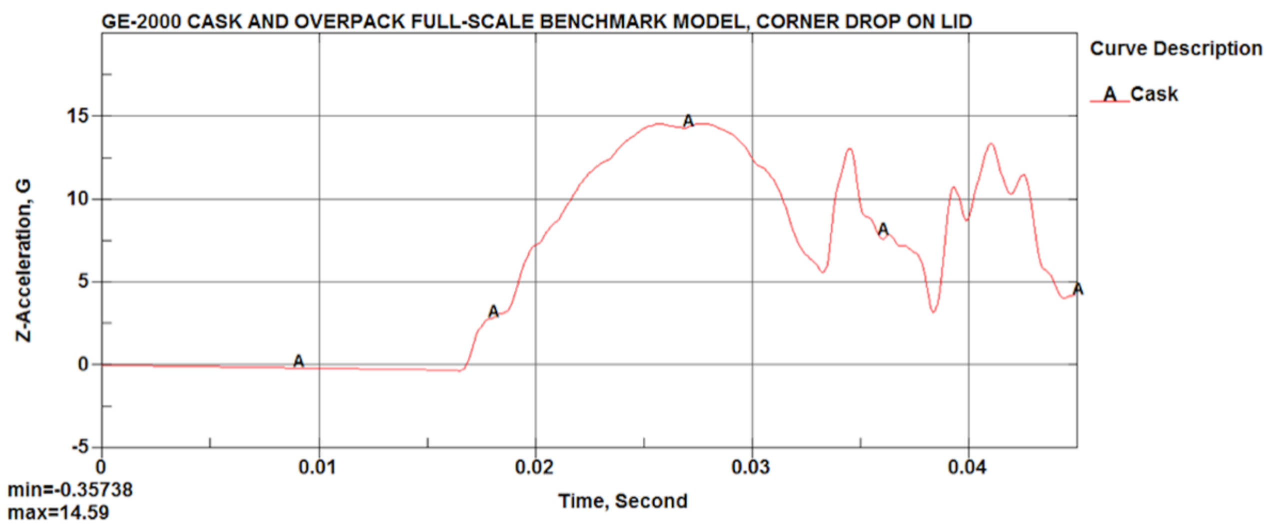
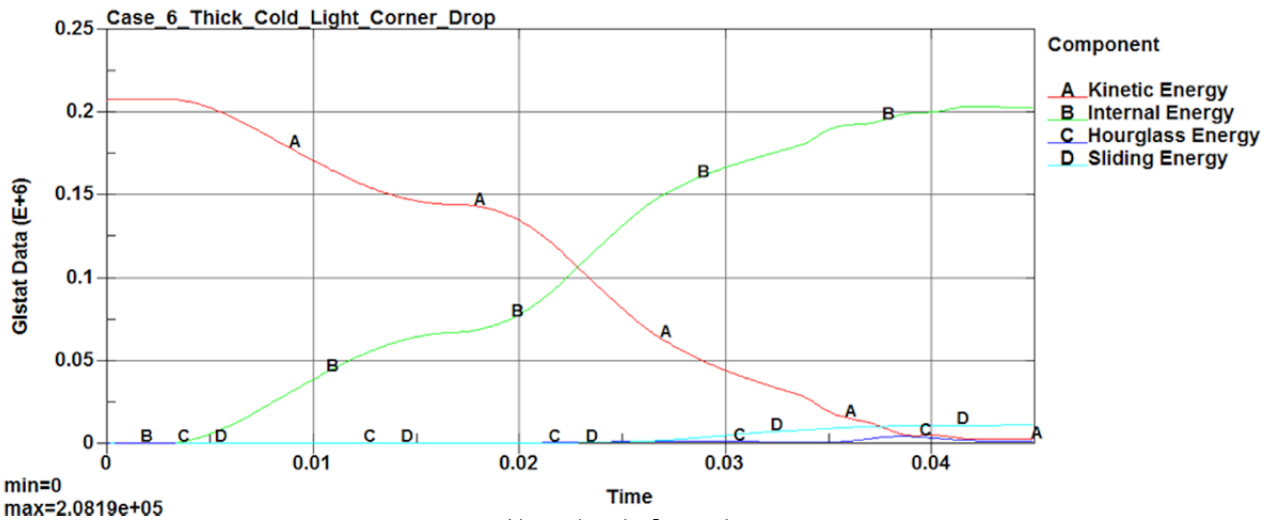
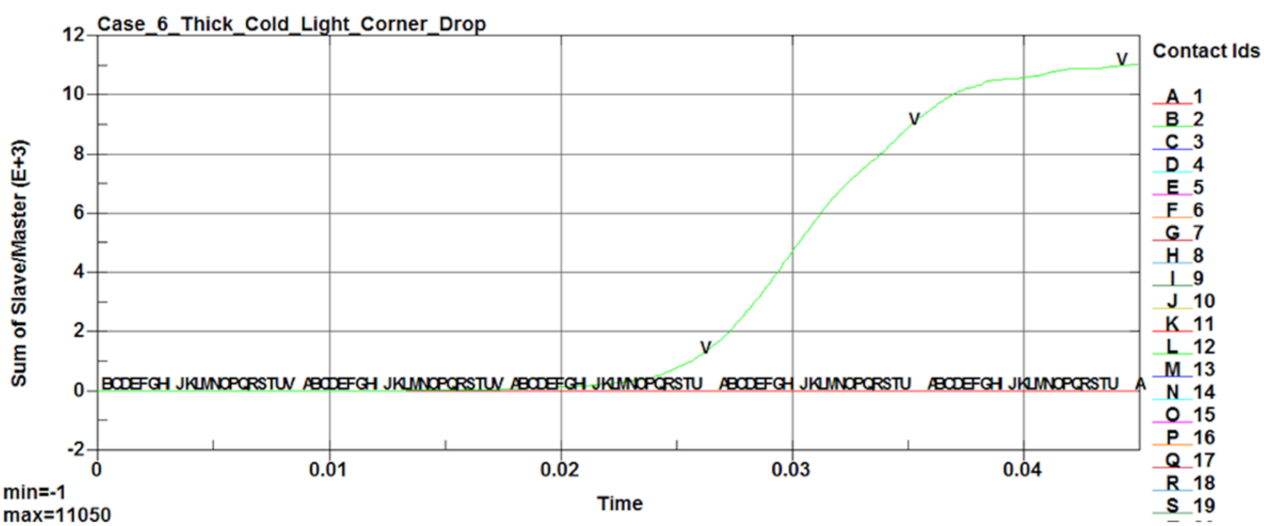



**Figure 2.12.1.11-22. Case 6 Payload Acceleration Time History**




Note: time in Seconds

**Figure 2.12.1.11-23. Case 6 Impact Energy Plot**




Note: time in Seconds

**Figure 2.12.1.11-24. Case 6 Interface Sliding Energy Time History**

### 2.12.1.11.7. Case 7 HAC End Drop with Thick Shell, Cold Condition and Light Payload

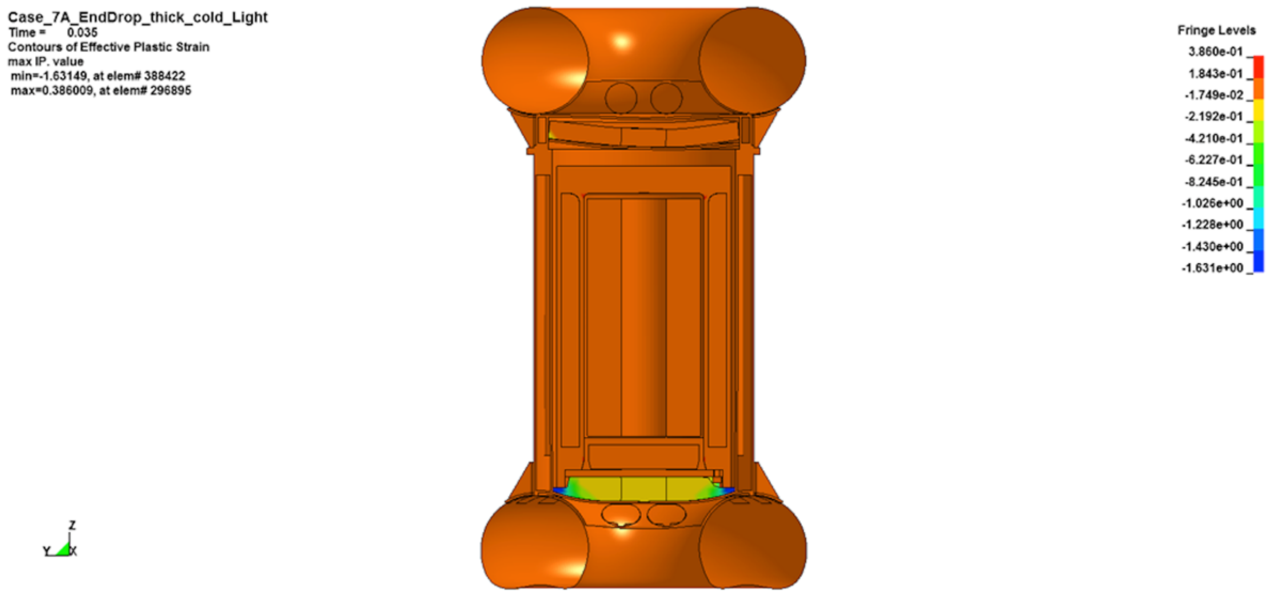



**Figure 2.12.1.11-25. Case 7 Deformed Overpack Shape (Effective Plastic Strain)**

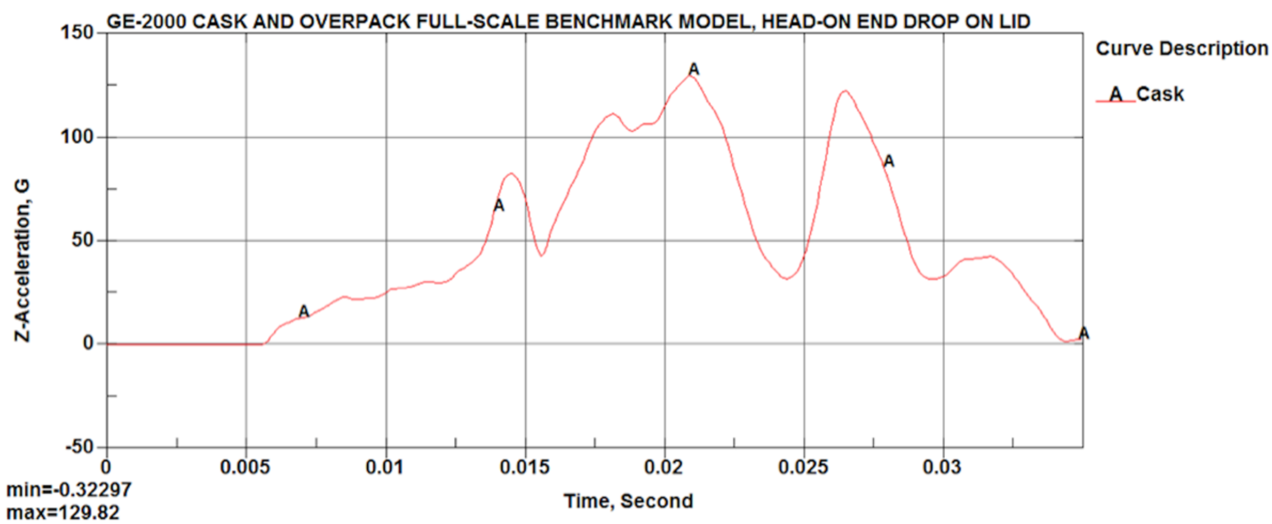



**Figure 2.12.1.11-26. Case 7 Payload Acceleration Time History**

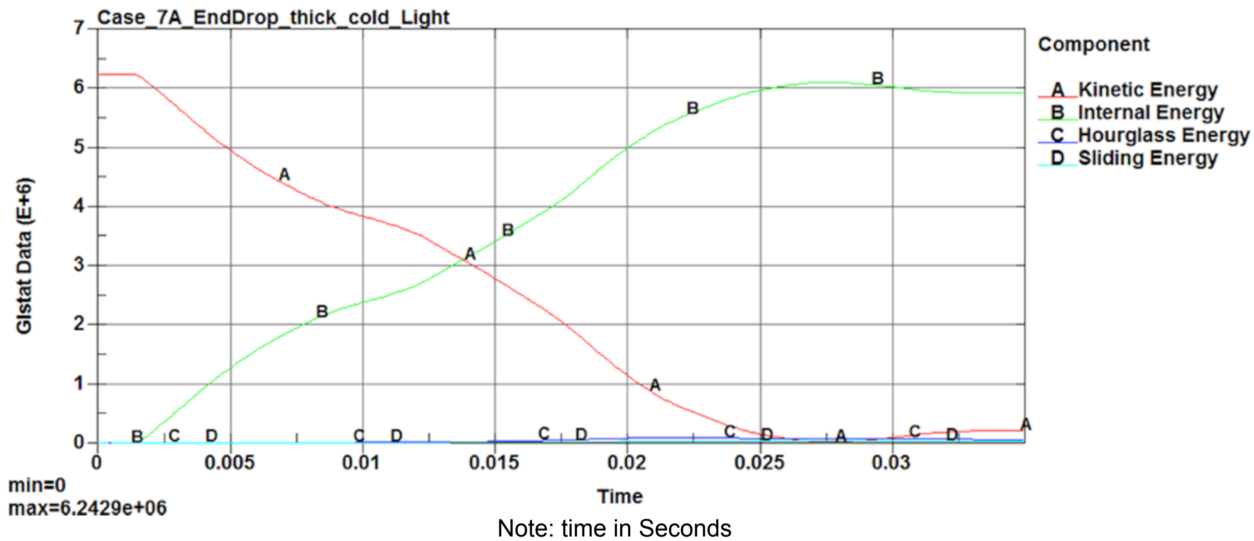



**Figure 2.12.1.11-27. Case 7 Impact Energy Plot**

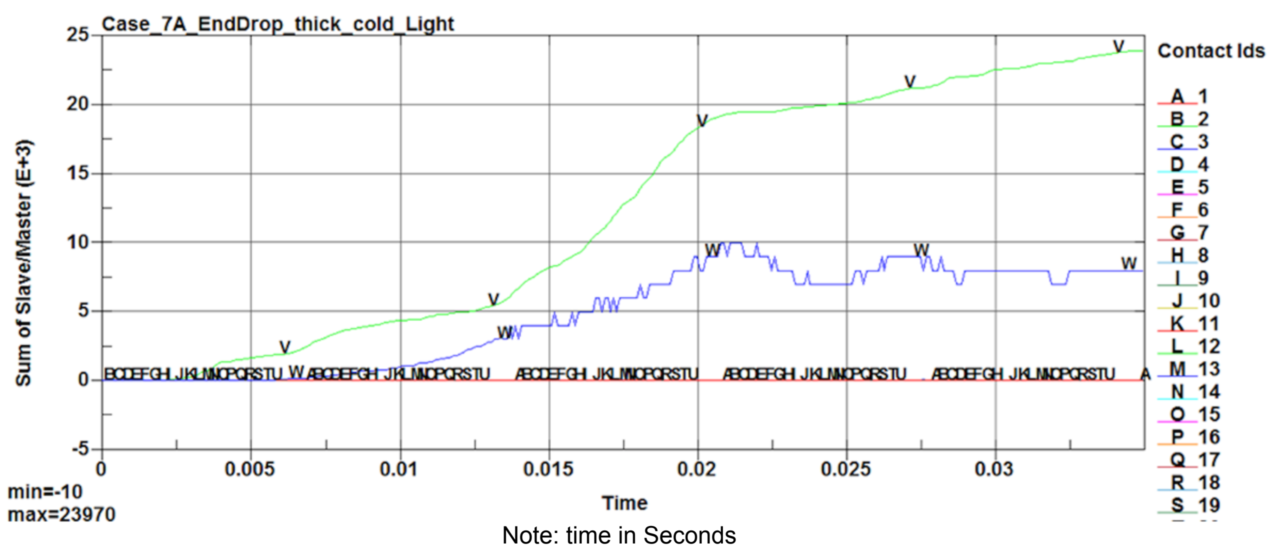



**Figure 2.12.1.11-28. Case 7 Interface Sliding Energy Time History**

#### 2.12.1.11.8. Case 8 HAC End Drop with Thick Shell, Hot Condition and Heavy Payload

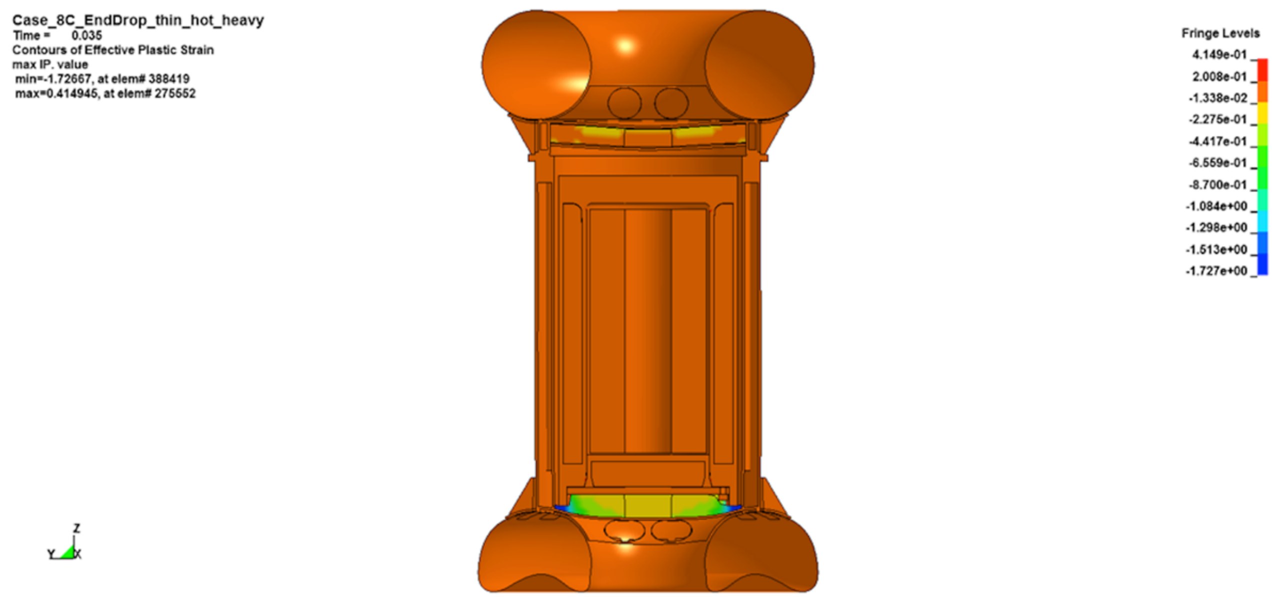



**Figure 2.12.1.11-29. Case 8 Deformed Overpack Shape (Effective Plastic Strain)**

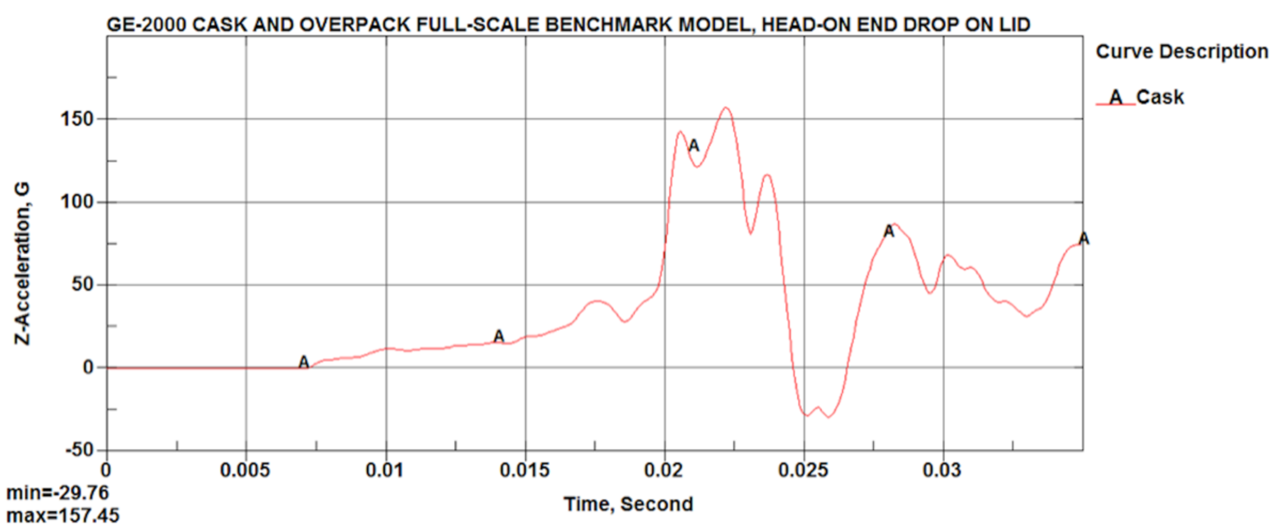



**Figure 2.12.1.11-30. Case 8 Payload Acceleration Time History**

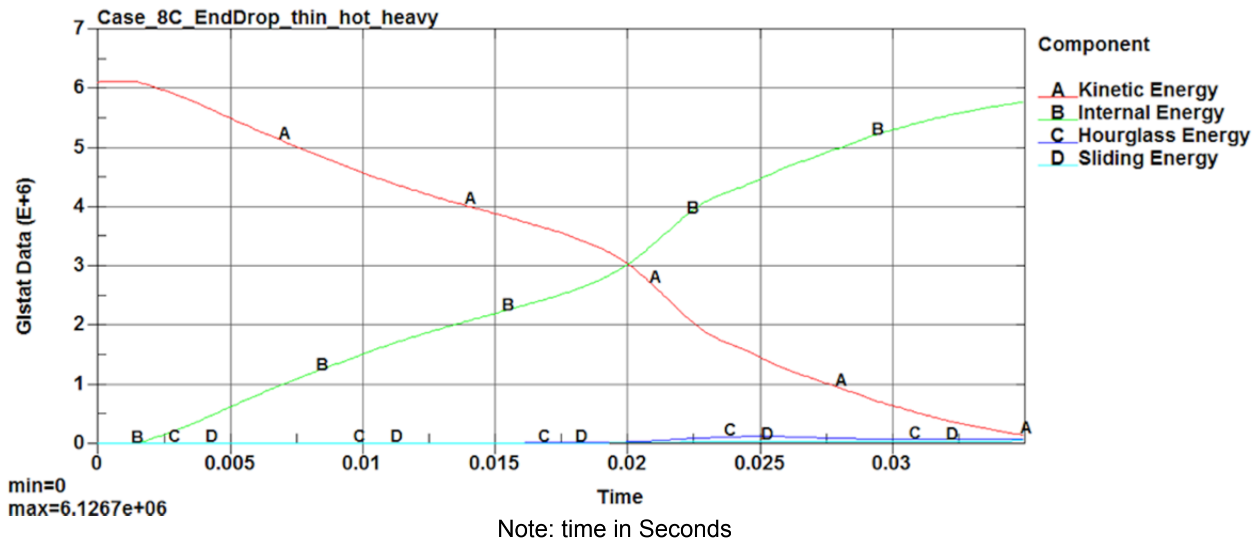



**Figure 2.12.1.11-31.  Case 8 Impact Energy Plot**

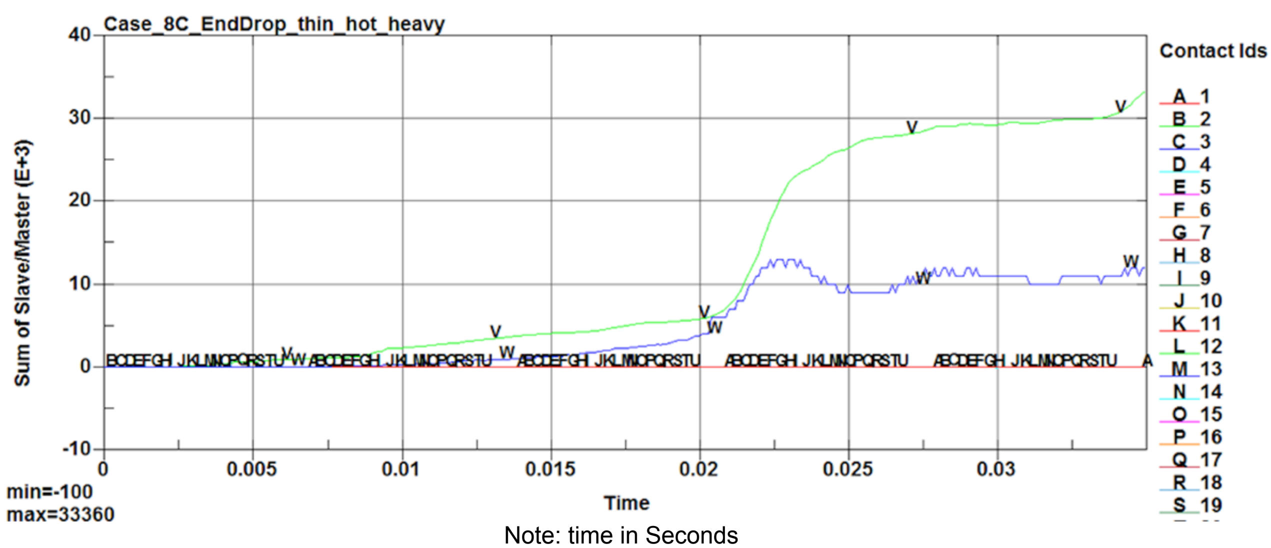



**Figure 2.12.1.11-32.  Case 8 Interface Sliding Energy Time History**

### 2.12.1.11.9. Case 9 Side Drop with Thick Shell, Cold Condition and Light Payload

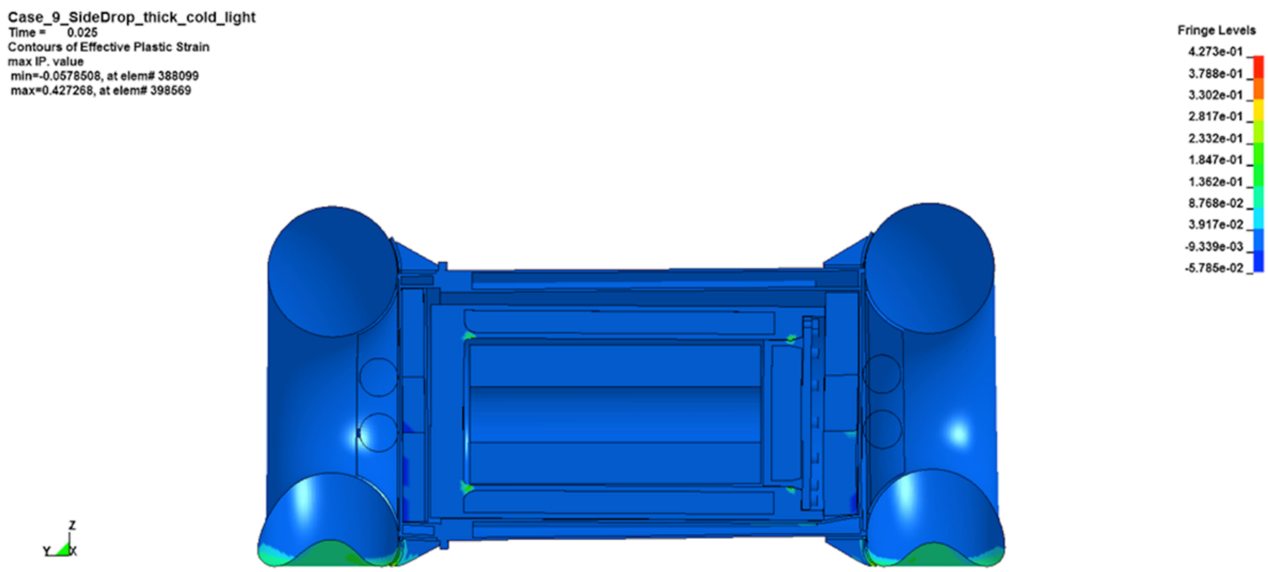



**Figure 2.12.1.11-33. Case 9 Deformed Overpack Shape (Effective Plastic Strain)**

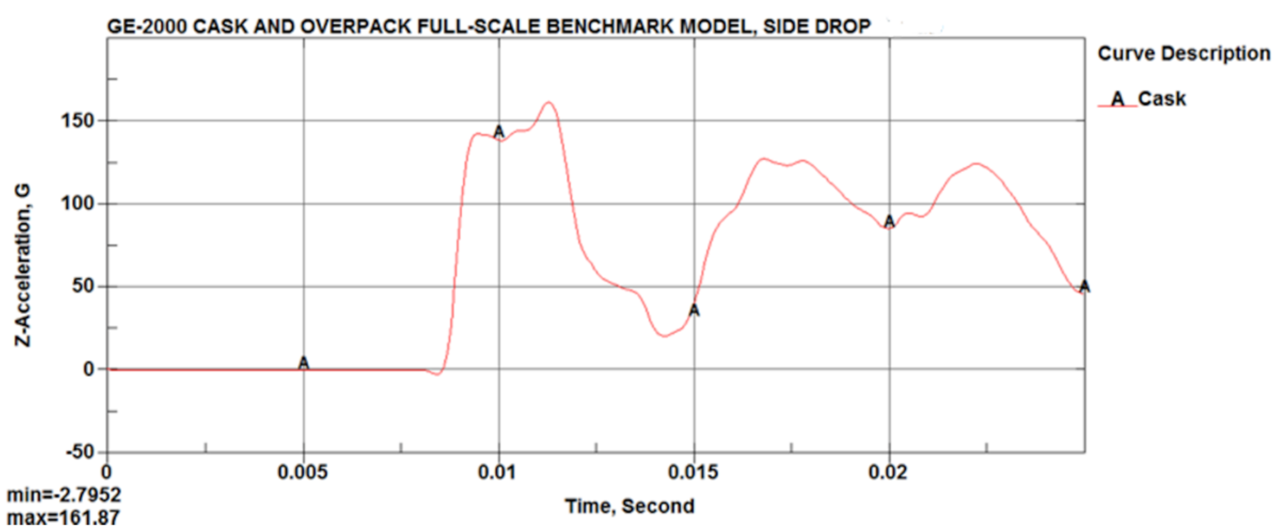
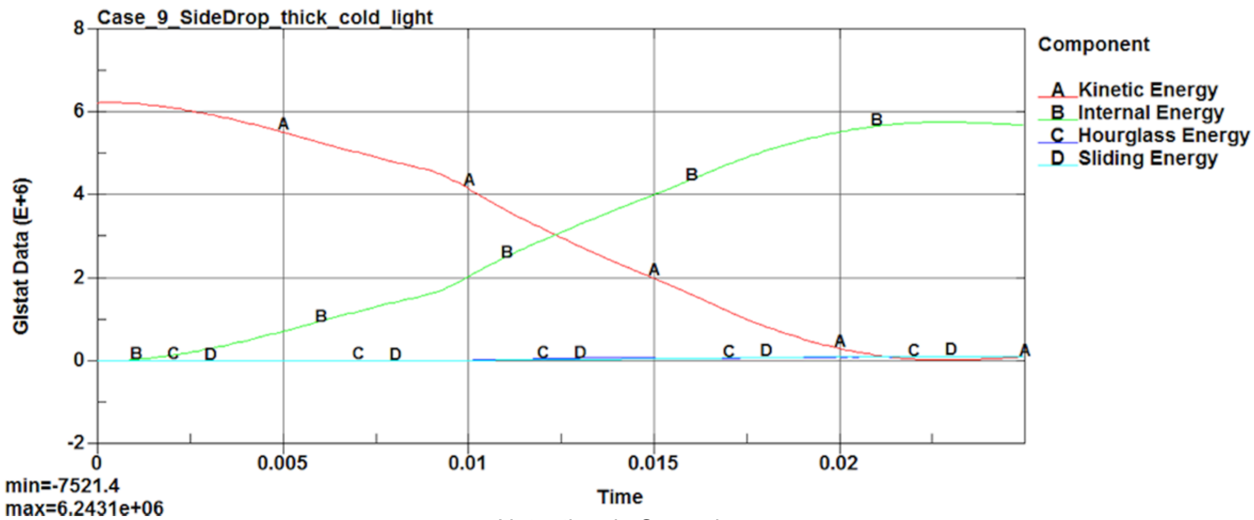
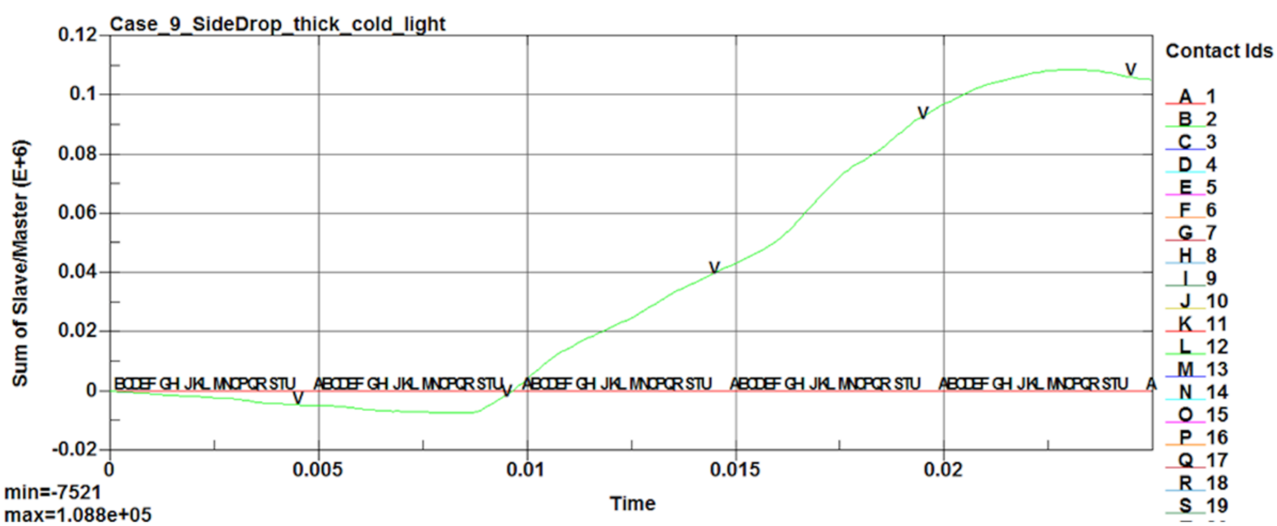



**Figure 2.12.1.11-34. Case 9 Payload Acceleration Time History**




Note: time in Seconds

**Figure 2.12.1.11-35. Case 9 Impact Energy Plot**




Note: time in Seconds

**Figure 2.12.1.11-36. Case 9 Interface Sliding Energy Time History**

### 2.12.1.11.10. Case 10 Side Drop with Thin Shell, Hot Condition and Heavy Payload

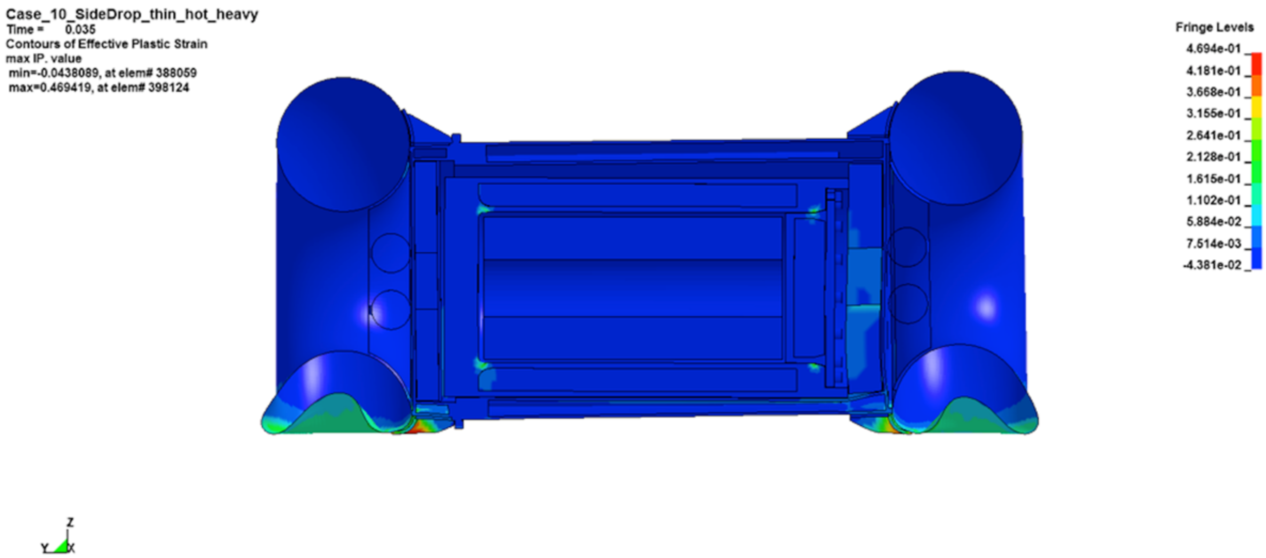



**Figure 2.12.1.11-37. Case 10 Deformed Overpack Shape (Effective Plastic Strain)**

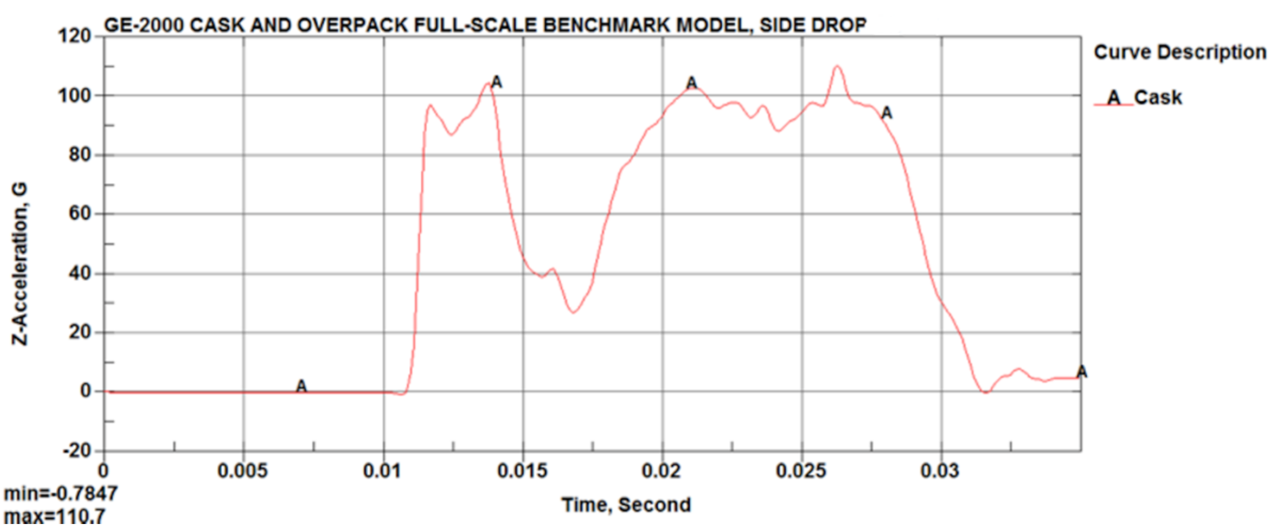



**Figure 2.12.1.11-38. Case 10 Payload Acceleration Time History**

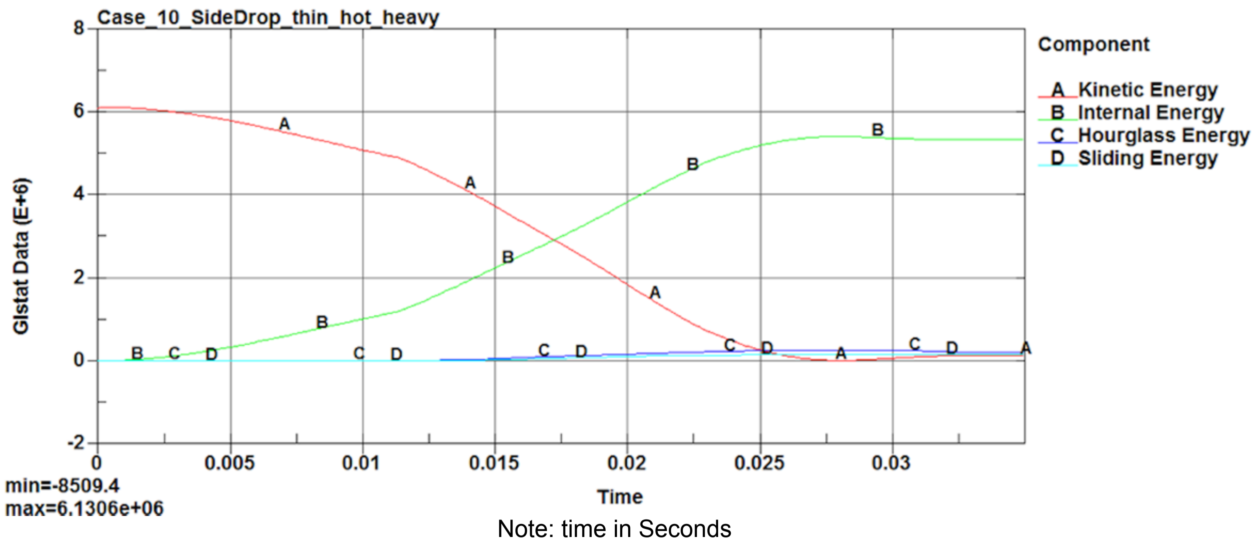



**Figure 2.12.1.11-39. Case 10 Impact Energy Plot**

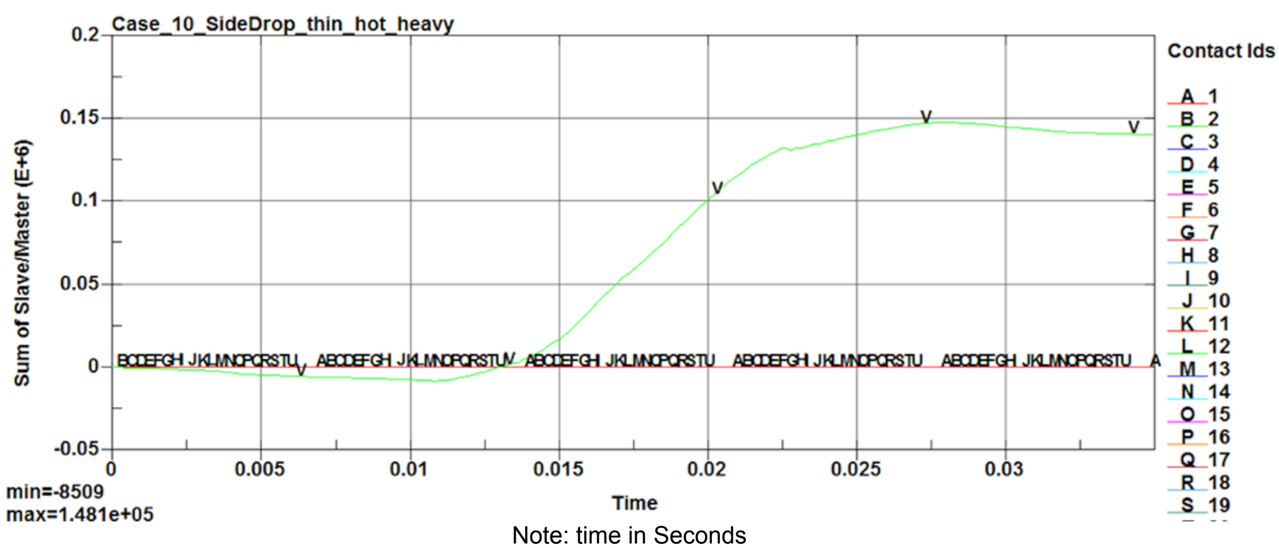



**Figure 2.12.1.11-40. Case 10 Interface Sliding Energy Time History**