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Radioactive Material Transport Packaging System

Safety Analysis Report

for Model AOS-025, AOS-050, and AOS-100 Transport Packages

Prepared by
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Revision History

Revision	Date	Description of Changes
A	January 11, 2008	Preliminary release.
B	June 20, 2009	Preliminary release.
C	September 11, 2009	Preliminary release.
D	September 28, 2010	Preliminary release.
E	October 11, 2011	Preliminary release.
F	February 1, 2012	Initial Release.
G	July 27, 2012	Update to include cask lid elastomeric seal, and included text so the cask lid metallic seal is differentiated from the new elastomeric seal. Applied miscellaneous corrections (table of changes included with cover page of the submittal).

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1 GENERAL INFORMATION

1.1 INTRODUCTION

This safety analysis report (SAR) is for a Type B(U)-96 non-fissile transport package, hereafter identified as a Radioactive Transport Packaging System, AOS Transport Packaging System, or transport package (in general). The transport package is configured in three (3) different sizes, identified as Models AOS-025, AOS-050, and AOS-100. These package models consist of three (3) main components – cask, impact limiter, and cask lid seal – as presented in Section 1.2. The transport packages will be used to transport Type B quantities of encapsulated solid materials or solid metals that meet *Normal* or *Special form* criteria. The authorized quantities of material to be transported is dependent upon the type of material being shipped and the associated decay heat load, or the radioactive shielding requirements, as appropriate, to provide containment and radiation shielding protection of the contents during Normal Accident conditions of transport (NCT) and Hypothetical Accident conditions (HAC) of transport, as required by *Title 10, Code of Federal Regulations, Part 71* (*10 CFR 71*) **[1.1]**. The AOS Transport Packaging System components are designed, fabricated, examined, and tested to the applicable requirements of the *ASME Boiler and Pressure Vessel (B&PV) Code* **[1.2]** (hereafter referred to as the "ASME Code"), as summarized in Subsection 2.1.4, "Identification of Codes and Standards for Package Design."

Methods and analysis for demonstrating compliance with the requirements of References **[1.1]** and **[1.2]** are present within this SAR. Chapter 2, "Structural Evaluation," documents compliance of the design and construction with the requirements of References **[1.1]** and **[1.2]**. Compliance is demonstrated by structural analyses and engineering evaluations for Normal and Hypothetical Accident conditions of transport requirements, and physical tests upon a prototype packaging, in accordance with *10 CFR 71.71* and *10 CFR 71.73* **[1.1]**. The mechanical properties for construction materials that affect the structural behavior of the transport packages are also included in Chapter 2.

In addition to the design criteria presented in Chapter 2, allowable stresses are evaluated for possible failure modes, including brittle fracture, fatigue, and buckling. Brittle fracture is not a consideration for the containment vessel, because the structural components are made of 300 series austenitic stainless steel, ASME/ASTM Type 304 or Type 316, including all components of the containment boundary. Austenitic stainless steels are not susceptible to brittle fracture at the minimum design and transport temperature, and their mechanical properties are relatively stable over the range of temperature required by regulations (References **[1.1]** and **[1.4]**).

The cask lid attachment bolts are fabricated from ASME SB-637, UNS N07718. This material is also excluded from brittle fracture consideration, in accordance with *ASME Code Section III, Division 1, paragraph NB-2311(a)(7)* in Reference **[1.2]**.

The structural analyses presented in Chapter 2 fully evaluates the mechanical requirements of the regulations (References **[1.1]** and **[1.4]**), and include the applied temperature effects generated by the thermal analyses. The evaluation results verify that the transport packages meet the performance requirements specified by *10 CFR 71* **[1.1]** and *IAEA TS-R-1* **[1.4]**.

Chapter 3, "Thermal Evaluation," documents the thermal evaluation required by the regulations, and verifies that the transport packages meet the performance requirements specified by References **[1.1]** and **[1.4]**.

Chapter 4, "Containment," documents the AOS Transport Packaging System's containment boundary and capabilities. The chapter also includes the cask lid attachment bolts analysis.

Chapter 5, "Shielding Evaluation," documents the radiation shielding evaluation for the transport package design.

Chapter 6, "Criticality Evaluation," is omitted from this SAR, because fissile materials and irradiated fissile materials containing fission products are not an authorized content for the AOS Transport Packaging System.

Chapter 7, "Package Operations," summarizes the instructions for the safe operation of all AOS Transport Packaging System models.

Chapter 8, "Acceptance Tests and Maintenance Program," presents the test program required by *10 CFR 71*, Subpart G **[1.1]**, to verify that the construction materials, fabrication processes, package design, and maintenance program requirements are fully addressed and satisfied at all times.

As previously noted, the AOS Transport Packaging System is available in three (3) model sizes – AOS-025, AOS-050, and AOS-100. The Model AOS-025 is scaled to 25% of the Model AOS-100, and the Model AOS-050 is scaled to 50% of the Model AOS-100. In addition to size, there are variations in shielding materials for the Model AOS-100, in which either tungsten alloy or carbon steel shielding is used. In the Model AOS-100, there is also a model that is double-ended (that is, the transport package opens on both ends). To distinguish the different models and their variations, the following designators are used throughout this SAR:

AOS-XXXY-Z

where:

XXX is the scale factor (25%, 50%, or 100%)

Y = A for tungsten alloy shielding (Models AOS-025A, AOS-050A, and AOS-100A) –or–

Y = B for carbon steel shielding (Model AOS-100B only)

Z = S to denote packages that have the double-ended opening configuration (Model AOS-100A-S only)

The transport packages are transported vertically, using a pallet design.

The difference between the Model AOS-100A and AOS-100B transport packages is the shielding material used. The difference between the Model AOS-100A and AOS-100A-S is the latter design has a double-ended opening configuration (that is, it can be loaded/unloaded from either end).

Figure 1-1 and Figure 1-2 provide an isometric view of the Model AOS-025A and AOS-050A, respectively. The isometric view of the Models AOS-100A, AOS-100B and AOS-100A-S is illustrated in Figure 1-3. Unless indicated otherwise throughout this SAR, all information related to the Model AOS-100A transport package is also applicable to the Model AOS-100B and AOS-100A-S transport packages.

The acceptance performance tests referenced in this SAR were conducted upon a prototype packaging, 165%-larger than the Model AOS-100, referred to herein, as the "AOS-165A prototype." Data pertaining to the AOS-165A prototype is used within this SAR solely for the evaluation of the Model AOS-025A, AOS-050A, AOS-100A, AOS-100B, and AOS-100A-S transport packages. This SAR does not request approval of the AOS-165A prototype.

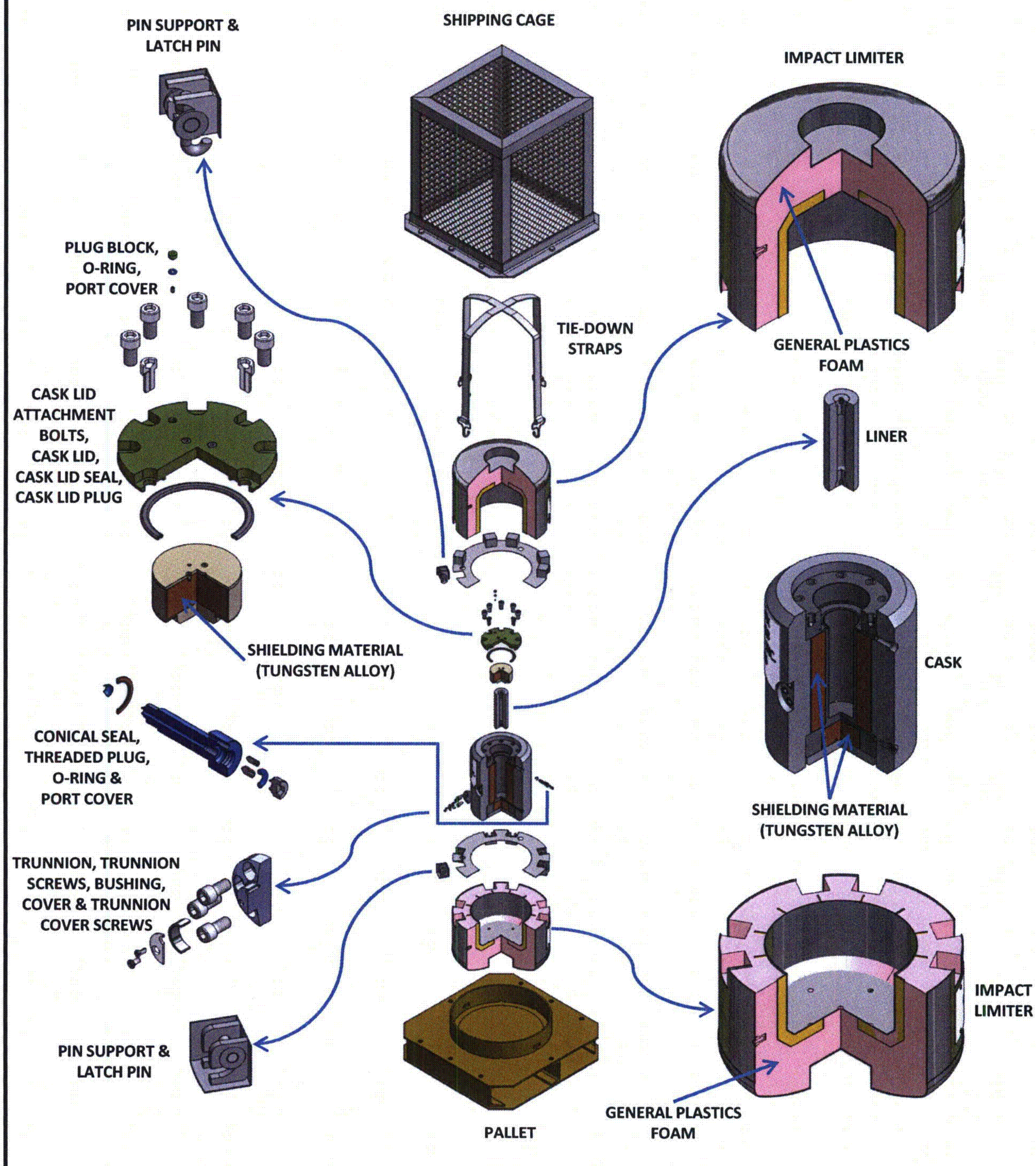

Figure 1-1. Isometric View – Model AOS-025A

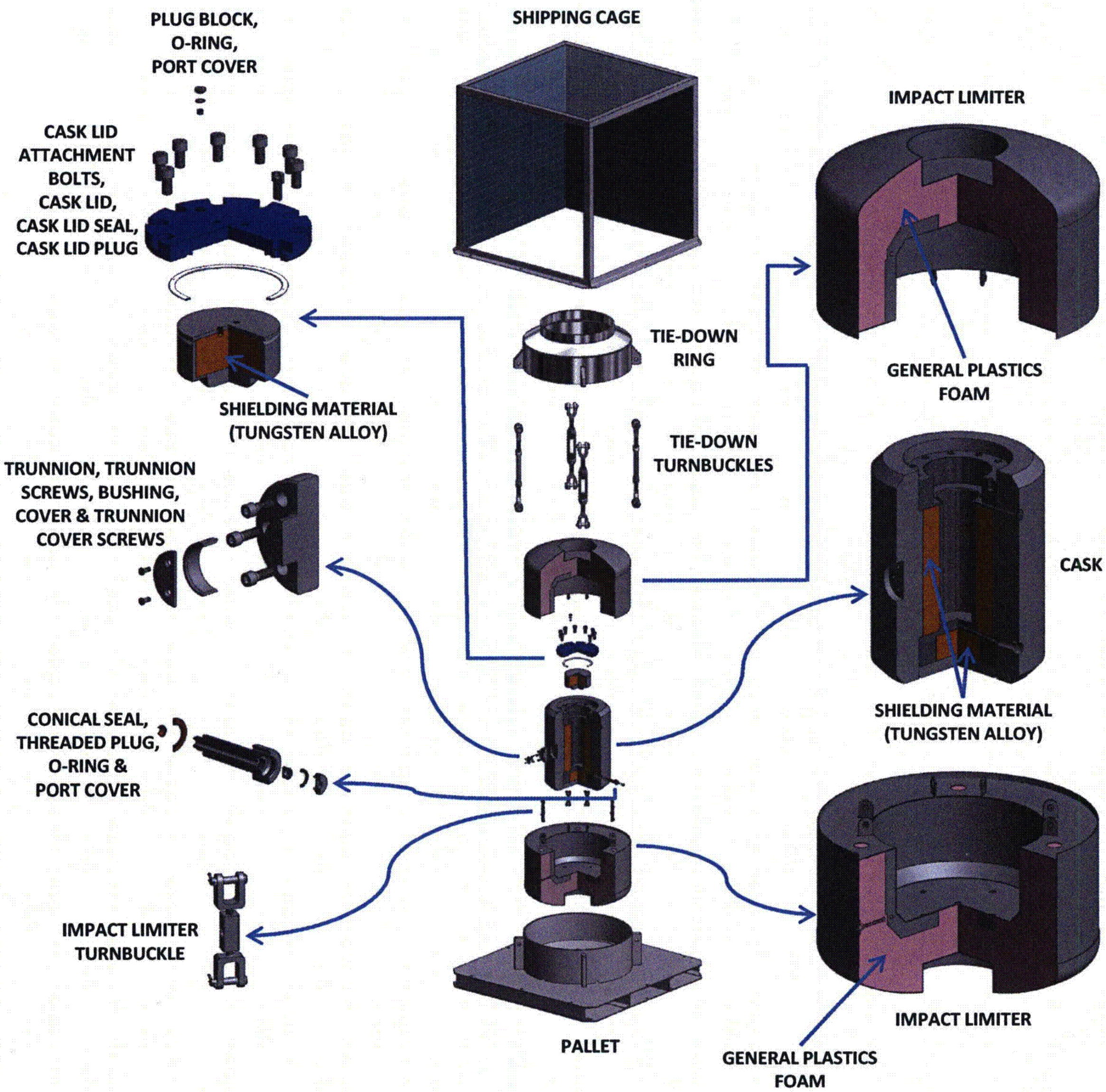

Figure 1-2. Isometric View – Model AOS-050A

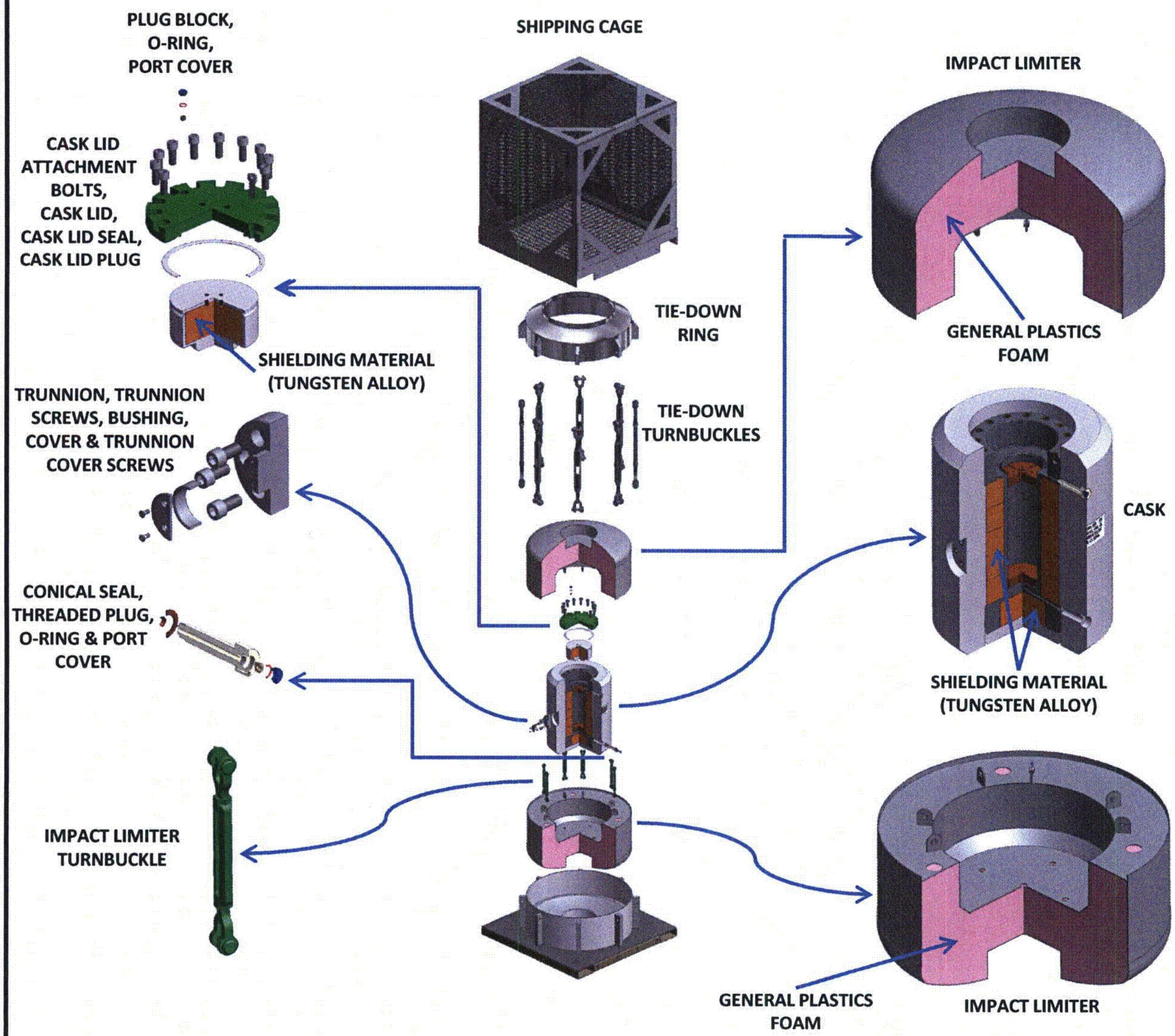

Figure 1-3. Isometric View – Models AOS-100A

Note: *The Model AOS-100A shown is typical for all Model AOS-100 configurations.*

1.2 PACKAGE DESCRIPTION

The AOS Transport Packaging System designs are symmetric vertically, as well as axisymmetric. Table 1-1 summarizes the dimensions of each AOS Transport Packaging System model's maximum authorized packaging weight (including contents and impact limiters). The maximum weight of the contents, including all associated hardware and packing material, shall not exceed the values listed in Table 1-1.

Each transport package shall be weighed after fabrication, and that weight plus the maximum allowable content weight shall be inscribed as the maximum gross weight on the impact limiter identification nameplate, which is affixed to the package.

Table 1-1. AOS Transport Packaging System Dimensions and Maximum Authorized Package Weight – All Models

Model	Category	Dimensions, Basic (cm / in.)						Maximum Authorized Package Weight[a] (kg / lbs.)
		Packaging		Cask		Cavity		
		Width	Height	OD	Height	OD	Height	
AOS-025A	I	45.72	50.30	17.78	22.86	4.12	12.70	100
		18.00	21.38	7.00	9.00	1.62	5.00	220
AOS-050A	I	100.97	105.10	35.56	45.72	8.26	25.40	681
		39.75	41.38	14.00	18.00	3.25	10.00	1,500
AOS-100A	I	155.14	179.63	71.12	91.44	16.51	50.80	5,675
		61.08	70.72	28.00	36.00	6.50	20.00	12,500
AOS-100B	II	155.14	179.63	71.12	91.44	16.51	50.80	4,994
		61.08	70.72	28.00	36.00	6.50	20.00	11,000
AOS-100A-S	I	155.14	179.63	71.12	91.44	16.51	50.80	5,675
		61.08	70.72	28.00	36.00	6.50	20.00	12,500

a. The weights that comprise the maximum authorized package weight are defined in Table 2-7, "AOS Transport Packaging System Maximum Authorized Package Weight and Cg Locations – All Models."

1.2.1 Packaging

Each AOS transport package consists of three (3) main components:

- Cask
- Impact Limiter
- Cask Lid Seal

The cask is constructed of 300 series stainless steel (SS300) material. Tungsten alloy or carbon steel materials are embedded within the cask body and cask lid plug, to enhance the cask's shielding capability. Tungsten alloy is used as the shielding material in casks whose model number includes suffix A. Carbon steel is used as the shielding material in casks whose model number includes suffix B. Material designation to a national standard is provided in the certification drawings listed in Table 1-5.

The solid cask outer shell, and the seal associated with the cask lid plug closure, use a double elastomeric O-Ring capture within two SS300 series flat rings or a double "C" cross-section seal within the cask lid seal joint, and provide containment under Normal and Hypothetical Accident conditions of transport. The two (2) impact limiters are connected to one another by eight (8) connectors, such that the cask ends are protected. The impact limiters are constructed of thin SS300 shells filled with polyurethane foam, which has been demonstrated to mitigate mechanical damage and thermal loads generated during Normal and Hypothetical Accident conditions of transport.

In addition to the three (3) main package components, a shipping cage and pallet ensure that accessible package surfaces are protected.

1.2.1.1 Cask

The cask is a cylindrical structure with a cavity that contains the payload. The cask structure is composed of seven (7) major components:

- Cask outer shell
- Cask cavity shell
- Cask shielding (tungsten alloy or carbon steel)
- Cask end plug(s)
- Bottom plate
- Cask lid
- Cask lid plug

Figure 2-4, "Isometric View – Typical Cask," presents an isometric view of the cask.

The cask outer shell and cask cavity shell interlock, to encase the cask shielding, which is a component constructed of tungsten alloy or carbon steel.

The cask shielding and cask end plug(s) enhance the cask's shielding characteristics. To provide shielding in the axial direction, the cask lid plug is placed in the open end of the cavity. At the cavity's closed end, the cask end plug is encased between the cavity bottom wall and bottom plate. The cask end plug encased on the cask lid plug is of the same size and material (tungsten alloy or carbon steel) as the one encased at the bottom of the cask.

The cask lid consists of a flat disk, with recessed areas concentric with the bolt holes on the top surface. This feature protects the cask lid attachment bolts from impact loads. The groove on the bottom surface of the cask lid houses the cask lid seal, as well as a central recess that accommodates the cask lid plug component.

Additional cask assembly components are cask lid attachment bolts and port plugs, with threaded pipe plugs, O-Ring seals, and port plug covers.

Both the cask lid and bottom plate are located below the surface of the cask cavity shell, for protection during impact events.

Containment for the AOS Transport Packaging System (containment boundary) is provided within the cask component. The dashed lines in Figure 4-1, "Containment Boundary (Cask Lid Metallic Seal Shown)," illustrate the containment boundary, typical to all transport package models. There are two (2) penetrations into the cask cavity, located within the cask's top and bottom regions of the side surface. These cavity penetrations are used to drain and vent the cavity. A third penetration, located in the cask lid, is used for testing the seal's leak tightness. (For further details, refer to Chapter 4, "Containment.")

To augment the AOS Transport Packaging System's shielding characteristics, Models AOS-025A, AOS-100A, AOS-100B, and AOS-100A-S, require the use of a liner or axial shielding plate, to convey certain quantities of radioactive materials. These liners/axial shielding plates are referenced in Table 1-5. To meet temperature regulation requirements, a shipping cage structure (refer to Paragraph 1.2.1.4) is used during package transport.

The AOS Transport Packaging System design does not require specific arrangement of the contents, other than those previously discussed, within the cavity. However, a basket or rack device can be used to shore the payload. These baskets or racks are typically made of aluminum or stainless steel material, and designed for the specific payload geometry.

1.2.1.2 Impact Limiter

The impact limiter is a major component consisting of a thin-walled cylindrical shell, with a dish head at one end and a flat disk at the other end. At the flat-disk end, there is a cylindrical recess, with an internal profile identical to that of the cask end profile. This cavity accommodates the cask in the transport configuration. Figure 2-5, "Isometric View – Typical Impact Limiter," presents an isometric view of the impact limiter.

Twelve (12) squared ribs are attached to the inside wall of the cylindrical recess section. Eight (8) of these ribs extend beyond the flat disk plate, which are used as turnbuckle attachment points. The turnbuckles are used to join the impact limiters and to partially enclose the cask component. For the Model AOS-025, the two (2) impact limiters entirely cover the cask, and the turnbuckles are replaced with "J" hooks.

The transport package exterior incorporates one (1) or more tamper-indicating devices, that are not readily breakable. While intact (that is, not broken), these devices provide evidence that the package has not been opened by unauthorized persons. (For further details regarding the tamper-indicating devices, refer to Chapter 7, "Package Operations.")

1.2.1.3 Cask Lid Seal

Two (2) types of cask lid seals are used. One consists of two (2) elastomeric O-Rings, a cross-section capture between two (2) flat metal retainer rings to form a unit. The other is a metallic, double "C" cross-section arrangement.

The elastomeric seal is comprised of two (2) components:

- **O-Rings** – Silicone, Parker Compound S1224-70, ASTM D2000
- **Retainer Rings** – ASME SA-240/ ASTM A240, Type 304 or 316 Stainless Steel

The metallic seal is comprised of three (3) components:

- **Jacket** – Silver, ASTM B742
- **Spring** – Nickel-chromium alloy 90 UNS N07090
- **Lining** – SS304L UNS S30403 (may/may not be present)

The seal design provides a means for leak testing between the two (2) O-Rings (elastomeric seal) or double "C" cross-sections (metallic seal), by way of the cask lid's Test Port feature. (For further details regarding the cask lid seal, refer to Appendix 4.5.1, "AOS Cask Lid Elastomeric Seal and Garlock Helicoflex Cask Lid Metallic Seal Drawings.")

1.2.1.4 Other Components

In addition to the previously mentioned components, the AOS Transport Packaging System uses other components or structures, in support of its operations. A series of liners and shielding plates enhances the shielding characteristics for shipments of specific content. Refer to Table 1-2 for the requirements of when to use these shielding devices.

A transport pallet is used as a base for the transport packages, for tying down the package during transport.

The shipping cage is a five (5)-sided metal structure, with the pallet creating a sixth side, which completes a cube shape. Each side covered with an expandable metal mesh or screen material, that keeps unauthorized persons away from the transport package surfaces during transport, and provides a means to meet temperature regulation requirements.

The packages have no tie-down devices nor structural parts that can be used for unintended tie-down, thus satisfying the additional requirements of *10 CFR 71.45(b)* **[1.1]**.

1.2.2 Contents

Table 1-2 provides a list of the isotopes authorized for use with the AOS Transport Packaging System. Additionally, Table 1-2 demonstrates the use of curie content to meet the radioactive and thermal maximum limits specified in Table 1-3, for each transport package model. Furthermore, the shielding requirements specified in Table 1-2 apply, where applicable.

The AOS Transport Packaging System can be used for transporting solid radioactive materials in *Normal* and *Special form*. Any materials with a melting point less than 538°C (1,000°F) are required to be in *Special form*. *Special form* materials require a current certificate of compliance. Dispersible *Normal form* materials are required to be enclosed within an inner container. An inner container is considered to be a "shoring device."

Fissile materials and irradiated fissile materials containing fission products are not authorized for these packagings. In addition, no free-standing liquid is permitted.

The package can be shipped by surface or air transport, and meets the requirements for non-exclusive transport. For air transport, quantities are limited to the lesser of Table 1-2 or 3,000 A_2.

All shoring materials within the cask cavity must have a melting point greater than 538°C (1,000°F).

Radioactive contents can be in any location within the cask cavity, and unconstrained within the inner containers. Holders, fixtures, and packaging materials (shoring devices) must be used to secure the inner containers, so that the inner containers are immobilized. The containers must be comprised of materials that are compatible with the radioactive contents and cask cavity.

Radioactive contents are limited by the external radiation levels specified in *10 CFR 71.47* and *71.51* **[1.1]**, and *49 CFR 173.441* **[1.3]**. Exclusive-Use mode of shipment is required whenever the radiation dose rates of the package exceed the external radiation standards in *10 CFR 71.47(a)* **[1.1]** for non-exclusive use shipment.

There are no materials added to the package for the purpose of neutron absorption nor moderation. Radiation shields (that is, liners and/or axial shielding plates) are required in certain cases, as stipulated in Table 1-2.

The construction materials of the AOS Transport Packaging System and their proposed contents are compatible with one another; no chemical nor galvanic reactions are expected to occur, including the generation of combustible gas.

The transport packages shall be loaded under ambient atmospheric pressure and temperature conditions. The containment boundary will not normally be pressurized; however, internal heating of the enclosed gases can increase the pressure.

The maximum gross weight of the AOS Transport Packaging System, including contents, is listed in Table 1-1.

The maximum decay heat, listed in Table 1-2, is calculated using the constants presented in Chapter 5, "Shielding Evaluation."

Table 1-2. Activity Limits – All Models

Isotope[a]	Decay Heat Ci/Watt[b]	Model							
		AOS-025		AOS-050		AOS-100			
		A (10W)		A (100W)		A, A-S (400W)		B (400W)	
		TBq	Ci	TBq	Ci	TBq	Ci	TBq	Ci
Co-60	6.49E+01	4.55E-03	1.23E-01	7.84E-02	2.12E+00	1.23E+02	3.33E+03	3.62E-01	9.78E+00
Co-60-B	6.49E+01	–		–		8.10E+02	2.19E+04	4.14E+00	1.12E+02
Cs-137	1.99E+02	3.92E-01	1.06E+01	1.11E+01	3.01E+02	2.95E+03	7.96E+04	1.95E+01	5.28E+02
Hf-181	2.28E+02	–		8.14E+01	2.20E+03	3.37E+03	9.12E+04	1.38E+02	3.73E+03
Ir-192	1.63E+02	2.68E+00	7.23E+01	4.77E+01	1.29E+03	2.41E+03	6.52E+04	8.58E+01	2.32E+03
Zr/Nb-95[c]	6.17E+01	–		1.06E+00	2.87E+01	9.13E+02	2.47E+04	2.36E+00	6.39E+01
Ho-166	2.33E+02	4.40E-01	1.19E+01	6.55E+00	1.77E+02	–		–	
Yb-169	3.98E+02	1.47E+02	3.98E+03	1.47E+03	3.98E+04	–		–	
Shipping Configuration		Use of Liner 183C8485 is required		No additional shielding is required		Use of Axial Shielding Plates 183C8491 is required for shipment of Co-60-B quantities		Use of Axial Shielding Plates 183C8491 is required for shipment of Co-60-B quantities	

a. *Solid material, including metals, that meets Normal or Special form criteria. Special form materials require a current certificate of compliance.*

b. *For detailed calculations of these values, refer to Appendix 5.5.1, "AOS Cask Isotopic Heat Load Calculations."*

c. *Activity limits for parent/daughter mixed isotope systems apply to the parent isotope. An equilibrium concentration of the daughter is assumed in the evaluations provided in Chapter 5, "Shielding Evaluation," to provide limiting dose and heat responses for the AOS Transport Packaging System.*

Table 1-3. Content Limitations – All Models

Model	Type	Content[a]	Decay Heat		Weight[b]	
			Watt	Btu/hr.	kg	lbs.
AOS-025A	Solid Material	*Normal Form* or *Special Form*	10	34.15	4.5	10
AOS-050A			100	341.5	27	60
AOS-100A			400	1,366	227	500
AOS-100B						
AOS-100A-S						

a. *Special form materials require a current certificate of compliance.*

b. *Maximum weight of contents including any additional shielding and shoring devices. Weight of contents can be adjusted so as not to exceed the maximum authorized gross weight of the package.*

1.2.3 Special Requirements for Plutonium

Not applicable. Plutonium is not an authorized content for the AOS Transport Packaging System.

1.2.4 Operational Features

The AOS Transport Packaging System is simple and easy-to-use. The transport packages do not incorporate any valve nor other device that allows the release or escape of the contents. Further, the package designs do not include any feature intended to allow continuous venting during transport. Positive closure for containment makes use of standard bolts and tools for opening and closing the packages. Cooling is provided by conduction and natural radiation from within the package. The seal is installed upon the cask lid and there are no alignment issues with it. Only standard practices for seal handling and use (that is, cleanliness, scratch prevention, and proper installation) are required. (For further details, refer to Chapter 7, "Package Operations.")

1.2.5 Fabrication Codes, Standards, and Acceptance Tests

The AOS Transport Packaging System design and fabrication is controlled by the Codes, Engineering Specifications, and Standards listed in Table 2-8, "Applicable Codes and Standards for Design, Fabrication, and Testing of the AOS Transport Packaging System." In addition, Table 2-8 lists the Safety Classification of all major system components, per Reference **[1.6]** guidelines.

Evaluation of the AOS Transport Packaging System, to show compliance with the applicable regulations (References **[1.1]** and **[1.4]**), is conducted by analyses, using the Finite Element Method (LIBRA Code) for all structural and thermal requirements. (For further details regarding the structural and thermal analyses and results, refer to Chapter 2, "Structural Evaluation," and Chapter 3, "Thermal Evaluation," respectively.)

Shielding requirements were evaluated, primarily using the Monte Carlo N-Particle (MCNP) Code. (For further details regarding shielding evaluations, refer to Chapter 5, "Shielding Evaluation.")

Table 1-4 presents a summary of the engineering evaluation and analyses conducted upon each AOS Transport Packaging System model, and detailed in Chapter 2 and Chapter 3.

Table 1-4. AOS Transport Packaging System Analyses Summary – All Models

Item	*10 CFR 71* [1.1]	*IAEA TS-R-1* [1.4]	Model					Applied Conditions/Criteria
			AOS-025A	AOS-050A	AOS-100A	AOS-100B	AOS-100A-S	
Package Category			Table 1-1	Table 1-1	Table 1-1	Table 1-1	Table 1-1	
Maximum Authorized Package Weight			Table 1-1	Table 1-1	Table 1-1	Table 1-1	Table 1-1	
Content			Refer to Subsection 1.2.2	Refer to Subsection 1.2.2	Refer to Subsection 1.2.2	Refer to Subsection 1.2.2	Refer to Subsection 1.2.2	
Physical Form (Normal or Special)			Solid	Solid	Solid	Solid	Solid	
Decay Heat								
Activated Materials			10W	100W Isotope	400W Isotope	400W Isotope	400W Isotope	
General	71.33	606 – 616	✔	✔	✔	✔	✔	
Design Pressure			207 kPa (30 psia)	414 kPa (60 psia)	1,930 kPa (280 psia)	1,930 kPa (280 psia)	1,930 kPa (280 psia)	
Structural								
Weight and Cg			✔	✔	✔	✔	✔	
Lifting Devices	71.45(a)	607, 608	✔	✔	✔			
Tie-Down Devices	71.45(b)	612, 636	✔	✔	✔			
Containment Shell Buckling			✔	✔	✔	✔	✔	
Normal Conditions of Transport	71.71(c)	651						
Heat	71.71(c)(1)	653, 654, 664, 676	✔	✔	✔			38°C (100°F) shade < 50°C (122°F)

Table 1-4. AOS Transport Packaging System Analyses Summary – All Models (Continued)

Item	*10 CFR 71* [1.1]	*IAEA TS-R-1* [1.4]	Model					Applied Conditions/Criteria
			AOS-025A	AOS-050A	AOS-100A	AOS-100B	AOS-100A-S	
Differential Thermal Expansion			✔	✔	✔			
Cold	71.71(c)(2)	664, 676	✔	✔	✔			
Reduced External Pressure	71.71(c)(3)	643	✔	✔	✔			
Increased External Pressure	71.71(c)(4)		✔	✔	✔			
Vibration	71.71(c)(5)	612	✔	✔	✔			(5, 5 and 10 g's) ANSI N14.23 Draft
Water Spray	71.71(c)(6)	719, 721	✔	✔	✔			
Free Drop	71.71(c)(7)	720, 722	1.2m (4 ft.)	1.2m (4 ft.)	0.9m (3 ft.)			Solid: 0.9m (3 ft.) and 1.2m (4 ft.)
Corner Drop	71.71(c)(8)	722(b)&(c)	–	–	–	–	–	
Compression (Stacking)	71.71(c)(9)	723(a)	✔	✔	✔			5x Weight or 13 kPa (2 psi) * Projected Area
Penetration	71.71(c)(10)	724(b)	✔	✔	✔			3.2 cm (1.25 in.) and 6 kg (13 lbs.) dropped 1.7m (67 in.)

Table 1-4. AOS Transport Packaging System Analyses Summary – All Models (Continued)

Item	10 CFR 71 [1.1]	IAEA TS-R-1 [1.4]	Model					Applied Conditions/Criteria
			AOS-025A	AOS-050A	AOS-100A	AOS-100B	AOS-100A-S	
Hypothetical Accident Conditions of Transport	71.73(a)&(b)	726						
Free Drop	71.73(c)(1)	727(a)	✔	✔	✔			
Crush	71.73(c)(2)	727(c)	–	–	–	–	–	
Puncture	71.73(c)(3)	727(b)	✔	✔	✔			15 cm (6 in.) diameter 20 cm (8 in.) long Distance of 1.0m (40 in.)
Thermal	71.73(c)(4)	728	✔	✔	✔			
Immersion	71.73(c)(6)	729	✔	✔	✔			150 kPa (21.7 psi)
Deep Water Immersion	71.61	730	✔	✔	✔			2 MPa (290 psia)

Table 1-4. AOS Transport Packaging System Analyses Summary – All Models (Continued)

Item	10 CFR 71 [1.1]	IAEA TS-R-1 [1.4]	Model					Applied Conditions/Criteria
			AOS-025A	AOS-050A	AOS-100A	AOS-100B	AOS-100A-S	
Thermal								
Normal Conditions of Transport								
38°C (100°F) Ambient + Decay Heat + Solar			✔	✔	✔			
38°C (100°F) Ambient + Decay Heat			✔	✔	✔			
-29°C (-20°F) Ambient + Decay Heat			✔	✔	✔			
-29°C (-20°F) Ambient			✔	✔	✔			
-40°C (-40°F) Ambient + Decay Heat			✔	✔	✔			
-40°C (-40°F) Ambient			✔	✔	✔			
Hypothetical Accident Conditions of Transport								
Fire			✔	✔	✔			
Containment								
Internal Pressure (Fission Gases)			–	–	–	–	–	
Cask Lid Seal Joint			✔	✔	✔			
Shielding								
Source Term			✔	✔	✔	✔	✔	
Decay Heat			✔	✔	✔	✔	✔	
Gamma Dose			✔	✔	✔	✔	✔	
Transportation Index			✔	✔	✔	✔	✔	

1.3 APPENDIX

1.3.1 AOS Transport Packaging System, Certification Drawings

Table 1-5 lists the certification drawings for the AOS Transport Packaging System's assembly, impact limiter, cask, and liner/axial shielding plates, by model.

Table 1-5. AOS Transport Packaging System Certification Drawing List – All Models

Model	Assembly	Rev.	Impact Limiter	Rev.	Cask[a]	Rev.	Liner/Axial Shielding Plates	Rev.
AOS-025A	166D8142	G	105E9722	F	166D8143	F	183C8485	E
AOS-050A	105E9718	G	166D8138	F	166D8137	F	–	–
AOS-100A	105E9711	G	105E9713	F	105E9712G001	F	183C8491	F
AOS-100B	105E9711	G	105E9713	F	105E9712G002	F	183C8491	F
AOS-100A-S	105E9711	G	105E9713	F	105E9719	F	183C8491	F

a. The G00x number appended to select drawing numbers represents a group within the drawing.

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1.3.1.1 AOS Transport Packaging System Drawings – Model AOS-025A

AOS Drawing No. 166D8142

Model AOS-025A Assembly

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Proprietary Information withheld from public disclosure per 10 CFR 2.390(a)(4).

AOS Drawing No. 105E9722

Model AOS-025A Impact Limiter

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Proprietary Information withheld from public disclosure per 10 CFR 2.390(a)(4).

AOS Drawing No. 166D8143

Model AOS-025A Cask

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Proprietary Information withheld from public disclosure per 10 CFR 2.390(a)(4).

AOS Drawing No. 183C8485

Model AOS-025A Liner/Axial Shielding Plates

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1.3.1.2 AOS Transport Packaging System Drawings – Model AOS-050A

AOS Drawing No. 105E9718

Model AOS-050A Assembly

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AOS Drawing No. 166D8138

Model AOS-050A Impact Limiter

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Proprietary Information withheld from public disclosure per 10 CFR 2.390(a)(4).

AOS Drawing No. 166D8137

Model AOS-050A Cask

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Proprietary Information withheld from public disclosure per 10 CFR 2.390(a)(4).

1.3.1.3 AOS Transport Packaging System Drawings – Model AOS-100A, AOS-100B, and AOS-100A-S

AOS Drawing No. 105E9711

Model AOS-100A / AOS-100B / AOS-100A-S Assembly

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Proprietary Information withheld from public disclosure per 10 CFR 2.390(a)(4).

AOS Drawing No. 105E9713

Model AOS-100A / AOS-100B / AOS-100A-S Impact Limiter

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Proprietary Information withheld from public disclosure per 10 CFR 2.390(a)(4).

AOS Drawing No. 105E9712G001

Model AOS-100A Cask

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Proprietary Information withheld from public disclosure per 10 CFR 2.390(a)(4).

AOS Drawing No. 105E9712G002

Model AOS-100B Cask

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Proprietary Information withheld from public disclosure per 10 CFR 2.390(a)(4).

AOS Drawing No. 105E9719

Model AOS-100A-S Cask

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Proprietary Information withheld from public disclosure per 10 CFR 2.390(a)(4).

AOS Drawing No. 183C8491

Model AOS-100A / AOS-100B / AOS-100A-S Liner/Axial Shielding Plates

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Proprietary Information withheld from public disclosure per 10 CFR 2.390(a)(4).

1.4 REFERENCES

[1.1] U.S. Nuclear Regulatory Commission (NRC), *Title 10, Code of Federal Regulations, Part 71 (10 CFR 71)*, "Packaging and Transportation of Radioactive Material."

[1.2] American Society of Mechanical Engineers, *ASME Boiler and Pressure Vessel Code*, 2004 Ed., No Addendum.

[1.3] U.S. Department of Transportation (DOT), *Title 49, Code of Federal Regulations, Part 173 (49 CFR 173)*, "Shippers – General Requirements for Shipments and Packagings."

[1.4] *International Atomic Energy Agency (IAEA) Safety Standards Series No. TS-R-1* (*IAEA TS-R-1*), "Regulations for the Safe Transport of Radioactive Material," 1996 Ed. (as amended 2003).

[1.5] Alpha-Omega Services, Inc. (AOS), *PR9000*, "Quality Assurance Program Radioactive Material Transport Packages," Latest.

[1.6] McConnell, J. W. Jr., A. L. Ayers, Jr., and M. J. Tyacke, *NUREG/CR-6407, Classification of Transportation Packaging and Dry Spent Fuel Storage System Components According to Importance to Safety*, Idaho National Engineering Laboratory, Prepared for U.S. Nuclear Regulatory Commission (NRC), February, 1996.

2 STRUCTURAL EVALUATION

This chapter presents the structural evaluation of the AOS Transport Packaging System, and demonstrates that the design meets all applicable structure criteria. All components that comprise the AOS Transport Packaging System are evaluated to their regulatory requirements. Normal Accident conditions of transport (NCT) and Hypothetical Accident conditions (HAC) of transport are applied, in accordance with *10 CFR 71* and *IAEA TS-R-1* requirements (References **[2.1]** and **[2.2]**, respectively). Analyses comply with the methodology presented in *Regulatory Guide 7.6*, and loadings are combined, as provided in *Regulatory Guide 7.8* (References **[2.3]** and **[2.4]**, respectively).

- **Engineering Analyses** – Most of the engineering analyses are conducted using Finite Element Methods (FEM). The computer program applied in the analysis, LIBRA, is a multi-purpose finite element program applicable to static and dynamic analyses of linear and non-linear structural systems. A detailed description of the LIBRA program and a summary of the verification and qualification studies conducted in support of this evaluation are provided in Appendix 2.12.3.

  The Finite Element Analyses (FEA) are primarily concentrated on the cask structure, due to its containment functions. For the evaluated conditions, finite element analyses and appropriate material properties are used. For all drop conditions, the deceleration forces are determined using finite element methods. Load distributions are obtained for the Drop Test results. Results from the analyses demonstrate that all AOS Transport Packaging System models have the capability to meet regulatory requirements.

- **Free-Drop Test** – Free-Drop tests are conducted to verify the analytical procedure(s) used to determine cask impact accelerations, and forces within the impact limiter and cask structures for three (3) drop orientations. The drop tests also confirm the distribution of impact forces upon the cask structure.

- **Component Tests** – Component tests are conducted to enhance and/or verify understanding of materials and the behavior of AOS Transport Packaging System components under design conditions.

A summary of the engineering evaluation analyses conducted upon each AOS Transport Packaging System model is provided in Table 1-4, "AOS Transport Packaging System Analyses Summary – All Models."

2.1 DESCRIPTION OF STRUCTURAL DESIGN

2.1.1 Discussion

The AOS Transport Packaging System encompasses a group of transport packaging, scaled from the Model AOS-100 transport package. There are variations between models in the use of shielding materials (tungsten alloy or carbon steel), the size and number of bolts, and the density of the polyurethane foam used as a thermal shielding and energy absorbing material. The cask structure is the only true scale of the basic design, with minor variations to accommodate standard size components and/or features.

The AOS Transport Packaging System consists of three (3) main components that are important to safely operate the transport packages – cask, impact limiter, and cask lid elastomeric or metallic seal:

- **Cask** – The cask body, together with the cask drain port closure, cask vent port closure, and cask lid seal joint, provide containment for the radioactive contents that are stored and transported within the transport package. (Refer to Figure 4-1, "Containment Boundary (Cask Lid Metallic Seal Shown)," for a depiction of the containment boundary.) The cask body is constructed of 300 series stainless steel (SS300) material.

  Tungsten alloy or carbon steel material is embedded within the cask body and cask lid plug, to enhance the assembled cask's shielding capability. This option of shielding materials are variable within the AOS Transport Packaging System models, dependent upon the isotope being transported. Refer to Figure 2-1 through Figure 2-3 for cutaway views of the Model AOS-025, AOS-050, and AOS-100, packaging, respectively, and to Figure 2-4 for an isometric view of a typical AOS cask.

- **Impact Limiter** – The impact limiter consists of two (2) sections, attached to one another by mechanical connectors. Each impact limiter section covers one end of the cask. The impact limiters are constructed of SS300 thin shell, filled with polyurethane foam, and mitigate mechanical and thermal loads generated during Normal and Hypothetical Accident conditions of transport. Refer to Figure 2-5 for an isometric view of a typical AOS impact limiter.

- **Cask Lid Seal** – All transport package models use either a double elastomeric O-Rings capture by SS300 series flat rings, or metallic double "C" cross-section seal. The cask lid metallic seal is a multiple-component assembly consisting of a nickel-chromium alloy spring and silver liner. Additional information specific to the cask lid seal is provided in Subsection 4.1.3, "Cask Lid Seal."

Refer to Section 1.2, "Package Description," for further details regarding the packaging.

The evaluation presented here is for three (3) model sizes – AOS-025A, AOS-050A, and AOS-100A and AOS-100B. The Model AOS-100A analyses are also applicable to the Model AOS-100A-S, a double-ended configuration with a cask lid and cask lid plug at both ends, because each variation of this model effectively has the same weight.

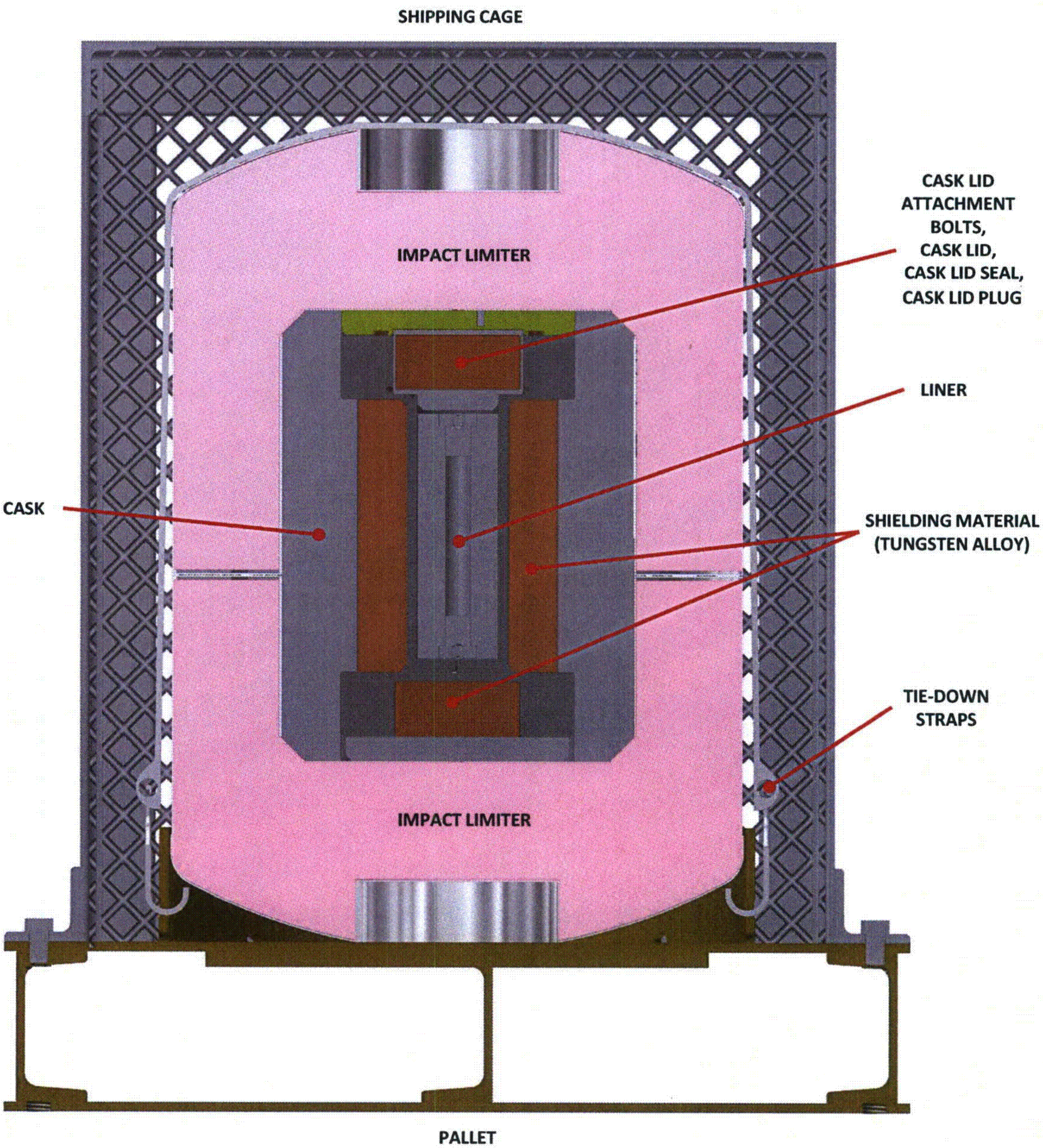

Figure 2-1. Assembled Transport Package Cutaway – Model AOS-025A

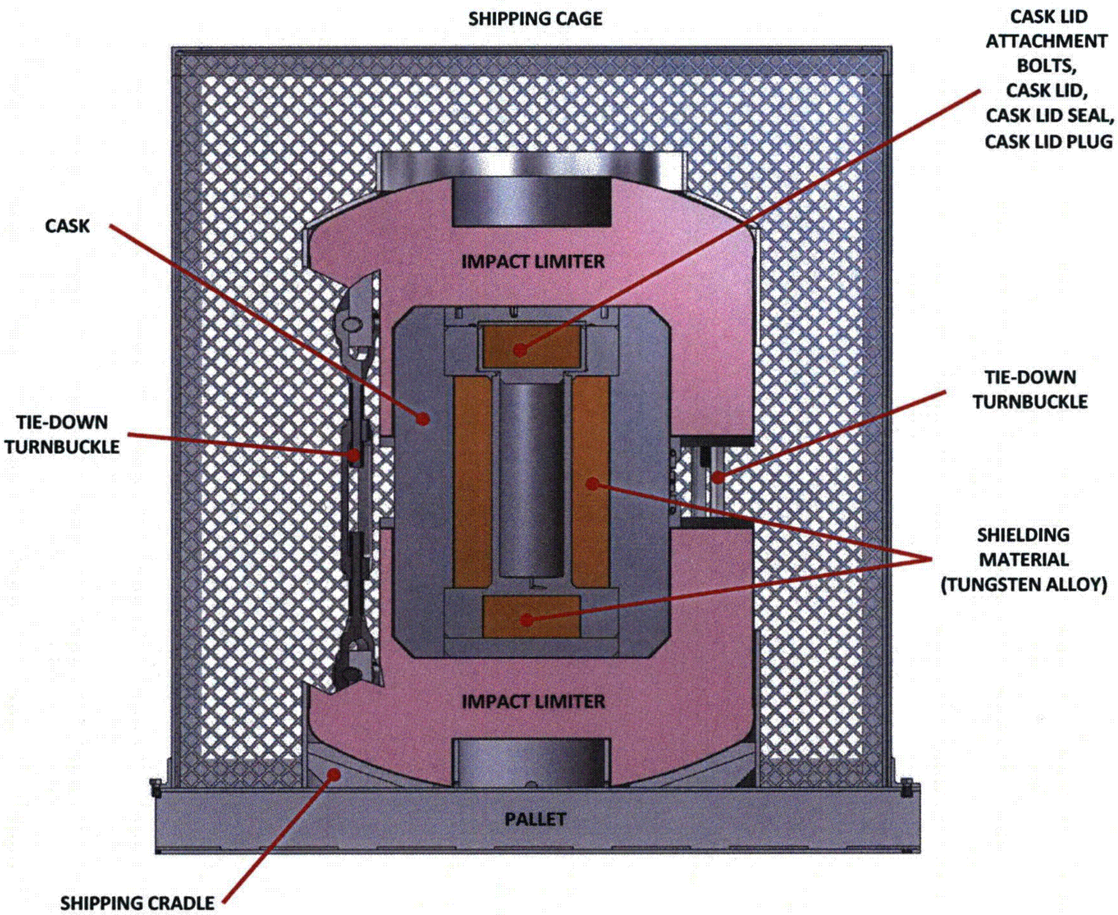

Figure 2-2. Assembled Transport Package Cutaway – Model AOS-050A

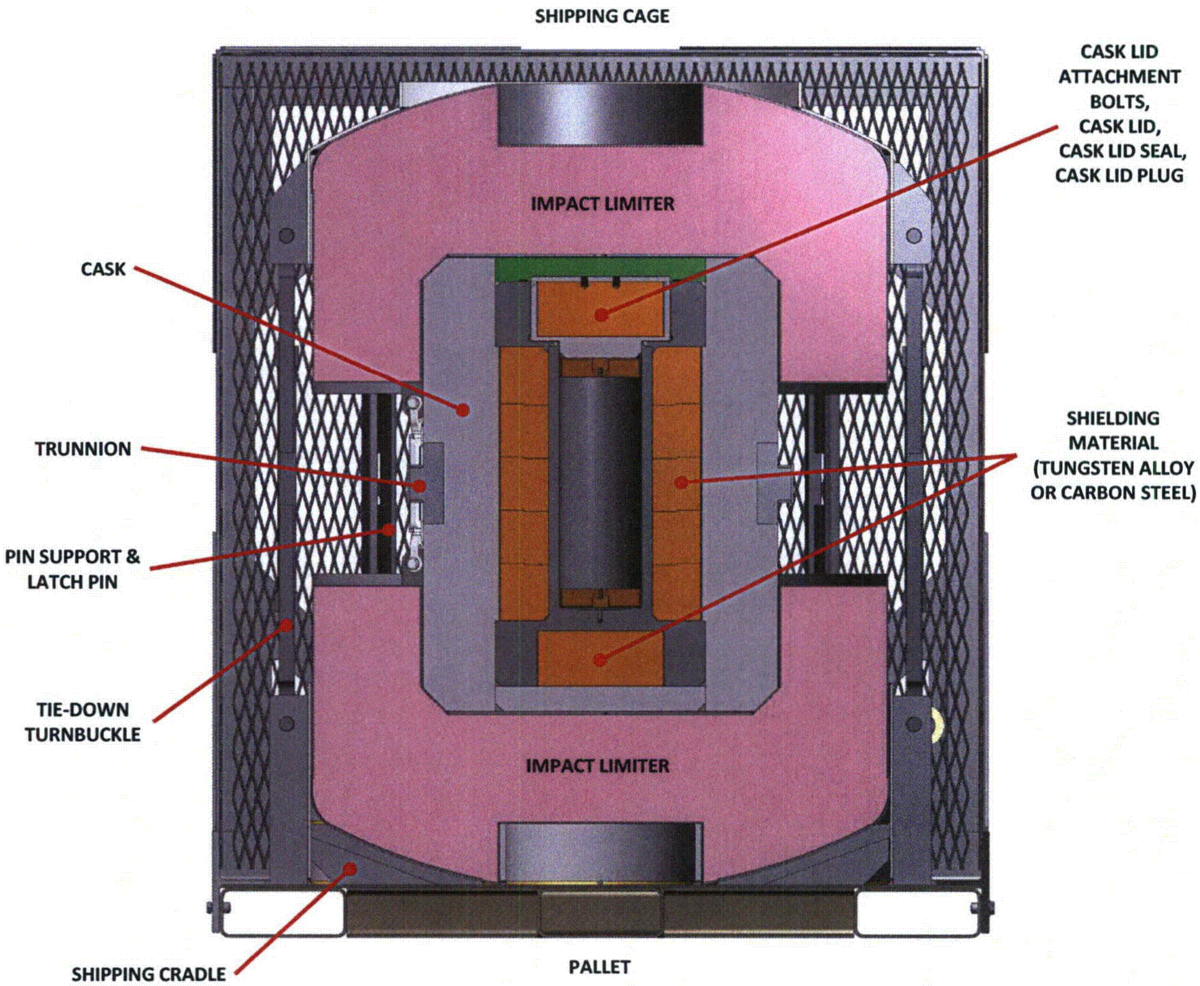

Figure 2-3. Assembled Transport Package Cutaway – Models AOS-100A and AOS-100B

Note: *Model AOS-100A-S is not shown, because of its similarity to the Model AOS-100A.*

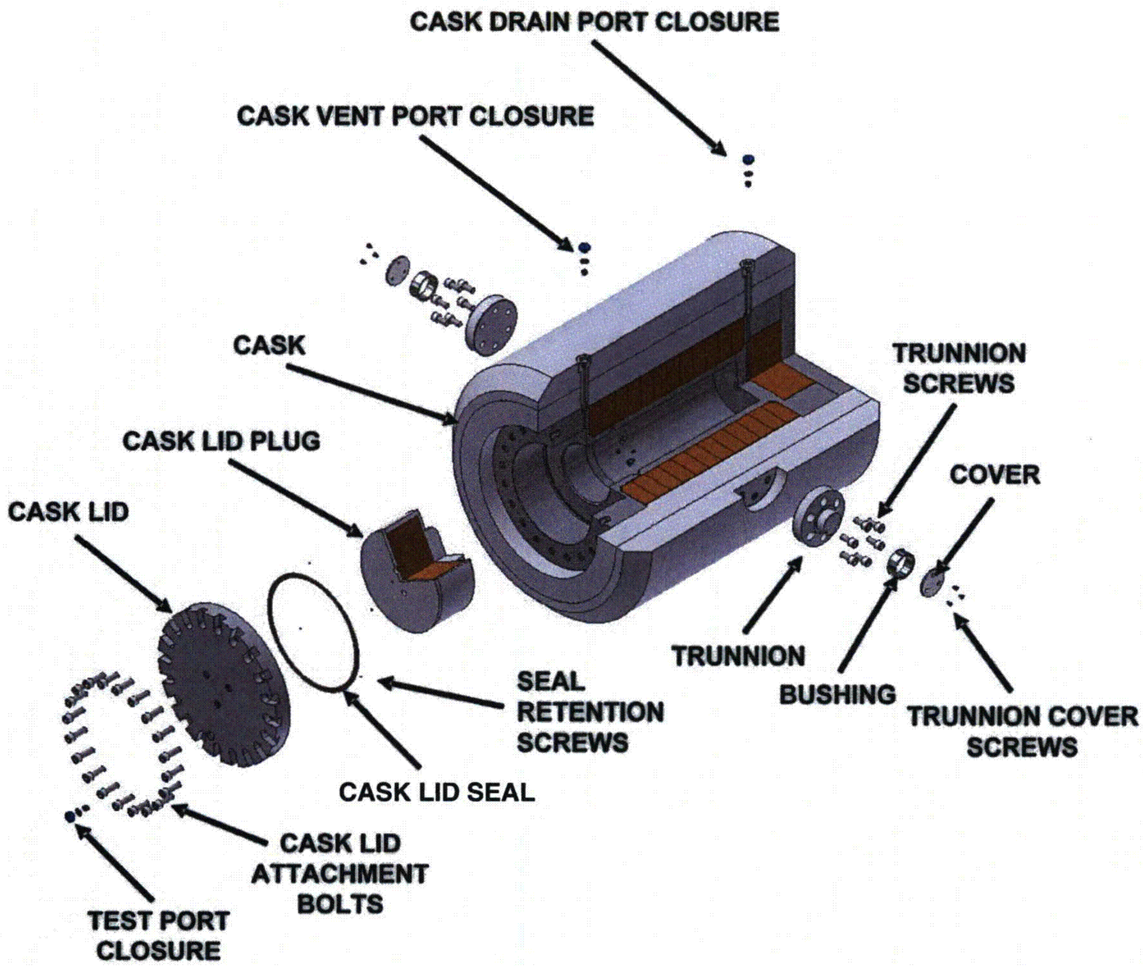

Figure 2-4. Isometric View – Typical Cask

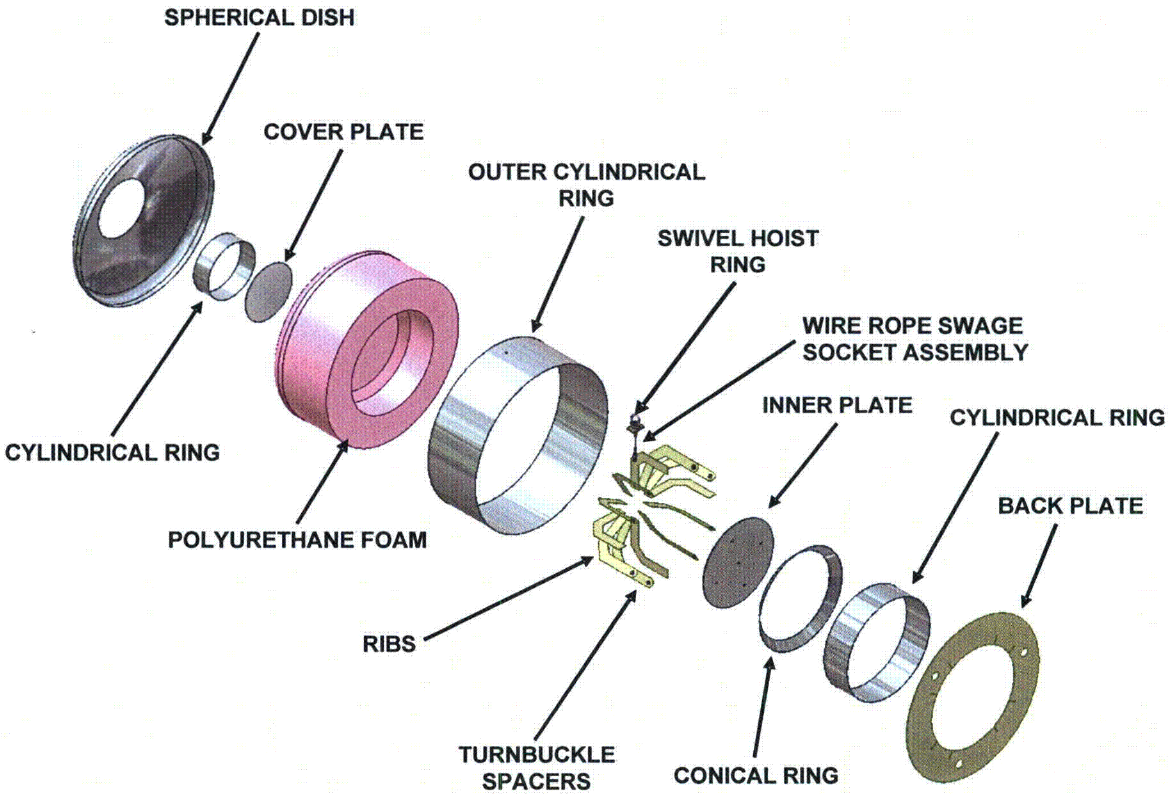

Figure 2-5. Isometric View – Typical Impact Limiter

2.1.2 Design Criteria

This subsection defines the allowable stress in accordance with *Regulatory Guide 7.6* (Reference [2.3]), for Load Combinations defined in *Regulatory Guide 7.8* (Reference [2.4]). Table 2-1 presents a summary of the Load Combinations for Normal and Hypothetical Accident conditions of transport, and lists the FEA models used in the evaluation. The Load Combinations presented in Table 2-1 are adapted from Reference [2.4], with some additions to reflect current regulatory requirements. The Normal and Hypothetical Accident conditions of transport design criteria for stress are obtained from Reference [2.3].

Under Normal conditions of transport, the following design criteria apply:

$P_m < S_m$

$P_m + P_b < 1.5\ S_m$

$P_m + P_b + Q < 3.0\ S_m$

Under Hypothetical Accident conditions of transport, the following design criteria apply:

P_m lesser of 2.4 S_m, or 0.7 S_u

$P_m + P_b$ lesser of 3.6 S_m, or S_u

where:

S_m	=	Allowable Primary Membrane Stress
P_m	=	Primary Membrane Stress
P_b	=	Primary Bending Stress
Q	=	Secondary Thermal Stress
S_u	=	Ultimate Stress

The above criteria is consistent with Reference [2.3]. The Margin of Safety is provided by:

$MS = (F / f) - 1.0$

where:

F	=	Allowable Stress
f	=	Calculated Stress

Table 2-1 lists the Load Combinations and other factors (Normal and Hypothetical Accident conditions of transport) that serve as design criteria. Each Normal and Hypothetical Accident condition of transport is analyzed, using various Load Combinations to demonstrate performance. Specific Load Combinations are grouped using unique designators (for example, Load Combination 101 refers to the specific combination of Ambient Temperature of 38°C, Maximum Decay Heat, Zero Insolation, and Minimum Internal Pressure). Table 2-6 summarizes the Load Combinations used in the analyses.

Allowable material properties are obtained from the ASME Code (Reference **[2.5]**) for ferrous materials, and from the manufacturer's data for tungsten alloy and polyurethane foam materials. The impact load evaluation is based upon limiting the forces transferred to the cask components during the event, to a level well below the cask's capacity to safely carry the load. Each AOS Transport Packaging System model is designed for specific pressures, based upon the cavity geometry and proposed payload.

In addition to the design criteria presented above, the following failure modes are also considered:

- Brittle Fracture
- Fatigue
- Buckling

These topics are described in Paragraph 2.1.2.1 through Paragraph 2.1.2.3.

Impact evaluations are provided by FEA models, as described in Paragraph 2.1.2.4.

Refer to Table 2-8 for a breakdown of the AOS Transport Packaging System, by component. The table lists the applicable Code or Standard, as well as the applicable Safety Classification.

Table 2-1. Summary of Load Combinations for Normal and Hypothetical Accident Conditions of Transport

Evaluation Conditions	Load Combinations[a]									
	Ambient Temperature			Decay Heat		Insolation		Internal Pressure		Fabrication Stresses
	38°C (100°F)	- 29°C (-20°F)	-40°C (-40°F)	Max.	Zero	Max.	Zero	Max.	Min.	
Normal Conditions of Transport (Analyzed Individually)										
Hot Environment	101			101			101		101	211
	102			102		102		201	102	211
Cold Environment		103			103		103		103	211
			104		104		104		104	211
			105	105					105	211
		106		106					106	211
Internal Design Pressure (varies by model)	102			102		102		201		211
Reduced External Pressure – 24.5 kPa (3.5 psia)	102			102		102		202		211
Increased External Pressure – 140 kPa (20 psia)		103			103		103	203	103	211
Compression Load (5x weight)	215			101			101	201	201	211
Rod Drop onto Cask	216			101			101	201		211
	216		104		104			201		211
Vibration, Forward Load	221			102		102		201		211
	221	103			103		103		103	211
Vibration, Lateral Load	222			102		102		201		211
	222	103			103		103		103	211
Vibration, Vertical Load	223			102		102		201		211
	223	103			103		103		103	211
3- or 4-ft. Head-On Drop	231	102		102		102		201	201	211
Impact Test	232			102		102		201		211

Table 2-1. Summary of Load Combinations for Normal and Hypothetical Accident Conditions of Transport (Continued)

Evaluation Conditions	Load Combinations[a]									
	Ambient Temperature			Decay Heat		Insolation		Internal Pressure		Fabrication Stresses
	38°C (100°F)	-29°C (-20°F)	-40°C (-40°F)	Max.	Zero	Max.	Zero	Max.	Min.	
Hypothetical Accident Conditions of Transport (Apply Sequentially)										
Free Drop										
Head-On Orientation	301			102		102		201		211
Side Orientation + Slap-Down	302			102		102		201		211
			305		104		104		104	211
Cg/Corner Orientation	303			102		102		201		211
			306		104		104		104	211
Puncture	311			101			101	201		211
Thermal										211
Fire at 30 minutes	111			102		102		201		211
Post Fire at 60, 90, 120, 150, and 180 minutes	112			102		102		201		211
Deep Water Immersion	204			101		101		201		211

a. *Numbers refer to a specific Load Condition (Case). For example, Load Case 101 refers to a condition in which the environment conditions are 38°C (100°F) ambient temperature, zero (0) insolation, maximum decay heat, and zero (0) internal pressure.*

2.1.2.1 Brittle Fracture

Brittle fracture is not considered in this evaluation, because all containment and non-containment structural components are fabricated of SS300. SS300 does not undergo ductile-to-brittle transition in the temperature range of interest [down to -40°C (-40°F)]; therefore, it is safe from brittle fracture.

The cask lid attachment bolts are fabricated from ASME SB-637, UNS N07718. This material is also excluded from brittle fracture consideration, in accordance with *Section III, Division 1, paragraph NB-2311(a)(7)* in Reference **[2.26]**.

2.1.2.2 Fatigue

The fatigue evaluation is limited to bolts that experience both preload shock and vibration loading during transportation. Pressurization and thermal loads do not significantly contribute to fatigue loading, because of their magnitude and long vibration period.

The allowable fatigue stress, S_{alt}, of package components corresponds to the number of vibration cycles. The design fatigue curve is provided in Reference **[2.14]**, Section 5, Figure 1-9.2. The value of S_{alt} is corrected by the ratio of the modulus of elasticity provided on the design fatigue curve to the modules of elasticity of the component material used in the analyses.

2.1.2.3 Buckling

The AOS Transport Packaging System cask shells are not likely to experience buckling instability, based upon their R/t ratio due to forces generated under Normal and Hypothetical Accident conditions of transport. However, because buckling is an unacceptable failure mode for the containment boundary (located within the cask component of the transport package), per Reference **[2.3]**, the buckling critical force, F_{cr}, is calculated for each packaging system model, in Table 2-2.

Cask buckling under external loading requires the cask outer shell to buckle. Buckling of the cask outer shell, under compressive loading, is conservatively evaluated using the formula provided in Reference **[2.6]**.

The reference formula for cylinder buckling under axial load is:

$$F_{cr} = k * E * t / r \qquad (2\text{-}1)$$

with the coefficient k = 0.182.

The well-known solution for buckling of a cylinder under axial load **[2.6]** is:

$$\sigma_{CR} = [\pi^2 k_c E / 12 (1 - \nu^2)] (t / L)^2 \qquad (2\text{-}2)$$

where, for moderate-length cylinders:

$$k_c = 0.702 * Z \qquad (2\text{-}3)$$

$$Z = \sqrt{(1 - \nu^2)} * L^2 / R * t \qquad (2\text{-}4)$$

The Z parameter in Equation 2-4 defines the cylinder length category – short, moderate, or long. The Z parameter is the same for all three (3) model sizes – AOS-025, AOS-050, and AOS-100 – because of their scale relationship:

$$Z = 14.5$$

This places the AOS cylinders in the short-to-moderate length category. For $E = 28.0 \times 10^6$, Equations 2-2, 2-3, and 2-4 provide:

$$k_c = 11.0$$

$$\sigma_{CR} = 6.98 \times 10^6 \text{ psi}$$

For short-to-moderate length cylinders with Z = 14.5, column buckling mode is precluded. Buckling stress under compressive load is then provided by:

$$\sigma_{CR} = 0.6\ E\ t / R$$

(2-5)

$$\sigma_{CR} = 6.87 \times 10^6 \text{ psi}$$

The above two solutions for σ_{CR} demonstrate that Equation 2-1 is an alternative to Equation 2-2 for buckling stress in short-to-moderate-length cylinders. The coefficient 0.6 in Equation 2-5 is applicable to perfect cylinders – cylinders with no variation in radius and thickness. For imperfect cylinders, a smaller coefficient must be used. The value in Equation 2-1, 0.182, is applicable to thin cylinders, and is conservative for thick cylinders such as the three (3) AOS casks.

The high F_{cr} values listed in Table 2-2 preclude buckling failure.

Table 2-2. Buckling Stress Values – All Models[a]

Model	Young Module of Elasticity, E at 25.6°C (78°F) (psi)[b]	Wall Thickness, t (in.)	Cylinder Radius, r (in.)[c]	Buckling Critical Force, F_{cr} (psi)[b]
AOS-025	28×10^6	1.5	2.75	2.78×10^6
AOS-050	28×10^6	3.0	5.5	2.78×10^6
AOS-100	28×10^6	6.0	11.0	2.78×10^6

a. *The equation used for buckling stress is $F_{cr} = 0.182\ E * t / r$.*

b. *Considering E at -100°F, 29.2×10^6, the value of F_{cr} increases by 4%.*
Considering E at 600°F, 25.3×10^6, the value of F_{cr} decreases by 10%.

c. *r is the average radius through wall thickness, [(Outside Diameter - Inside Diameter) / 2].*

2.1.2.4 FEA Models

Three (3) Finite Element Analysis (FEA) analytical models are used in the stress analyses of the Model AOS-025, AOS-050, and AOS-100 transport packages – axisymmetric (2D) and 3D models of the cask component and a 3D model of the impact limiter component – for each AOS Transport Packaging System model. The cask component FEA models are used to evaluated the symmetric and non-symmetric loading condition on the cask, while the impact limiter FEA model is used to establish the free drop condition-limiting force.

The 2D model of the cask contains approximately 5,500 nodes and 5,500 elements, and is represented in Figure 2-6. The 3D model of the cask contains approximately 72,700 nodes and 66,400 elements, and is represented in Figure 2-7. A rendered plot of the 3D model of the cask is illustrated in Figure 2-8. The 3D model of the impact limiter is presented later, in Figure 2-32.

The 3D model is generated by rotation of the 2D model about the cask longitudinal axis. In this way, the 2D and 3D models are compatible for stress combinations that involve both 2D and 3D models. The 3D model is composed of 12 identical sections, over a 180° azimuth. In all 3D analyses, there is symmetry around the 0 to 180° meridian plane, requiring only a 180° model. The nodal and element numbers are defined such that adjacent meridian node and element numbers differ by 10,000. Quad and triangular elements in the 2D model are transformed into solid brick and wedge elements in the 3D model. Spring elements are preserved in the 3D model, and gaps are assumed closed in 3D analyses.

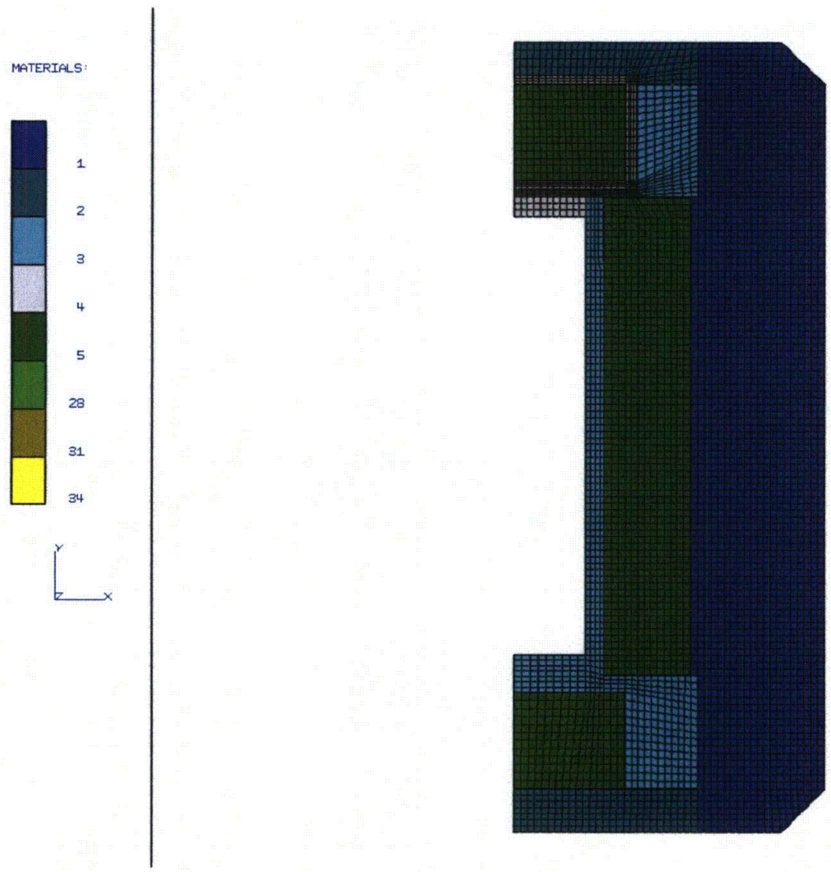

Figure 2-6. Axisymmetric (2D) Model – Models AOS-025, AOS-050, and AOS-100

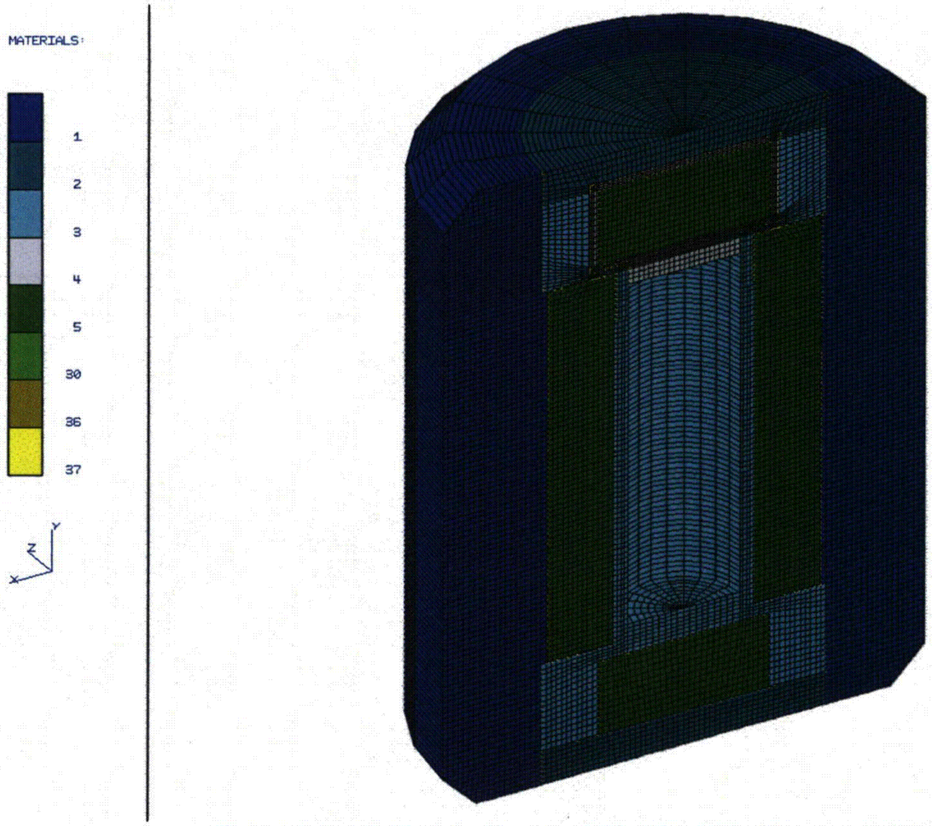

Figure 2-7. 3D Model – Models AOS-025, AOS-050, and AOS-100

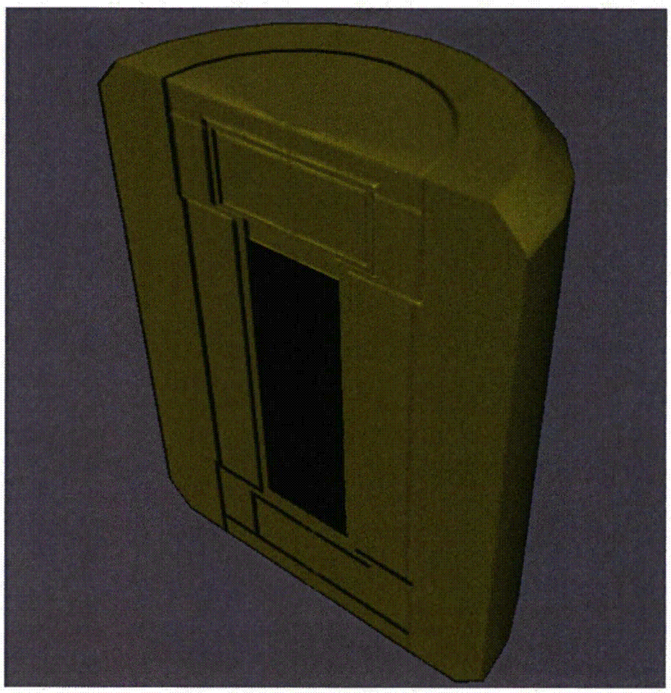

Figure 2-8. 3D Rendered Model – Models AOS-025, AOS-050, and AOS-100

2.1.2.4.1 Stress Monitoring Locations

The Model AOS-025, AOS-050, and AOS-100 transport packages have 22 stress monitoring locations, illustrated in Figure 2-9. Each location is a cross-section of an inside or outer shell, containing several elements. Table 2-3 lists the elements that comprise each cross-section.

Force and moment resultants at each monitored cross-section are evaluated by integrating the element stresses in the cross-section elements. In the LIBRA FEA program, element stresses are output at element Gaussian integration points, and the integrations for force and moment resultants are based upon the stress and geometry data at the gauss points. The integrated force and moment resultants are used to determine P_m and P_b stresses for the monitored cross-section.

In 3D analyses, stress is evaluated at monitoring locations in each of the 12 azimuth sections. Therefore, stresses are evaluated at 12 times (12x) the number of locations used in 2D analyses. The maximum values found in any of the 12 azimuth sections are used in forming stress combinations.

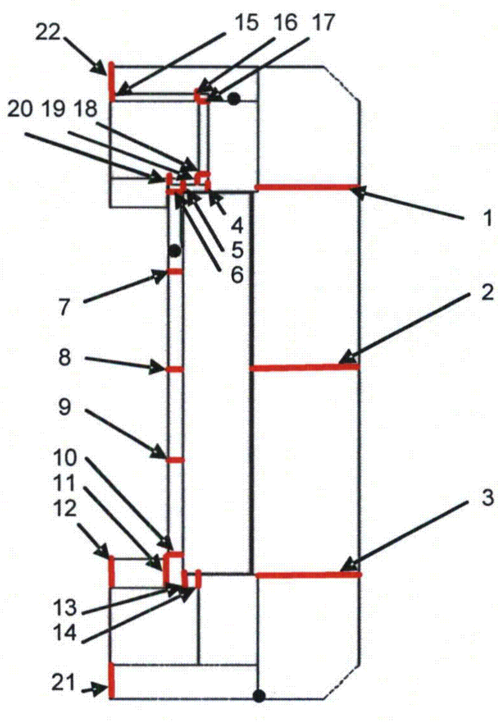

Figure 2-9. P_m and P_b Stress Monitoring Points – All Models

Table 2-3. P_m and P_b Stress Monitoring Section Elements – All Models

Section	Elements
1	1957, 1958, 1959, 1960, 1961, 1962, 1963, 1964, 1965, 2146, 2147, 2148, 2149, 2150, 2151, 2152, 2153, 2154, 2155
2	552, 904, 905, 906, 907, 908, 909, 910, 911, 912, 1587, 1588, 1589, 1590, 1591, 1592, 1593, 1594, 1595, 1596
3	348, 349, 350, 351, 352, 353, 354, 355, 356, 507, 508, 509, 510, 511, 512, 513, 514, 515, 516
4	4587, 4591, 4595, 4599
5	4572, 4575, 4578, 4581
6	4552, 4553, 4554, 4555
7	4476, 4477, 4478, 4479
8	4408, 4409, 4410, 4411
9	4344, 4345, 4346, 4347
10	4280, 4281, 4282, 4283
11	4141, 4150, 4159, 4168, 4177, 4186, 4195
12	4133, 4142, 4151, 4160, 4169, 4178, 4187
13	4212, 4215, 4218, 4221
14	4214, 4217, 4220, 4223
15	5218, 5236, 5254
16	5235, 5253, 5271
17	5214, 5215, 5216, 5217
18	5166, 5167, 5168, 5169
19	5140, 5143, 5146, 5149
20	5122, 5126, 5130, 5134
21	3001, 3017, 3033, 3049, 3065, 3081, 3097
22	3190, 3208, 3226, 3244

2.1.2.4.2 Load Cases and Load Combinations

Table 2-4 lists the 31 Load Cases (18 Normal, and 13 Hypothetical Accident, conditions of transport) involved in evaluating each AOS Transport Packaging System model. Each Load Case represents specific conditions of transport. Table 2-5 summarizes the numbering designations for these Load Cases. These Load Cases are then combined as "Load Combinations" in Table 2-6.

The 2D model is the predominate model used in the stress analyses of the 31 Load Cases. The 3D model is used to evaluate stress for analysis of vibration and shock loadings, as well as for Side and Cg/Corner Drop loadings.

The 31 Load Cases are combined into 34 Load Combinations (19 Normal, and 15 Hypothetical Accident, conditions of transport), listed in Table 2-6. Load Combinations numbered 100 to 299 are used for Normal conditions of transport. Load Combinations numbered 300 to 399 are used for Hypothetical Accident conditions of transport.

Table 2-4. Load Cases

<table>
<tr><th>Conditions of Transport</th><th>Load Case</th><th colspan="2">Description</th></tr>
<tr><td rowspan="18">Normal</td><td>101</td><td colspan="2">100°F Ambient, Maximum Decay Heat</td></tr>
<tr><td>102</td><td colspan="2">100°F Ambient, Maximum Decay Heat, Maximum Insolation</td></tr>
<tr><td>103</td><td colspan="2">-20°F Ambient, Zero Decay Heat, Zero Insolation</td></tr>
<tr><td>104</td><td colspan="2">-40°F Ambient, Zero Decay Heat, Zero Insolation</td></tr>
<tr><td>105</td><td colspan="2">-40°F Ambient, Maximum Decay Heat</td></tr>
<tr><td>106</td><td colspan="2">-20°F Ambient, Maximum Decay Heat</td></tr>
<tr><td>201</td><td>Internal Design Pressure
• Model AOS-025 –
• Model AOS-050 –
• Model AOS-100 –</td><td>
207 kPa (30 psia)
414 kPa (60 psia)
1,930 kPa (280 psia)</td></tr>
<tr><td>202</td><td colspan="2">Minimum External Pressure, 24 kPa (3.5 psia)</td></tr>
<tr><td>203</td><td colspan="2">Maximum Increased External Pressure, 140 kPa (20 psia)</td></tr>
<tr><td>204</td><td colspan="2">Additional Increased External Pressure, 2 MPa (290 psia)</td></tr>
<tr><td>211</td><td colspan="2">Fabrication Stress</td></tr>
<tr><td>215</td><td colspan="2">Compression Load (5x weight)</td></tr>
<tr><td>216</td><td colspan="2">Rod Drop onto Cask</td></tr>
<tr><td>221</td><td colspan="2">Forward 10g Vibration Inertia Load</td></tr>
<tr><td>222</td><td colspan="2">Lateral 5g Vibration Inertia Load</td></tr>
<tr><td>223</td><td colspan="2">Vertical 2g Vibration Inertia Load</td></tr>
<tr><td>231</td><td>Head-On Drop
• Model AOS-025 –
• Model AOS-050 –
• Model AOS-100 –</td><td>
4-ft. Head-On Drop
4-ft. Head-On Drop
3-ft. Head-On Drop</td></tr>
<tr><td>232[a]</td><td colspan="2">30-ft. Head-On Drop Impact Test, Normal Conditions</td></tr>
</table>

Table 2-4. Load Cases (Continued)

Conditions of Transport	Load Case	Description
Hypothetical Accident	111	Fire at 30 Minutes, 1,475°F Ambient, Maximum Decay Heat
	112	Post Fire at 60 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation
		Post Fire at 90 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation
		Post Fire at 120 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation
		Post Fire at 150 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation
		Post Fire at 180 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation
	301	30-ft. Head-On Drop
	302	30-ft. Side Drop + Slap-Down
	303	30-ft. Cg/Corner Drop
	304	30-ft. Head-On Drop at -40°F, Low Temperature
	305	30-ft. Side Drop + Slap-Down at -40°F, Low Temperature
	306	30-ft. Cg/Corner Drop at -40°F, Low Temperature
	311	4-ft. Drop onto Rod

a. *Load Combination 232 is documented only for the Model AOS-025A and AOS-050A transport packages, and demonstrates compliance with the requirements of IAEA TS-R-1, Paragraph 737 (Reference* **[2.2]**).

Table 2-5. Load Case Designation Summary

Conditions of Transport	Designating Number	Load Case Designation
Normal	101 to 106	Thermal Loading
	201 to 204	Pressure Loading
	211	Fabrication Stress Loading
	215	Compression Load
	216	Rod Impact Loading
	221 to 223	Vibration and Shock Loading
	231	3- or 4-ft. Drop Loading
	232[a]	Impact Test, Normal Condition
Hypothetical Accident	111 and 112	Fire Accident
	301 to 306	30-ft. Accident Drop Loading
	311	4-ft. Accident Drop Loading

a. *Load Combination 232 is documented only for the Model AOS-025 and AOS-050 transport packages, and demonstrates compliance with the requirements of IAEA TS-R-1, Paragraph 737 (Reference* **[2.2]**).

Table 2-6. Load Combinations

Conditions of Transport	Load Combination	Load Cases[a]	Description	
Normal	101	102, 201, 211	Hot Environment	
	102	104, 201, 211	Cold Environment	
	103	103, 202, 211	Increased External Pressure	
	104	101, 201, 202, 211	Minimum External Pressure	
	105	105, 201, 202, 211	Cold Environment with Maximum Decay Heat	
	106	101, 201, 203, 211	Maximum Pressure, Hot Environment	
	107	105, 201, 203, 211	Maximum Pressure, Cold Environment	
	215	215, 101, 201, 211	Compression Load	
	216	216, 101, 201, 211	Rod Drop	
	217	216, 104, 201, 211	Rod Drop, Cold Environment	
	221	221, 101, 201, 211	Forward Vibration	
	222	222, 101, 201, 211	Lateral Vibration	
	223	223, 101, 201, 211	Vertical Vibration	
	224	221, 103, 201, 211	Forward Vibration at Cold Temperature	
	225	222, 103, 201, 211	Lateral Vibration at Cold Temperature	
	226	223, 103, 201, 211	Vertical Vibration at Cold Temperature	
	231	231, 102, 201, 211	Head-On Drop, Normal Conditions • Model AOS-025 – • Model AOS-050 – • Model AOS-100 –	 4-ft. Head-On Drop, Normal Conditions 4-ft. Head-On Drop, Normal Conditions 3-ft. Head-On Drop, Normal Conditions
	232[b]	232, 102, 201, 211	30-ft. Head-On Drop, Normal Conditions (Impact Test)	
	233	231, 103, 211	Drop at Cold Temperature • Model AOS-025 – • Model AOS-050 – • Model AOS-100 –	 4-ft. Drop at Cold Temperature 4-ft. Drop at Cold Temperature 3-ft. Drop at Cold Temperature

Table 2-6. Load Combinations (Continued)

Conditions of Transport	Load Combination	Load Cases[a]	Description
Hypothetical Accident	301	301, 102, 201, 211	Head-On Drop Orientation
	302	302, 102, 201, 211	Side Drop Orientation
	303	303, 102, 201, 211	Cg/Corner Drop Orientation
	304	304, 105, 202, 211	Head-On Drop Orientation at -40°F, Cold Environment
	305	305, 105, 202, 211	Side Drop Orientation at -40°F, Cold Environment
	306	306, 105, 202, 211	Cg/Corner Drop Orientation at -40°F, Cold Environment
	310	204, 101, 211	Additional Increased External Pressure (290 psi)
	311	311, 101, 201, 211	4-ft. Drop onto Rod
	312	311, 104, 201, 211	4-ft. Drop onto Rod at -40°F, Cold Environment
	350	111, 201, 211	Fire at 30 Minutes
	351	112, 201, 211	Post Fire at 60 Minutes
	352		Post Fire at 90 Minutes
	353		Post Fire at 120 Minutes
	354		Post Fire at 150 Minutes
	355		Post Fire at 180 Minutes

a. *Some Normal conditions of transport Load Cases are included in Hypothetical Accident conditions of transport Load Combinations, to meet regulatory requirements.*

b. *Load Combination 232 is documented only for the Model AOS-025 and AOS-050 transport packages, and demonstrates compliance with the requirements of IAEA TS-R-1, Paragraph 737.66 (Reference* [2.2]*).*

2.1.3 Weights and Centers of Gravity

Table 2-7 lists the package weight and center of gravity of each AOS Transport Packaging System model. The package is defined as the assembly of two (2) impact limiters and their mechanical connectors, the cask, and the cask contents. The content weight includes the weight of the radioactive materials, plus the weight of any shielding devices and shoring devices, if used in the assembly. The content weight excludes the weight of the shipping cage, pallet or shipping cradle, and tie-down hardware.

Figure 2-10, Figure 2-11, and Figure 2-12 illustrate the AOS Transport Packaging System center of gravity for the Model AOS-025, AOS-050, and AOS-100 transport packages, respectively.

Table 2-7. AOS Transport Packaging System Maximum Authorized Package Weight and Cg Locations – All Models

Model	Category	Maximum Authorized Package Weight (kg / lbs.)					Cg Locations[a] (cm / in.)		
		Package[b]	Impact Limiters[c]	Cask[d]	Contents	Pallet, Shipping Cage, and Tie-Down Devices	X	Y	Z
AOS-025A	I	100	13	64	4.5	24.9	19.05	27.18	22.86
		220	28	140	10	55	7.50	10.70	9.00
AOS-050A	I	681	56	480	27	135.2	50.5	50.5	46.0
		1,500	123	1,058	60	298	19.9	19.9	18.1
AOS-100A	I	5,675	467	3,850	227	1,685.1	77.7	77.7	79.5
		12,500	1,029	8,481	500	3,715	30.6	30.6	31.3
AOS-100B	II	4,994	467	3,192	227	1,685.1	77.7	77.7	79.5
		11,000	1,029	7,030	500	3,715	30.6	30.6	31.3
AOS-100A-S	I	5,675	467	3,850	227	1,685.1	77.7	77.7	79.5
		12,500	1,029	8,481	500	3,715	30.6	30.6	31.3

a. *AOS Transport Packaging System center of gravity. Refer to Figure 2-10, Figure 2-11, and Figure 2-12 for the Model AOS-025, AOS-050, and AOS-100 transport packages, respectively.*

b. *Authorized package weight includes the components listed in this table; however, not all components will be at maximum weight.*

c. *Includes the weight of both impact limiters.*

d. *Includes the weight of the contents.*

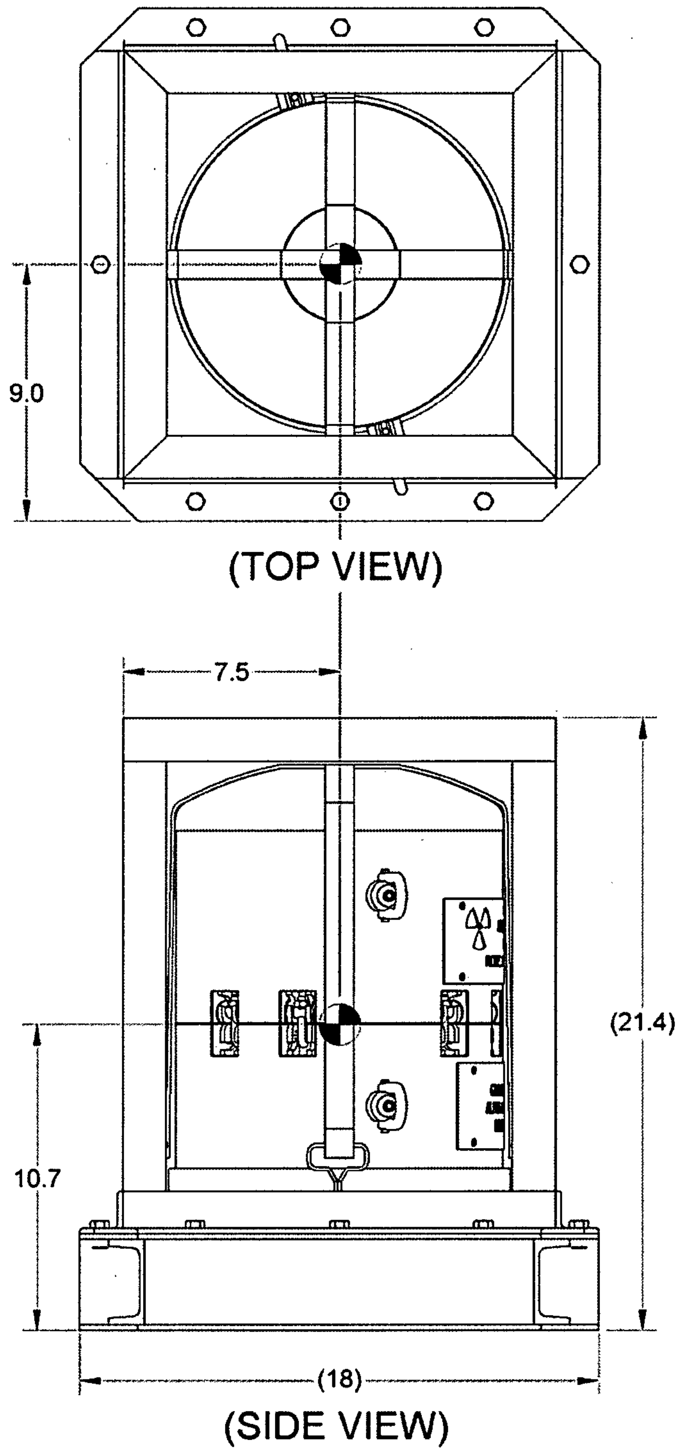

Figure 2-10. Center of Gravity – Model AOS-025

Note: *Dimensions are in inches.*

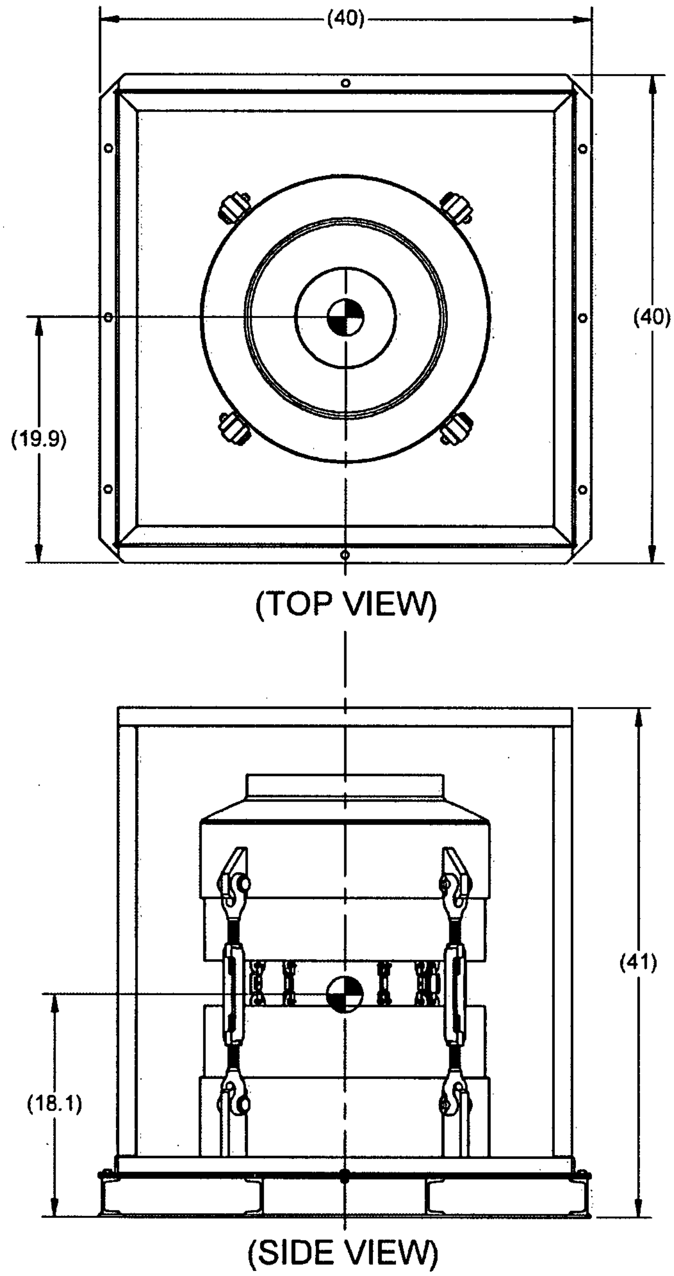

Figure 2-11. Center of Gravity – Model AOS-050

Note: *Dimensions are in inches.*

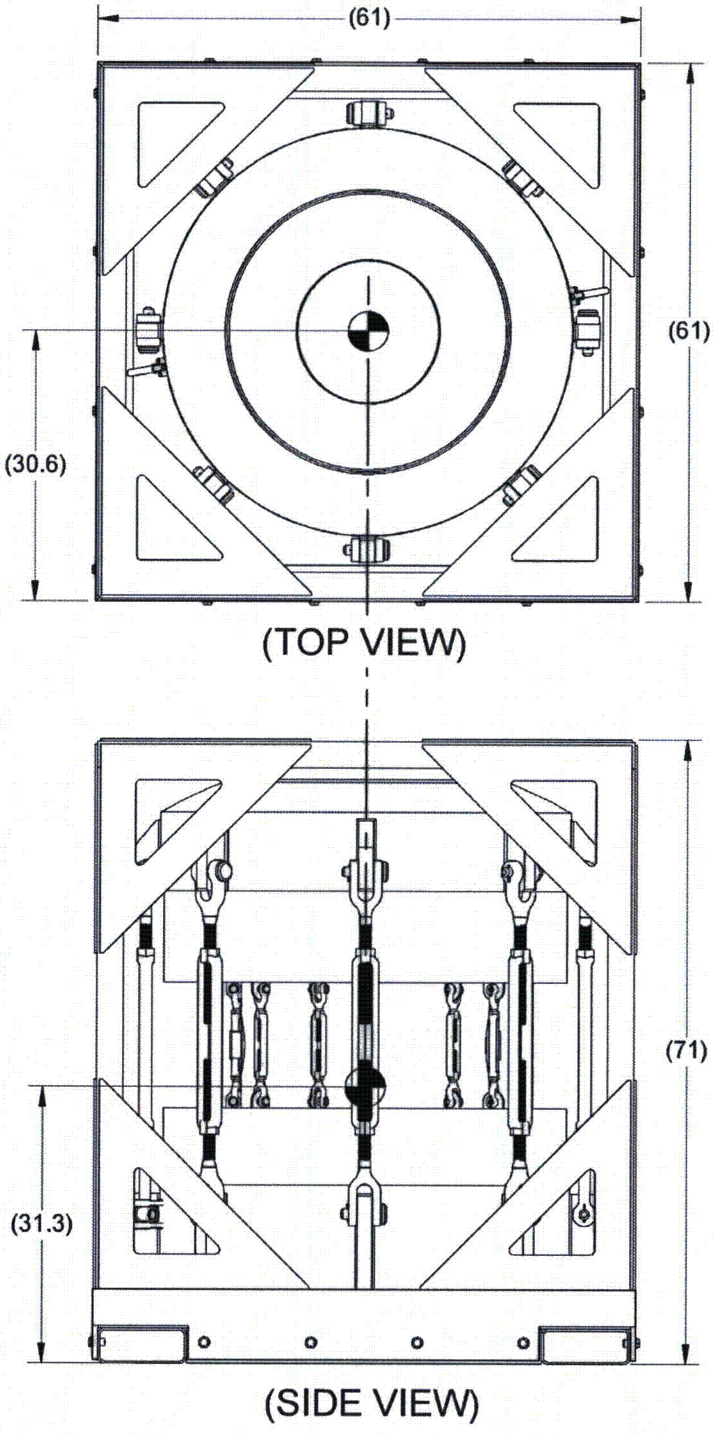

Figure 2-12. Center of Gravity – Model AOS-100

Note: *Dimensions are in inches.*

2.1.4 Identification of Codes and Standards for Package Design

Table 2-8 presents the applicable Codes and Standards for design, fabrication, and testing of the AOS Transport Packaging System, broken down by component category or functionality. For each category, the table addresses the applicable Code and/or Standard, as well as the Safety Classification.

Table 2-8. Applicable Codes and Standards for Design, Fabrication, and Testing of the AOS Transport Packaging System[a]

Package Components or Features	Component Safety Group									
	Containment		Criticality[b]	Other Safety						
	Cask Cavity Shell, Port Plugs, Threaded Pipe Plugs, Cask Lid Attachment Bolts	Cask Lid Seal	Criticality Liner	Cask Shielding (Tungsten Alloy or Carbon Steel)	Cask Outer Shell, Cask Lid Plug, Bottom Plate, Plate Shell	Port Plug Seals[c]	Neutron Shielding, Liner	Cask Trunnion	Tie-Down Devices	Impact Limiters
Safety Classification	A	A	A	B	B	B	B	B	B	A
B&PV Code Section	Section III, Division 1, Subsection NB		Section III, Division 1, Subsection NG	Section III, Division 1, Subsection NF						Section VIII, Division 1
Material Requirements	NB-2000		NG-2000	AMS-T-21014, Class 3	NF-2000		NF-2000	NF-2000	NF-2000	UG
Forming, Fitting, and Aligning	NB-4200		NG-4200		NF-4200		NF-4200	NF-4200	NF-4200	UG
Welding	NB-4400		NG-4400		NF-4400		NF-4400	NF-4400	NF-4400	UW
Qualification of Weld Procedure and Personnel	NB-4300		NG-4300		NF-4300		NF-4300	NF-4300	NF-4300	UW
Weld Heat Treatment	NB-4600		NG-4600		NF-4600		NF-4600	NF-4600	NF-4600	UW

Table 2-8. Applicable Codes and Standards for Design, Fabrication, and Testing of the AOS Transport Packaging System[a] (Continued)

Package Components or Features	Component Safety Group									
	Containment		Criticality[b]	Other Safety						
	Cask Cavity Shell, Port Plugs, Threaded Pipe Plugs, Cask Lid Attachment Bolts	Cask Lid Seal	Criticality Liner	Cask Shielding (Tungsten Alloy or Carbon Steel)	Cask Outer Shell, Cask Lid Plug, Bottom Plate, Plate Shell	Port Plug Seals[c]	Neutron Shielding, Liner	Cask Trunnion	Tie-Down Devices	Impact Limiters
Examination	NB-5000		NG-5000		NF-5000		NF-5000	NF-5000	NF-5000	UW/UG
Acceptance Testing	NB-6000	ANSI N14.5		Straight Beam method per NG-2532.1, Section III, Division 1, 2001 Edition with 2003 Addendum	Per Applicable Code Standards	ANSI N14.5		ANSI N14.6	ANSI N14.6	Per Table 8-1

a. *This table is derived from NUREG/CR-3854, Fabrication Criteria for Shipping Containers (Reference [2.24]).*

b. *Criticality does not apply to the AOS Transport Packaging System.*

c. *Port plug seals includes the conical seals.*

2.2 MATERIALS

2.2.1 Material Properties and Specifications

As previously discussed in Subsection 2.1.1, the allowable material properties used in the structural evaluation are obtained from Reference [2.5] for ferrous materials, and from the manufacturers' data for tungsten alloy and polyurethane foam materials.

The AOS Transport Packaging System is designed using the following materials:

- Stainless steel, 300 series (SS300; refer to the certification drawings, provided in Appendix 1.3.1, "AOS Transport Packaging System, Certification Drawings," for applicable national material specification)
- Cask lid attachment bolts (ASME SB-637, UNS N07718)
- Tungsten alloy (Tungsten ATI Densalloy® SD180 per AMS-T-21014, Class 3)
- Carbon steel (Carbon Steel Forging per ASME SA-105/ASTM A105)
- Rigid, closed-cell, polyurethane foam (General Plastics, FR-3700 series foam)
- Trunnion screws (ASME SA-193, Grade B6 UNS S41000)

The AOS Transport Packaging System has an impact limiter component consisting of rigid, closed-cell, polyurethane foam encased by a 300 series stainless steel (SS300) shell. This energy-absorbing and temperature insulation material is a General Plastics LAST-A-FOAM® FR-3700 resin.[a] The impact limiter's force-deflection data, for each AOS Transport Packaging System model, is provided in Subsection 2.7.1. These curves are obtained by conducting a collapsed analysis with the LIBRA Finite Element code. A complete description of the analytical procedure, as well as all testing and validation conducted to verify the procedure, are also provided in Subsection 2.7.1.

Table 2-9 lists the mechanical properties used for stainless steel analyses. Due to the variations in the 300 series stainless steel, the material properties used in the evaluations were chosen to be conservative. Properties selected are those of lesser values among the material choices.

Table 2-10 lists the mechanical properties used for the cask lid attachment bolt analysis.

Table 2-11 lists the mechanical properties used for the tungsten alloy structural and shielding analyses.

Table 2-12 lists the mechanical properties used for the carbon steel shielding analysis.

Table 2-13 lists the mechanical properties used for the trunnion screw analysis.

Table 2-14 and Table 2-15 list the mechanical properties for the General Plastics LAST-A-FOAM FR-3700 series foam used in the current AOS Transport Packaging System design [2.13].

Selected material properties are also provided in Appendix 2.12.5, "Selected Material Properties References."

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a. *FR-3700 resin is capable of producing foam with a variety of parameters, specified by contract, and verified by measurement during manufacturing.*

Table 2-9. Stainless Steel Mechanical Properties (Reference [2.5])

Temperature (°F)	Module of Elasticity[a], E (10^6 psi)	Poisson's Ratio	Coefficient of Thermal Expansion[b], α (10^{-6} in/in/°F)	Density, ρ (lbm/in^3)	Ultimate Tensile Stress[c], S_u (ksi)	Yield Stress[d], S_y (ksi)	Design Stress Intensity[e], S_m (ksi)
-20 to 100	28.3	0.30	8.6	0.29	70.0	30.0	20.0
150	–		8.8		–	26.7	–
200	27.6		8.9		66.3	25.0	20.0
250	–		9.1		–	23.6	–
300	27.0		9.2		61.8	22.4	20.0
400	26.5		9.5		59.7	20.7	18.7
500	25.8		9.7		59.2	19.4	17.4
600	25.3		9.8		59.2	18.4	16.4
650	–		9.9		59.2	18.0	16.1
700	24.8		10.0		59.2	17.6	16.0
750	–		10.0		59.0	17.2	15.5
800	24.1		10.1		58.6	16.9	15.1
850	–		10.1		57.9	16.5	–
900	23.5		10.2		56.8	16.2	–
950	–		10.3		55.4	15.9	–
1,000	22.8		10.3		53.6	15.5	–

a. *Module of Elasticity, Material Group G, Table TM-1, page 671.*

b. *Coefficient of Thermal Expansion for Austenitic Stainless Steels (Group 3), Table TE-1, page 651.*

c. *Ultimate Tensile Stress, for SA-182, Grade F304, Table U, line 32, page 450.*

d. *Yield Stress for SA-182, Grade F304, Table Y-1, line 37, page 552.*

e. *Design Stress Intensity for SA-351, Grade CF8, Table 2A, line 26, page 312.*

Table 2-10. Cask Lid Attachment Bolt Mechanical Properties (Reference [2.5])

Temperature (°F)	Module of Elasticity[a], E (10^6 psi)	Poisson's Ratio	Coefficient of Thermal Expansion[b], α (10^{-6} in/in/°F)	Density, ρ (lbm/in^3)	Ultimate Tensile Stress[c], S_u (ksi)	Yield Stress[c], S_y (ksi)	Design Stress Intensity[d], S_m (ksi)
-100	29.9	0.31	–	0.297	–	–	–
70	29.0		7.0		185.0	150.0	50.0
200	28.3		7.2		177.6	144.0	48.0
300	27.8		7.3		173.5	140.7	46.9
400	27.6		7.5		170.6	138.3	46.1
500	27.1		7.6		168.7	136.8	45.6
600	26.8		7.7		166.8	135.3	45.1
700	26.4		7.8		165.8	134.4	44.8
800	25.8		7.9		164.3	133.2	44.0

a. *"Module of Elasticity, Material Group B Nickel Steel," Table TM-4, page 675, ASME Code, Section II, Part D – Properties (Reference [2.5]).*

b. *"Coefficient of Thermal Expansion for Material N07718," Table TE-4, page 658, ASME Code, Section II, Part D – Properties (Reference [2.5]).*

c. *Ultimate Tensile Stress and Yield Stress calculated from the Stress Intensity values, provided in Table 4, Line 33, page 416, ASME Code, Section II, Part D – Properties (Reference [2.5]).*

$$\frac{S_{m\ temp}}{S_{m\ 70°F}}(S_{u\ 70°F}) = S_{u\ temp}$$

d. *Stress Intensity values for Material N07718, provided in Table 4, Line 33, page 416, ASME Code, Section II, Part D – Properties (Reference [2.5]).*

Table 2-11. Tungsten Alloy Material Mechanical Properties

Module of Elasticity[a], E (10^6 psi)	Poisson's Ratio[b]	Coefficient of Thermal Expansion[c], α (10^{-6} in/in/°F)	Density[a], ρ (lbm/in^3)	Yield Stress[d], S_y (ksi)
50.0	0.29	2.5	0.655	75.0

a. *"Grade Specification Conformance" Table, page 16 (Reference* **[2.15]***).*

b. *Chapter 6, Table 6.1, page 274 (Reference* **[2.18]**).

c. *Reference* **[2.17]**; $\alpha = 4.6 \times 10^{-6}$ *in/in/°C * 5/9 =* 2.5×10^{-6} *in/in/°F.*

d. *"Typical Densalloy Properties," page 7 (Reference* **[2.15]***).*

Table 2-12. Carbon Steel (SA-105) Material Mechanical Properties (Reference [2.5])

Temperature (°F)	Module of Elasticity[a], E (10^6 psi)	Poisson's Ratio	Coefficient of Thermal Expansion[b], α (10^{-6} in/in/°F)	Density, ρ (lbm/in^3)	Ultimate Tensile Stress[c], S_u (ksi)	Yield Stress[d], S_y (ksi)	Design Stress Intensity[e], S_m (ksi)
-100	30.2	0.30	–	0.283	–	–	–
70	29.5		6.4		70.0	36.0	23.3
200	28.8		6.7		70.0	33.0	21.9
250	–		6.8		70.0	32.4	–
300	28.3		6.9		70.0	31.8	21.3
400	27.7		7.1		70.0	30.8	20.6
500	27.3		7.3		70.0	29.3	19.4
600	26.7		7.4		70.0	27.6	17.8
650	–		7.5		70.0	26.7	17.4
700	25.5		7.6		70.0	25.8	17.3
750	–		7.7		69.1	24.9	–
800	24.2		7.8		64.3	24.1	–
850	–		7.9		58.6	23.4	–
900	22.4		7.9		52.3	22.8	–
950	–		8.0		45.9	22.1	–
1,000	20.4		8.1		40.4	21.4	–

a. *"Module of Elasticity, Carbon Steel with C ≤ 0.30%," Table TM-1, page 671 (Reference* **[2.5]***).*

b. *"Coefficient of Thermal Expansion for Carbon and Low Alloy Steel (Group 1)," Table TE-1, page 648 (Reference* **[2.5]***).*

c. *"Ultimate Tensile Stress, for SA-105, Forging," Table U, line 23, page 424 (Reference* **[2.5]***).*

d. *"Yield Stress for SA-105, Forging," Table Y-1, line 26, page 500 (Reference* **[2.5]***).*

e. *"Design Stress Intensity for SA-105, Forging," Table 2A, line 35, page 260 (Reference* **[2.5]***).*

Table 2-13. Trunnion Screw Mechanical Properties (Reference [2.5]) – All Models

Model	Screw Size / ASME Standard	Stress Area		Minimum Tensile Strength[a]		Yield Strength[a]	
		cm^2	in^2	kPa	ksi	kPa	ksi
AOS-025	1/4-28 UNF-2A / ASME SA-193, Grade B6 UNS S41000	0.235	0.036	7.58E+05	110	5.86E+05	85
AOS-050	3/8-24 UNF-2A / ASME SA-193, Grade B6 UNS S41000	0.566	0.088	7.58E+05	110	5.86E+05	85
AOS-100	3/4-16 UNF-2A / ASME SA-193, Grade B6 UNS S41000	2.406	0.373	7.58E+05	110	5.86E+05	85

a. Table 4, line 26, page 413 (Reference **[2.5]***).*

This SAR contains two sets of material properties for the FR-3700 foam materials. One set is presented in Table 2-14 and Table 2-15 **[2.13]**, and the second set is presented in Appendix 2.12.5 **[2.19]**. The foam analyses, free drops, were performed using the properties values of the foam properties presented in Appendix 2.12.5. When the new data was published in 2005, AOS assessed the difference in the data between the two revisions of the document, and after consulting with the manufacturer, it was concluded not to revise the analytical work for the new values, but rather address this issue at the time of manufacturing and to provide verification by the testing program imposed by the purchase order. To ensure that the required crush strength limits are met during fabrication by the current foam formulation, AOS has reduced the prescribed foam density provided in Revision E of this SAR; therefore, instead of using foam densities of 20 pcf, 10 pcf, and 12 pcf for the Model AOS-025, AOS-050, and AOS-100, respectively, the new densities are 18 pcf, 8 pcf, and 11 pcf, respectively. In addition, AOS has assigned the values presented in Appendix 2.12.5 as the maximum value limits, which represent a tolerance of +15%. The current foam formulation **[2.13]** has a higher crush strength than the 2003 version **[2.19]** of the model.

Table 2-14 and Table 2-15 present the properties for the new density values.

Table 2-14. LAST-A-FOAM FR-3700 Series Foam Dynamic Strength, psi, Parallel to Direction of Rise – All Models[a]

AOS-025 (FR-3718 18-pcf. Foam)								
Temp (°F)	Strain (in./in.)							
	10%	20%	30%	40%	50%	60%	65%	70%
-20	2,215	2,077	2,112	2,268	2,647	3,418	4,258	4,694
75	1,624	1,558	1,603	1,730	2,026	2,640	3,334	3,761
100	1,390	1,355	1,412	1,522	1,805	2,380	3,004	3,653
140	1,157	1,151	1,204	1,297	1,523	2,016	2,540	3,073
180	991	979	1,044	1,123	1,322	1,729	2,142	2,599
220	892	869	917	985	1,140	1,440	1,810	2,194
260	630	619	661	725	837	1,151	1,445	1,824
AOS-050 (FR-3708 8-pcf. Foam)								
Temp (°F)	Strain (in./in.)							
	10%	20%	30%	40%	50%	60%	65%	70%
-20	465	472	464	455	496	615	776	892
75	357	346	352	353	394	483	603	660
100	309	305	314	314	355	440	549	634
140	258	259	268	271	308	378	477	558
180	229	228	237	240	273	330	411	475
220	214	207	212	215	242	287	357	411
260	157	152	163	165	190	239	297	353
AOS-100 (FR-3711 11-pcf. Foam)								
Temp (°F)	Strain (in./in.)							
	10%	20%	30%	40%	50%	60%	65%	70%
-20	851	797	798	814	929	1,169	1,525	1,633
75	624	598	606	621	711	904	1,194	1,308
100	534	520	534	546	633	815	1,076	1,271
140	444	442	455	465	535	690	910	1,069
180	381	375	395	403	464	591	767	904
220	343	333	346	353	400	493	648	763
260	242	238	250	260	294	394	517	634

a. *Information provided in Reference* [2.13].

Table 2-15. LAST-A-FOAM FR-3700 Series Foam Dynamic Strength, psi, Perpendicular to Direction of Rise – All Models[a]

AOS-025 (FR-3718 18-pcf. Foam)								
Temp (°F)	Strain (in./in.)							
	10%	20%	30%	40%	50%	60%	65%	70%
-20	2,183	2,063	2,097	2,283	2,617	3,372	4,104	4,347
75	1,614	1,548	1,591	1,715	2,018	2,646	3,316	3,739
100	1,348	1,314	1,369	1,509	1,758	2,333	2,922	3,380
140	1,149	1,127	1,179	1,302	1,517	2,020	2,527	2,983
180	985	972	1,021	1,113	1,317	1,732	2,164	2,547
220	838	817	862	942	1,095	1,443	1,801	2,145
260	610	600	640	701	834	1,074	1,338	1,628
AOS-050 (FR-3708 8-pcf. Foam)								
Temp (°F)	Strain (in./in.)							
	10%	20%	30%	40%	50%	60%	65%	70%
-20	470	452	449	456	504	633	800	892
75	353	334	335	345	383	478	599	664
100	298	290	295	307	345	436	545	613
140	262	257	262	273	303	379	474	536
180	219	220	229	238	265	336	415	472
220	205	196	202	210	231	289	355	407
260	155	150	158	165	185	232	289	329
AOS-100 (FR-3711 11-pcf. Foam)								
Temp (°F)	Strain (in./in.)							
	10%	20%	30%	40%	50%	60%	65%	70%
-20	832	781	783	811	912	1,148	1,497	1,515
75	615	586	594	609	703	901	1,210	1,304
100	514	497	512	536	612	795	1,066	1,178
140	438	427	441	463	529	688	922	1,040
180	375	368	381	396	459	590	790	888
220	319	309	322	335	382	492	657	748
260	233	227	239	249	290	366	488	568

a. Information provided in Reference [2.13].

2.2.2 Chemical, Galvanic, and/or Other Reactions

Galvanic reaction occurs when two dissimilar metals with different potentials are in contact in the presence of an electrolyte. Removing or reducing these factors can decrease the possible interactions leading to a galvanic reaction. Avoiding joints using dissimilar metals, selecting joint materials that have lower potential differences, and/or eliminating the electrolyte can prevent galvanic interaction.

Table 2-16 lists the six (6) permanent dissimilar metal joints that are used within the cask component of the AOS Transport Packaging System. The joints described in Table 2-16 are shown in the certification drawings for each cask, listed in Table 1-5, "AOS Transport Packaging System Certification Drawing List – All Models."

The materials involved in joints 1, 2, 4, 5, and 6 are 300 series stainless steel and tungsten alloy or carbon steel. For joint 3, the materials are 300 series stainless steel and copper alloy. These joints are all located within the cask component of the AOS Transport Packaging System. The potential difference between stainless steel and tungsten alloy and stainless steel and copper is sufficiently low, as to not produce galvanic effects. (Refer to Reference **[2.12]** for potential difference information for these materials.) For the stainless steel and carbon steel joint, the carbon steel is electroless nickel-plated, with a minimum thickness of 21 microns (0.00083 in.) to reduce the different potentials.

Table 2-17 lists the four (4) temporary joints, where dissimilar metals are connected. In the case of these temporary joints, it can be said that their duration as a jointed unit, service life of their components, and continuous operational inspection preclude galvanic corrosion from occurring or going undetected.

Table 2-16. Permanent Dissimilar Metal Joints within Cask Component

Joint Number	Joint Description
1	Outside surfaces of the cask cavity shell, and shielding material inside diameter surfaces
2	Inside diameter surface of the cask outer shell, and outside diameter surface of the shielding material
3	Two (2) flat contact surfaces between the port and cask vent port plugs, and recessed cavity within the cask outer shell
4	Cask lid plug shell inside surface, and cask end plug
5	Cask cavity end outside recess inner surface, and cavity end plug
6	Bottom plate, and cask end plug

Table 2-17. Temporary Dissimilar Metal Joints within Cask Component

Joint Number	Joint Description
a	Cask lid closure joint
b	Radioactive content against its holders
c	Content holder against the shoring devices
d	Content holder or shoring device against the cask cavity surfaces

The cask's fabrication process excludes any moisture (electrolyte) from being present within the cask. During shipment (jointed unit), the cavity must be dry, regardless of how it was loaded. If the cavity was loaded in water, the cavity must be vacuum-dried. Following this procedure eliminates the presence of the electrolyte, one of the factors for galvanic interaction. Refer to Paragraph 7.1.3.1, "Securing the Cask Lid," for the vacuum drying procedure.

Possible galvanic interaction is eliminated by controlling the potential difference for both permanent and temporary dissimilar metal joints, and by preventing the presence of an electrolyte, during fabrication and shipment.

2.2.3 Effects of Radiation on Materials

The AOS Transport Packaging System's cask component is comprised of the following construction materials:

- 300 series stainless steel (SS300), tungsten alloy or low carbon steel alloy for the cask body, cask lid, and cask lid plug components
- Nickel alloy for the cask lid attachment bolts
- Silver, nickel-chromium alloy, and stainless steel for the cask lid metallic seal
- Silicone material for the O-Rings used in the cask lid elastomeric seal and port cover

Of all these materials, the one most affected by radiation is the silicone material. However, these port cover O-Ring components are replaced after each use, thus eliminating the cumulative effect of radiation.

The impact limiters are constructed of 300 series stainless steel and polyurethane foam materials. The effect of radiation upon the stainless steel material is minimal. Also, according the manufacturer's data for the polyurethane foam (Reference **[2.13]**), its material does not incur any physical property changes when subjected to a maximum cumulative dose of 2×10^8 rads. Therefore, the impact limiters are not affected by radiation.

2.3 FABRICATION AND EXAMINATION

2.3.1 Fabrication

This subsection describes the fabrication processes used for the AOS Transport Packaging System, such as fitting, aligning, welding and brazing, heat treatment, and foam pouring. Table 2-8 provides a breakdown of the AOS Transport Packaging System by category of functionally, the corresponding applicable Code and/or Standard, and the Safety Classification. The information provided in Table 2-8 follows the guidelines presented in *NUREG/CR-3854, Fabrication Criteria for Shipping Containers*, and *NUREG/CR-3019, Recommended Welding Criteria For Use in the Fabrication of Shipping Containers for Radioactive Materials* (References **[2.24]** and **[2.25]**, respectively).

Table 2-18 lists the material selection specifications for the major components used in the AOS Transport Packaging System.

Table 2-18. Material Selection of Major AOS Transport Packaging System Components (Typical)

Component	Material Selection	First Alternate Material	Second Alternate Material	Certification Drawing[a]	Item No.
Cask					
Cask Outer Shell	ASME SA-182/ ASTM A182, Grade F304 or F316	ASME SA-351/ ASTM A351, Grade CF 8	ASME SA-451/ ASTM A451, Grade CPF 8	105E9712	1
Cask Lid	ASME SA-240/ ASTM A240, Type 304 or 316	ASME SA-182/ ASTM A182, Grade F304 or F316	–		2
Cask Cavity Shell	ASME SA-182/ ASTM A182, Grade F304 or F316	ASME SA-351/ ASTM A351, Grade CF 8	ASME SA-451/ ASTM A451, Grade CPF 8		3
Shielding Material	Tungsten ATI Densalloy SD180 per AMS-T-21014, Class 3	Carbon Steel Forging per ASME SA-105/ ASTM A105	–		4, 8, 12
Trunnion	ASME SA-479/ ASTM A479, Type 304 or 316	–	–		5
Cask Lid Plug	ASME SA-240/ ASTM A240, Type 304 or 316	ASME SA-182/ ASTM A182, Grade F304 or F316	–		6
Cover Plate	ASME SA-240/ ASTM A240, Type 304 or 316	ASME SA-182/ ASTM A182, Grade F304 or F316	–		7
Cask Lid Attachment Bolts	ASME SB-637, UNS N07718	–	–		15
Bottom Plate	ASME SA-240/ ASTM A240, Type 304 or 316	ASME SA-182/ ASTM A182, Grade F304 or F316	–		16
Trunnion Screws	ASME SA-193, Grade B6 UNS S41000	–	–		24
Port Plug	ASME SA-182/ ASTM A182, Grade F304 or F316	ASME SA-479/ ASTM A479, Type 304 or 316	–		32
Impact Limiter					
Shell and Ribs	ASME SA-240/ ASTM A240, Type 304 or 316	–	–	105E9713	1 – 11
Foam	Polyurethane Foam (General Plastics FR-3700 Series Foams)	–	–		12

a. *The Model AOS-100A certification drawings are used for the* ***Item No.*** *(column) references for completeness of the table information.*

2.3.1.1 Materials

- Materials are procured by the Fabricator from material manufacturers or suppliers that have been audited and approved by the Fabricator, under their approved Quality Plan.
- Materials are in accordance with the applicable rules of ASME Section II Parts A, B, and C, as applicable; ASME Section III NCA-3800; Heat treatment of new material is controlled by the material procurement procedure and Quality Plan.
- Material purchased requiring upgrading (ASME) or commercial grade dedication uses procedures and/or checklists approved in accordance with the Fabricator's approved Quality Plan.
- Material certification is approved prior to final acceptance of the material.
- Deviations and non-conformances relating to the material are dispositioned by a written procedure as specified in the Fabricator's Quality Plan, prior to material acceptance.

2.3.1.2 Fabrication

- Fabrication is conducted by the Fabricator, in accordance with established, written process documentation (travelers, bills of material, weld maps, inspection and test reports), and using written procedures for processes.
- Process documentation provides for the identification and control of all materials to be used in the fabrication process of components and assembly. Material is identified and recorded on the appropriate process documents. The process documentation provides for "hold points," to allow for critical verifications by the purchaser.

2.3.1.3 Forming

- Forming has limited use in the fabrication of the AOS Transport Packaging System. It may be used in producing the impact limiter heads and shells.

2.3.1.4 Machining

- Forgings, plates, and round bars (purchased in the "stock-on" condition) are machined to established dimensional configurations, as identified on the drawings, and delineated by the Fabricator's process documentation. The dimensional configurations established allow for fitting and alignment of the components that are part of components, sub-assemblies, and assemblies.
- Welded components are final machined to established dimensional configurations, as identified on the drawings, and delineated by the Fabricator's process documentation.
- Those components that are not a part of the assembly (cask lid, trunnions, and trunnion details) are machined to final configuration as identified on the drawings, and delineated by the Fabricator's process documentation.

2.3.1.5 Fitting and Assembling

- Components of the AOS Transport Packaging System are fitted and assembled in accordance with the Fabricator's process documentation. Recording of the completion of work is maintained in the process documents.
- Alignment of sections to be joined by welding is controlled in accordance with the Fabricator's process documentation and the applicable drawings.

2.3.1.6 Welding

- These welding processes can be used in the fabrication of the AOS Transport Packaging System – Shielded Metal Arc Welding (SMAW), Flux Cored Arc Welding (FCAW), Gas Tungsten Arc Welding (GTAW), Gas Metal Arc Welding (GMAW) Submerged Arc Welding (SAW) or Plasma-Transferred Arc Welding (PTAW). Additional American Welding Society (AWS) welding processes can also be used.
- Welding Procedure Specifications (WPSs) are in accordance with ASME Section IX requirements, and supplemented as required by ASME Section III NF/NG-4330.
- Qualified welders assigned by the Fabricator must conduct all welding activities.
- Welder Qualification records are in accordance with ASME B&PV Code Section III NF/NG-4320, and are on file at the Fabricator's location.

2.3.1.7 Heat Treating

- There are no heat treating requirements for the AOS Transport Packaging System, with the exception of heat treatment conducted, where required, by applicable material specifications.

2.3.2 Examination

Table 2-19 summarizes the AOS Transport Packaging System examination program. Additional detailed information is provided in Chapter 8, "Acceptance Tests and Maintenance Program."

Table 2-19. Examination Program Summary

Test Category	Test Type	Reference	Test Description
Materials			
Stainless Steel	Certified Material Test Report	ASME Code, Section II, Part A, and applicable requirements of NX-2500, Section III.	Series of chemical and mechanical tests to determine conformance with material specification.
Tungsten Alloy	Density Verification	Straight Beam method per NG-2532.1, Section III, Division 1, 2001 Edition with 2003 Addendum.	One UT examination of the material surfaces and calculating the resulting component density by weighing and dimensionally inspecting the component, to determine its volume.
Foam	Formulation Verification	Table 8-5, "LAST-A-FOAM FR-3700 Series Foams – Testing Program."	Series of tests to establish the material characteristics baseline.
Fabrication			
Component	Adherence to Drawing	Certification Drawings. Refer to Table 1-5, "AOS Transport Packaging System Certification Drawing List – All Models."	Visual and Dimensional inspections.
Sub-assembly			
Assembly	Pressure and Containment	ASME Code, Section V, and applicable requirements of NB-6000, Section III.	Hydrostatic and He Leak test.
Weldment	NDE	ASME Code, Section V, and applicable requirements of NX-5000, Section III.	Visual, Penetrant, and Ultrasonic tests (VT, PT, and UT, respectively).

2.4 GENERAL REQUIREMENTS FOR ALL PACKAGES

2.4.1 Minimum Package Size

All AOS Transport Packaging System model dimensions are greater than 10 cm (4 in.), and therefore exceed minimum package size requirements.

2.4.2 Tamper-Indicating Feature

A tamper-indication feature, installed across the impact limiter joint section, provides evidence of unauthorized tampering. With the package assembled for transportation and the impact limiter installed, there are no additional covers, ports, nor other accesses that must be closed during Normal conditions of transport. Refer to Paragraph 7.1.3.4, "Preparing the Cask for Transport of Radioactive Material," for further details.

2.4.3 Positive Closure

The AOS Transport Packaging System models are used for shipping radioactive materials within the cask component. The first level of closure of the cask cavity is provided by the cask lid seal joint. The cask cavity shell consists of two SS300 series forgings, machined to form and joined together by a full-penetration weld. The cask lid seal joint consists of the cask lid, a cask lid seal, and a series of cask lid attachment bolts. The bolts are tightened to a prescribed torque value. There are two (2) other penetration points into the cavity. The port plugs are threaded into the cask cavity and welded onto the outside to the cask outer shell. Copper seals, located at both ends of the port plugs, ensure the leak tightness of these joints. The port plug conduits are closed and sealed by pipe plugs and straight thread caps with silicone O-Rings.

2.5 LIFTING AND TIE-DOWN STANDARDS FOR ALL PACKAGES

The following information is presented:

- Lifting Devices
- Tie-Down Devices
- Other Devices

2.5.1 Lifting Devices

10 CFR 71.45(a) **[2.1]** requires that lifting devices that are a structural part of the transport package must be capable of supporting three times the weight (3 W) of the loaded package, without generating stress in any material of the package in excess of its yield stress.

Figure 2-13 presents a cross-section of the trunnion area, as well as the force diagram associated with the lifting loads. The dimensions for the figure are listed in Table 2-20.

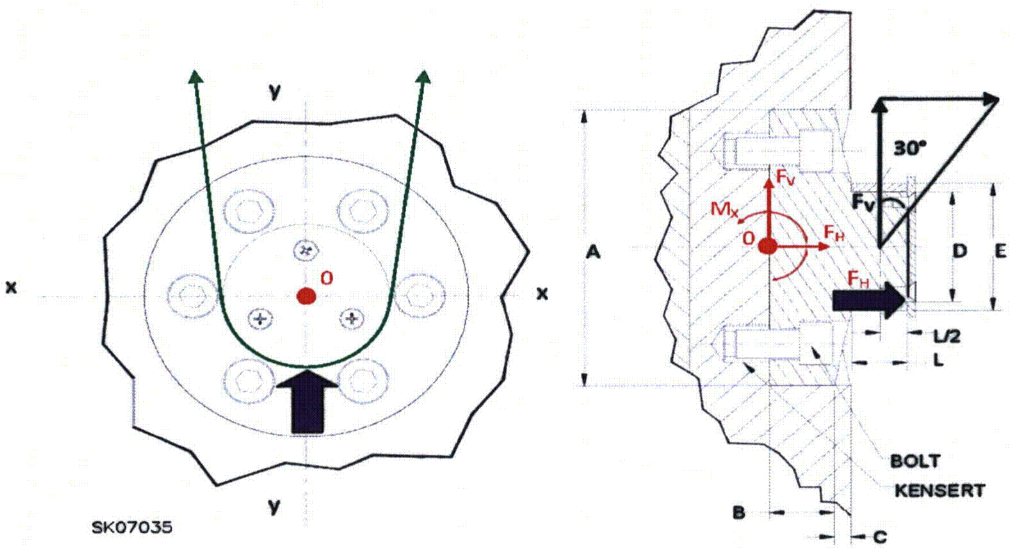


Figure 2-13. Trunnion Area Cross-Section and Force Diagram Associated with Lifting Loads

2.5.1.1 Cask Lifting Analysis – Trunnion Bolting Evaluation

The vertical force, F_V, applied to each trunnion is defined as:

$$F_V = (DLF * 1.0 * \text{package weight}) / 2$$

where:

DLF = Dynamic Load Factor, 1.2

The horizontal force, F_h, is located at the bottom of the trunnion, and is defined as:

$$F_H = F_V * \tan 30°$$

The effects of forces F_V and F_H are transferred from their location at the bottom of the trunnion to the bolt centroid, located within the interface of the trunnion and cask. The trunnion design is made such that the vertical force, F_V, is reacted to by the cask in bearing and does not load the bolts in shear.

Moment about the bolt centroid x-axis is:

$$M_x = F_V * (B + C + L/2) + F_H * E/2$$

Tensile force in the bolt furthest away from the bolt centroid about the x-axis due to moment, and assumes each bolt area is equal to 1.0:

$$F_b = (M_x * C_L) / I_{x\text{-}x}$$

where:

$$I_{x\text{-}x} = \Sigma (r_y)^2$$

Tensile force in each bolt due to horizontal force is:

$$F_t = F_H / 6$$

The resulting load on the bolt is (from Reference **[2.28]**):

$$F_B = (k_b / (k_b + k_m)) * P + F_{preload}$$

where:

k_b	=	Bolt stiffness	=	$\Pi * D^2_{nominal} * E_{bolt} / (4 * l)$
k_m	=	Member stiffness	=	$2 * \Pi * D^2_{nominal} * E_{member} / l$
P	=	Maximum total load on the bolted assembly	=	$F_b + F_t$
$F_{preload}$	=	Pre-torque / (0.2 * $D_{nominal}$)		

Maximum total bolt tensile stress is:

$$S_T = F_b / A_{tensile}$$

Factor of safety is defined as:

$$FS = S_y / S_T$$

Table 2-20. Lifting Load Analysis – All Models

Item	Units		Model					
			AOS-025		AOS-050		AOS-100	
			Metric	English	Metric	English	Metric	English
Weight	kg	lbs.	76	168	536	1,181	4,314	9,510
A	cm	in.	4.14	1.63	8.26	3.25	16.51	6.50
B	cm	in.	0.84	0.33	1.65	0.65	3.30	1.30
C	cm	in.	0.19	0.08	0.41	0.16	0.84	0.33
D	cm	in.	1.65	0.65	3.30	1.30	6.60	2.60
E	cm	in.	1.91	0.75	3.81	1.50	7.65	3.01
L	cm	in.	0.71	0.28	1.45	0.57	2.69	1.06
1/2L	cm	in.	0.36	0.14	0.72	0.29	1.35	0.53
F_T	N	lbf.	518	116	3,640	818	29,308	6,589
F_H	N	lbf.	259	58	1,820	409	14,654	3,294
F_V	N	lbf.	448	101	3,152	709	25,382	5,706
Bolt Size			1/4-28 UNF - 2A × 0.5L		3/8 - 24 UNF - 2A × 0.75L		3/4 - 16 UNF- 2A × 1.50L	
Material			SA 193 Grade B6		SA 193 Grade B6		SA 193 Grade B6	
Pre-Torque	Nm	lbf-ft.	5.42	4	16.27	12	135.58	100
Bolt Circle	cm	in.	2.90	1.14	5.77	2.27	10.80	4.25
S_u	MPa	ksi	758	110	758	110	758	110
S_y	Pa	psi	5.86E+08	8.50E+04	5.86E+08	8.50E+04	5.86E+08	8.50E+04
Quantity			6		6		6	
Keensert			KNH 428J		KNH 624J		KNH 1216J	
			1/4-28 UNF - 3B × 0.37		3/8-24 UNF - 3B × 0.50		3/4-16 UNF - 3B × 1.12	
$D_{nominal}$	cm	in.	0.64	0.25	0.95	0.38	1.91	0.75
$A_{tensile}$	cm^2	in^2	0.23	0.036	0.57	0.088	2.41	0.373
M_x	Nm	lbf-in.	9	77	122	1,083	1,953	17,283
C_L	cm	in.	1.25	0.49	2.50	0.98	4.67	1.84
$I_{x\text{-}x \text{ per unit area}}$ [a]	cm^2	in^2	6.29E+00	9.75E-01	2.49E+01	3.86E+00	8.74E+01	1.35E+01
F_b	N	lbf.	1.73E+02	3.89E+01	1.22E+03	2.75E+02	1.04E+04	2.35E+03
F_t	N	lbf.	4.31E+01	9.70E+00	3.03E+02	6.82E+01	2.44E+03	5.49E+02

Table 2-20. Lifting Load Analysis – All Models (Continued)

Item	Units		Model					
			AOS-025		AOS-050		AOS-100	
			Metric	English	Metric	English	Metric	English
E_{bolt}	Pa	psi	2.01E+11	2.92E+07	2.01E+11	2.92E+07	2.01E+11	2.92E+07
E_{member}	Pa	psi	1.95E+11	2.83E+07	1.95E+11	2.83E+07	1.95E+11	2.83E+07
l	cm	in.	9.40E-01	3.70E-01	1.27E+00	5.00E-01	2.84E+00	1.12E+00
k_b	N/m	lbf/in.	6.78E+08	3.87E+06	1.13E+09	6.45E+06	2.02E+09	1.15E+07
k_m	N/m	lbf/in.	5.26E+09	3.00E+07	8.76E+09	5.00E+07	1.56E+10	8.93E+07
$k_b / (k_b + k_m)$			1.14E-01	1.14E-01	1.14E-01	1.14E-01	1.14E-01	1.14E-01
0.373P	N	lbf.	2.16E+02	4.86E+01	1.53E+03	3.44E+02	1.29E+04	2.90E+03
$F_{preload}$	N	lbf.	4.27E+03	9.60E+02	8.54E+03	1.92E+03	3.56E+04	8.00E+03
F_B	N	lbf.	4.29E+03	9.66E+02	8.72E+03	1.96E+03	3.71E+04	8.33E+03
S_T	Pa	psi	1.83E+08	2.65E+04	1.54E+08	2.23E+04	1.54E+08	2.23E+04
$FS = S_y / S_T$			3.20	3.20	3.81	3.81	3.81	3.81

a. *This method is shown in Equation 6-25, Section 6.12 of Reference* **[2.28]**.

Typically in a bolting joint design, a preload torque is assigned to the bolt(s). This is to ensure that the joint will have the capability to react to the applied working load. Therefore, the working load in the bolt must be within the magnitude of, or less than, the resultant load from the preload. In the analysis presented in Table 2-20, the resultant bolt load due to the preload ($F_{preload}$) is 8.00E+03 lbf., while the working load is 330 lbf.[a] Hence, the preload value of 100 lbf-ft is an adequate value applied to the Model AOS-100 trunnion design. In addition to applying a preload, the bolts are coated with anti-vibration compound prior to installation, to enhance the bolted joint's efficiency.

a. *The working load value of 330 lbf. is obtained by subtracting the preload force ($F_{preload}$) value of 8.00E+03 lbf. from the total force (F_b) of 8.33E+03 lbf* **[2.28]**.

2.5.1.2 Cask Socket Bearing Stress Check

The bearing area, as illustrated in Figure 2-13, is:

$$\text{Area} = A * B$$

where:

A and B are provided in Table 2-20.

The ultimate stress for the cask material is 70 ksi.

Margin of safety is defined as:

$$MS = (S_u / S_t) - 1.0$$

Table 2-21 lists the average bearing stress.

Table 2-21. Average Bearing Stress – All Models

Model	Force, F_V (lbf.)	Area (in^2)	Stress (psi)	Margin
AOS-025	101	0.54	559	124.2
AOS-050	709	2.11	1,008	68.4
AOS-100	5,706	8.45	2,026	33.6

2.5.1.3 Shear Stress at Trunnion Neck

The maximum shear stress for a circular section is:

$$S_V = (4 * F_V) / (3 * A)$$

Yield stress in shear is 0.58 times the tensile yield stress. Then, S_y = 17.4 ksi.

Margin of safety is defined as:

$$MS = (S_y / S_t) - 1.0$$

Table 2-22 lists the maximum shear stresses.

Lifting device margins of safety, in all transport package models, are greater than 3.0. The neck of the trunnion has the lowest margin of safety. Should failure occur in the trunnion neck, no damage to the transport package will occur.

Table 2-22. Maximum Shear Stress, S_V – All Models

Model	Force, F_V (lbf.)	Area (in^2)	Stress (psi)	Margin
AOS-025	101	0.33	1,220	13.26
AOS-050	709	1.33	2,131	7.17
AOS-100	5,706	5.31	4,298	3.05

2.5.2 Tie-Down Devices

The transport package contents and shield material are sealed within the cask. The cask is placed within the impact limiter, which is then placed upon the tie-down hardware. (Refer to Figure 1-1 through Figure 1-3 for an isometric view of each transport package model.)

10 CFR 71.45(b) **[2.1]** requires that, if there is a system of tie-down devices that is a structural part of the transport package, the system must be capable of withstanding a static force applied to the center of gravity of the package with the following:

1. Vertical component of two times the weight (2 W) of the package and its contents;
2. Horizontal component along the direction of travel of ten times the weight (10 W) of the package and its contents; and
3. Horizontal component in the transverse direction of five times the weight (5 W) of the package and its contents.

These applied loads do not generate stresses in any package material in excess of the yield strength of that material, as discussed in the following tables:

- Table 2-217, "Load Case 221, Forward 10g Vibration Inertia Load, Normal Conditions of Transport – Models AOS-100A and AOS-100A-S"
- Table 2-218, "Load Case 222, Lateral 5g Vibration Inertia Load, Normal Conditions of Transport – Models AOS-100A and AOS-100A-S"
- Table 2-219, "Load Case 223, Vertical 2g Vibration Inertia Load, Normal Conditions of Transport – Models AOS-100A and AOS-100A-S"

Detailed analyses of tie-down devices are presented in Appendix 2.12.12.

2.5.3 Other Devices

The following information demonstrates the analysis of other individual devices, and demonstrates conformance to or with *10 CFR 71.45(b)* **[2.1]**:

- Analyses of Shipping Cage and Shipping Cage Fasteners
  - Stress Analysis of Shipping Cages
  - Analysis of Shipping Cage Fasteners – Model AOS-025
  - Analysis of Shipping Cage Fasteners – Model AOS-050
  - Analysis of Shipping Cage Fasteners – Model AOS-100
- Analysis of Impact Limiter Mechanical Connectors
- Analyses of Shielding Devices
  - Stress Analysis of Axial Shield Plate – Model AOS-100
  - Stress Analysis of Cavity Liner – Model AOS-025

2.5.3.1 Analyses of Shipping Cage and Shipping Cage Fasteners

2.5.3.1.1 Stress Analysis of Shipping Cages

The combination of shipping cage wire mesh panels and angle x-section frame behaves as a Tension Field Beam. In Tension Field Beams, web panels are assumed to buckle upon load application, and shear forces, V, are transmitted by web tension stress, σ_t **[2.9]**. The wire mesh behaves as an ideal Tension Field web panel, because wire mesh can transmit only tension stress. Panel dimensions used in the analysis are larger than actual dimensions, to accommodate possible changes. Use of larger panel dimensions is conservative. Additionally, the shipping cage design used in the evaluation is a more simple design that the actual design, making the analysis conservative.

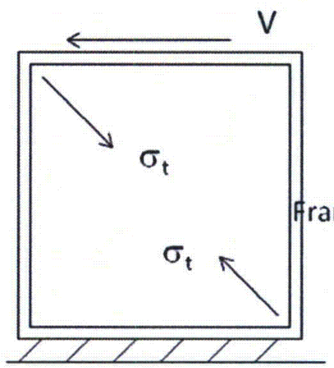


Figure 2-14. Mesh Diagonal Tension

The web thickness equivalent to the wire mesh is determined using Reference **[2.10]**. For the AOS Transport Packaging System, the shipping cage mesh size corresponds, approximately, to the 22 × 60 mm steel mesh in Reference **[2.10]**. From Reference **[2.10]**, this mesh weight is:

$$w = 3.69 \text{ kg/m}^2 = 0.00525 \text{ lb/in}^2$$

The equivalent web thickness for steel with density $\rho = 0.28$ lb/in^3 is then:

$$t_W = w / \rho = 0.00525 / 0.28 = 0.019 \text{ in.}$$

From Reference **[2.9]**, with f_t and f_s web tension and shear stress resultants, and α the web diagonal tension angle:

$$f_t = 2 * f_s / \sin 2\alpha$$

$$\alpha = 45°$$

$$f_t = 2 * f_s$$

Web strain energy due to tension stress, σ_t, is:

$$U = (1/2)\ (\sigma_t)^2\ (A_w * t_w) / E$$

where:

A_w = Web area

t_w = Web thickness

For square panels with side length L, and shear force V:

$$A = L^2$$

$$\sigma_t = f_t / t_w = 2f_s / t_w$$

$$f_s = V / L$$

$$U = 2V^2 / E * t_w$$

The maximum displacement, δ, is provided by:

$$\delta = \partial U / \partial V = 4\ V / E * t_w$$

For the equivalent web, $E = 10^7$ psi, and $t_w = 0.019$ inches.

Assuming shear force on each of two webs equals half (1/2) the total weight, W, under a 10 g acceleration:

$$V = 10\ W / 2 = 5\ W$$

The maximum axial stress in the frame members is:

$$\sigma_F = V * L / A_F * L = V / A_F$$

where, for the frame angles:

A_F = $1.5 * 1.5 * 0.19 = 0.4275\ in^2$

δ = Maximum shipping cage displacement

σ_t = Web diagonal tension stress

σ_F = Frame axial stress

MS = Margin of safety, $F_y / \sigma - 1$, $F_y = 20$ ksi

Calculated values for the shipping cage margins of safety are presented in Table 2-23, by model.

Table 2-23. Calculation of Shipping Cage Margins of Safety – All Models

Model	V (lb.)	δ (in.)	L (in.)	σ_t (ksi)	σ_F (ksi)	MS
AOS-025	144	0.030	18.0	0.84	0.34	> 10
AOS-050	696	0.147	36.0	2.04	1.63	8.8
AOS-100	2,169	0.457	72.0	3.17	5.07	2.9

2.5.3.1.2 Analysis of Shipping Cage Fasteners – Model AOS-025

Vertical Frame

$w = 0.1\ lb/in^3$

$W_1 = 4 * 18 * 1.5 * 1.5 * 0.19 * 0.1 = 3.1$ lbs.

$H_1 = 9.0$

Top Frame

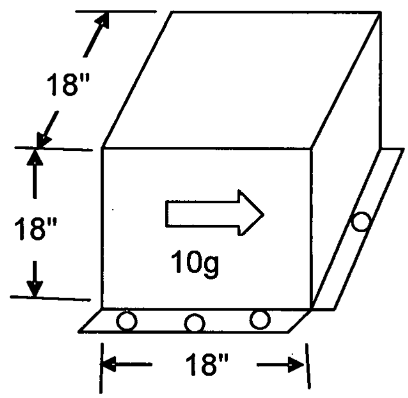
$W_2 = 4 * 18 * 1.5 * 1.5 * 0.19 * 0.1 = 3.1$ lbs.

$H_2 = 18.0$

Vertical Screens

$w = 2.0\ lb/ft^2$

$W_3 = 4 * 1.5 * 1.5 * 2 = 18.0$ lbs.



Top Screen

$w = 2.0\ lb/ft^2$

$W_4 = 1.5 * 1.5 * 2 = 4.5$ lbs.

Fastener Properties

8-9/16 bolts

$A_s = 0.1816$

$F_y = 20$ ksi

Maximum Inertia Force

$G = 10.0g$

Fastener Shear Stress

$V = W_1 + W_2 + W_3 + W_4 = 3.1 + 3.1 + 18.0 + 4.5 = 28.7$

$\tau = (G * V) / (8 * A_s) = (10 * 28.7) / (8 * 0.1816) = 198$ psi

Fastener Axial Stress

$M = (G\ (W_1 + W_3) * H_1) + (G\ (W_2 + W_4) * H_2)$

$= (10\ (3.1 + 18.0) * 9.0) + (10\ (3.1 + 4.5) * 18.0) = 3{,}258$

$L = 4.2$

$\sigma = M / (3 * L * A_s) = 3{,}258 / (3 * 4.2 * 0.1816) = 1{,}424$

Equivalent Stress

$f = \sqrt{(\sigma^2 + 3\tau^2)} = \sqrt{(1{,}424^2 + 198^2)} = 1{,}438$ psi

Margin of Safety

$MS = F_y / f - 1 = 20{,}000 / 1{,}438 - 1 = 12.9$

2.5.3.1.3 Analysis of Shipping Cage Fasteners – Model AOS-050

Vertical Frame

$w = 0.1\ lb/in^3$

$W_1 = 4 * 32 * 1.5 * 1.5 * 0.19 * 0.1 = 28.8$ lbs.

$H_1 = 16.0$

Top Frame

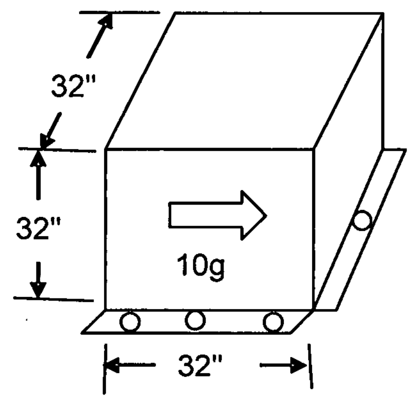
$W_2 = 4 * 36 * 1.5 * 1.5 * 0.19 * 0.1 = 32.4$ lbs.

$H_2 = 32.0$

Vertical Screens

$w = 2.0\ lb/ft^2$

$W_3 = 4 * 2.5 * 3.0 * 2 = 60.0$ lbs.



Top Screen

$w = 2.0\ lb/ft^2$

$W_4 = 3.0 * 3.0 * 2 = 18.0$ lbs.

Fastener Properties

8-1/2 in. bolts

$A = 0.137\ in^2$

8-9/16 bolts

$A_s = 0.1816$

$F_y = 20$ ksi

Maximum Inertia Force

$G = 10.0g$

Fastener Shear Stress

$V = W_1 + W_2 + W_3 + W_4 = 28.8 + 32.4 + 60.0 + 18.0 = 139.2$

$\tau = (G * V) / (8 * A_s) = (10 * 139.2) / (8 * 0.137) = 1{,}270$ psi

Fastener Axial Stress

$M = (G\ (W_1 + W_3) * H_1) + (G\ (W_2 + W_4) * H_2)$

$= (10\ (28.8 + 60) * 16.0) + (10\ (32.4 + 18) * 32.0) = 30{,}340$

$L = 30$

$\sigma = M / (3 * L * A_s) = 30{,}340 / (3 * 30.0 * 0.137) = 2{,}461$ psi

Equivalent Stress

$f = \sqrt{(\sigma^2 + 3\tau^2)} = \sqrt{(1.27^2 + 3 * 2.46^2)} = 4.45$ ksi

Margin of Safety

$MS = F_y / f - 1 = 20.0 / 4.45 - 1 = 3.49$

2.5.3.1.4 Analysis of Shipping Cage Fasteners – Model AOS-100

Vertical Frame

$w = 0.3\ lb/in^3$

$W_1 = 4 * 72 * 1.5 * 1.5 * 0.19 * 0.3 = 36.9$ lbs.

$H_1 = 36.0$

Top Frame

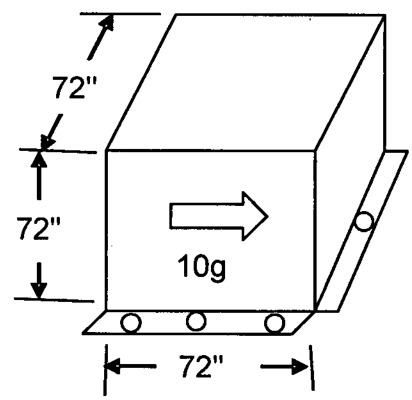
$W_2 = 4 * 72 * 1.5 * 1.5 * 0.19 * 0.3 = 36.9$ lbs.

$H_2 = 72.0$

Vertical Screens

$w = 2.0\ lb/ft^2$

$W_3 = 4 * 6.0 * 6.0 * 2 = 288.0$ lbs.



Top Screen

$w = 2.0\ lb/ft^2$

$W_4 = 6.0 * 6.0 * 2 = 72.0$ lbs.

Fastener Properties

16-1/2 in. bolts

$A = 0.137\ in^2$

$F_y = 20$ ksi

Maximum Inertia Force

$G = 10.0g$

Fastener Shear Stress

$V = W_1 + W_2 + W_3 + W_4 = 36.9 + 36.9 + 288 + 72.0 = 433.8$

$\tau = (G * V) / (16 * A) = (10 * 433.8) / (16 * 0.137) = 1.97$ ksi

Fastener Axial Stress (assume 4 fasteners in tension)

$M = (G (W_1 + W_3) * H_1) + (G (W_2 + W_4) * H_2)$

$= (10 (28.8 + 60) * 36.0) + (10 (32.4 + 18) * 72.0) = 57{,}917$

$L = 72$

$\sigma = M / (4 * L * A) = 57{,}917 / (4 * 72 * 0.137) = 1.47$ ksi

Equivalent Stress

$f = \sqrt{(\sigma^2 + 3\tau^2)} = \sqrt{(1.97^2 + 3 * 1.47^2)} = 2.46$ ksi

Margin of Safety

$MS = F_y / f - 1 = 20.0 / 2.46 - 1 = 7.13$

2.5.3.2 Analysis of Impact Limiter Mechanical Connectors

Maximum stress in the impact limiter mechanical connectors occurs under a Side Drop. Configuration of forces in a Side Drop are illustrated in Figure 2-15, where P is the impact force due to a 30-ft. drop. The mechanical connectors are loaded by the moment produced by the couple forces, P/2, and the offset distance, d.

While the impact load, P, is known, the offset distance, d, is indeterminate and depends upon the stiffness of the cask and impact limiter. The connector force is evaluated by an FEA analysis that takes cask and impact limiter stiffness into account. A displacement pattern simulating deformation due to a Side Drop is applied to the impact limiter, and reacted by fixing the cask. The maximum stressed mechanical connector and attached rib are included in the model, and the force in the connector is determined by the analysis.

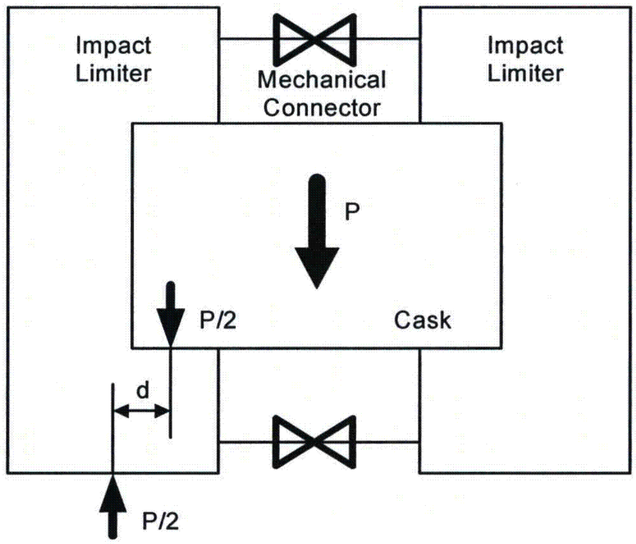


Figure 2-15. Side Drop Impact Forces

2.5.3.2.1 Description of FEA Models

The Model AOS-100 cask and impact limiter FEA model used in the analysis is illustrated in Figure 2-16. The FEA model contains 18,026 nodes and 18,281 elements, comprising 54,276 degrees of freedom (DOF). The foam stiffness used in the analysis is approximately the average foam stiffness value determined in the 30-ft. drop analysis. The impact loading due to the 30-ft. Side drop is applied by applying displacements to the impact limiter and fixing the top of the cask. The location of the applied displacements and fixed nodes are illustrated in Figure 2-17. A check of the total reaction forces at the cask's fixed nodes is made, to ensure that sufficient loading is applied. A single mechanical connector and rib are modeled in the position that produces maximum stress. The connector is modeled as a spring element, and the spring force is found from the stress post-processor. FEA models for the Model AOS-025 and AOS-050 transport packages are scaled from the Model AOS-100 transport package, by a factor of 0.25 and 0.50, respectively.

LIBRA input data that defines the Side drop deformation is generated by the Fortran program, GENERATOR. This program uses the FEA model nodal data to search out the displaced nodes, and generates boundary condition records for these nodes. GENERATOR includes a SCALE parameter that accounts for the scaled Model AOS-025 and AOS-050 FEA models.

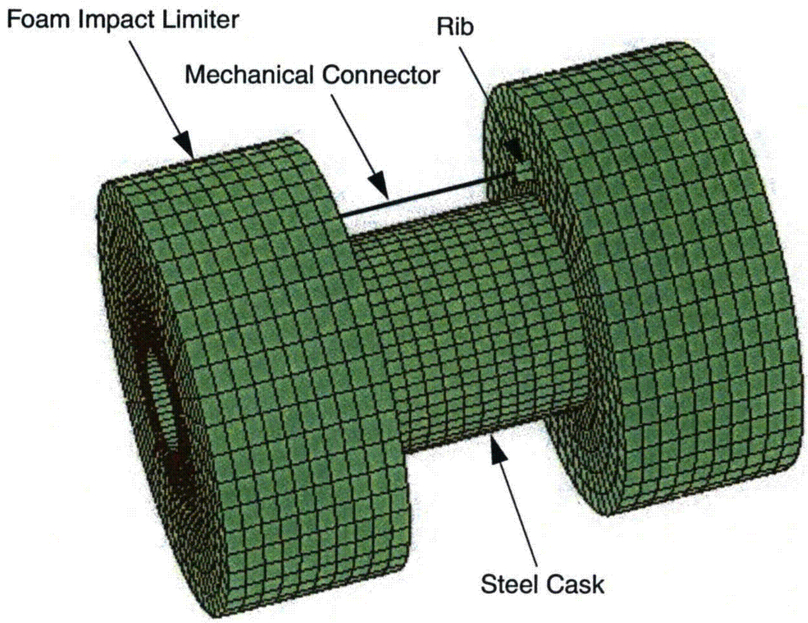


Figure 2-16. Cask and Impact Limiter FEA Model – Model AOS-100

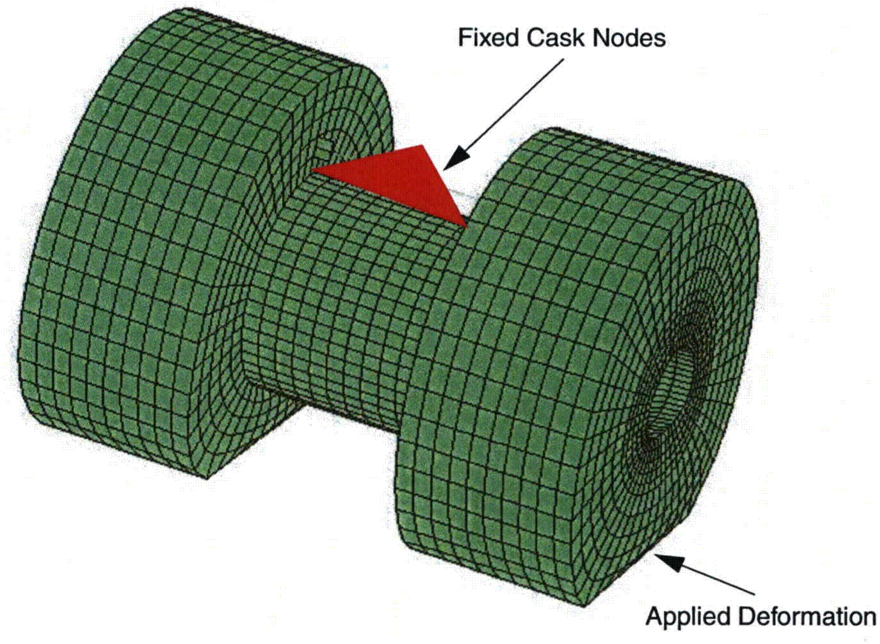


Figure 2-17. Cask and Impact Limiter Deformed FEA Model – Model AOS-100

2.5.3.2.2 Applied Force Check – Model AOS-025

The total force due to the applied displacements is the sum of y-direction (DOF_2) reaction forces at the 11 fixed cask nodes. The fixed cask node numbers start at 1978 and increase sequentially by 150. The force summation is provided in Table 2-24.

In Load Case 305 of the SAR, the maximum side impact loading is 1.80×10^5 lbs. Thus, the applied loading of 1.861×10^6 lbs. is conservative.

Table 2-24. Boundary Forces – Model AOS-025

NODE	DOF_1	DOF_2	DOF_3
1978	-5.0006E-02	-2.4066E+04	-3.4473E-02
2128	2.4348E-03	-2.0315E+04	4.3499E-04
2278	-1.1101E-02	-1.6074E+04	-1.0881E-02
2428	4.7964E-03	-1.3833E+04	1.3197E-02
2578	-2.0154E-02	-1.2640E+04	-1.2181E-02
2728	-2.6443E-02	-1.2268E+04	8.6025E-03
2878	8.6144E-02	-1.2641E+04	-5.9291E-03
3028	4.3648E-02	-1.3837E+04	-2.1374E-02
3178	5.0801E-02	-1.6080E+04	2.2134E-02
3328	1.5450E-02	-2.0326E+04	-8.3435E-03
3478	5.2142E-03	-2.4082E+04	-2.0837E-02

		$\Sigma = -1.861 \times 10^5$	

2.5.3.2.3 Mechanical Connector Force – Model AOS-025

From the LIBRA stress post-processor, the force in the mechanical connector is:

F(025) = 306.4 lbs.

2.5.3.2.4 Applied Force Check – Model AOS-050

The total force due to the applied displacements is the sum of y-direction (DOF_2) reaction forces at the 11 fixed cask nodes. The fixed cask node numbers start at 1978 and increase sequentially by 150. The force summation is provided in Table 2-25.

In Load Case 305 of the SAR, the maximum side impact loading is 3.30×10^5 lbs. Thus, the applied loading of 3.74×10^6 lbs. is conservative.

Table 2-25. Boundary Forces – Model AOS-050

NODE	DOF_1	DOF_2	DOF_3
1978	-3.5198E-02	-4.8342E+04	-2.7608E-02
2128	1.5677E-02	-4.0804E+04	5.3950E-03
2278	7.9958E-03	-3.2282E+04	-5.5868E-03
2428	2.7825E-02	-2.7781E+04	8.8376E-03
2578	8.2703E-03	-2.5383E+04	3.4030E-04
2728	-4.5529E-02	-2.4638E+04	1.9109E-02
2878	9.0454E-02	-2.5389E+04	-1.3850E-02
3028	4.1124E-02	-2.7793E+04	-1.7814E-02
3178	1.9868E-02	-3.2303E+04	1.7507E-02
3328	-2.8472E-03	-4.0837E+04	-4.7354E-03
3478	-5.0954E-03	-4.8386E+04	-1.6034E-02

		$\Sigma = -3.738 \times 10^5$	

2.5.3.2.5 Mechanical Connector Force – Model AOS-050

From the LIBRA stress post-processor, the force in the mechanical connector is:

F(050) = 598.5 lbs.

2.5.3.2.6 Applied Force Check – Model AOS-100

The total force due to the applied displacements is the sum of y-direction (DOF_2) reaction forces at the 11 fixed cask nodes. The fixed cask node numbers start at 1978 and increase sequentially by 150. The force summation is provided in Table 2-26.

In Load Case 305 of the SAR, the maximum side impact loading is 1.36×10^6 lbs. Thus, the applied loading of 1.50×10^6 lbs. is conservative.

Table 2-26. Boundary Forces – Model AOS-100

NODE	DOF_1	DOF_2	DOF_3
1978	-3.7453E-02	-1.9344E+05	-2.8953E-02
2128	-2.6102E-02	-1.6327E+05	-9.0397E-03
2278	1.5500E-02	-1.2917E+05	-9.9378E-04
2428	1.8349E-02	-1.1116E+05	-1.8342E-02
2578	2.2709E-02	-1.0156E+05	1.6758E-02
2728	-5.7000E-02	-9.8571E+04	-3.3229E-02
2878	3.0340E-02	-1.0157E+05	-2.4999E-03
3028	6.9976E-03	-1.1118E+05	-3.9185E-02
3178	-2.1879E-02	-1.2922E+05	-3.7539E-02
3328	1.4692E-02	-1.6335E+05	-1.7748E-02
3478	4.3024E-02	-1.9354E+05	-1.2194E-02

		$\Sigma = -1.50 \times 10^6$	

2.5.3.2.7 Mechanical Connector Force – Model AOS-100

From the LIBRA stress post-processor, the force in the mechanical connector is:

$$F(100) = 2.37\ k$$

2.5.3.2.8 Side Impact Load Summary

Table 2-27 summarizes the mechanical connector side impact loads, by model.

Table 2-27. Mechanical Connector Impact Load Summary – All Models

Model	Impact Load (lbs.)	Applied Load (lbs.)	Total Connector Load (lbs.)	Quantity of Effective Connectors	Load/ Connector (lbs.)
AOS-025	1.80×10^5	1.861×10^5	306.4	2	153
AOS-050	3.30×10^5	3.738×10^5	598.5	2	300
AOS-100	1.36×10^6	1.500×10^6	2,370.0	2	1,185

2.5.3.2.9 Mechanical Connector Stress Analysis

Two loading conditions are considered in the mechanical connector stress analyses:

- Connector impact loads due to side impact
- 10g impact limiter mass inertia load

Table 2-28 lists the 10g inertia loads, with connector load, P, provided by:

$$P = (10 * W) / 8$$

where:

W = Weight of a single impact limiter

Inertial force = 10g

Connectors = Eight (8) mechanical connectors

A comparison of Table 2-27 and Table 2-28 shows that the side impact loadings summarized in Table 2-27 produce maximum connector load, for all three (3) transport package models.

Table 2-28. Mechanical Connector Loads for 10g Inertia Force – All Models

Model	Limiter Weight (lbs.)	Connector Load (P) (lbs.)
AOS-025	14.0	17.5
AOS-050	62.0	77.5
AOS-100	515.0	643.8

2.5.3.2.9.1 Mechanical Connector Stress Analysis – Model AOS-025

In the Model AOS-050 transport package, the critical stress is the connection of the skin and J-bolt box. For the bearing, use F = 18.0 ksi. (Refer to Figure 2-18.)

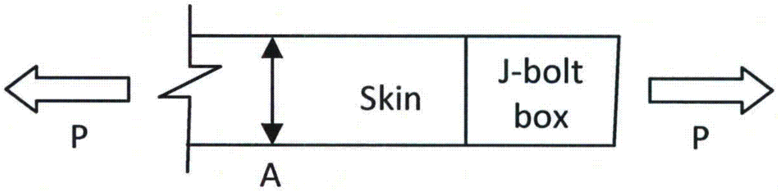


Figure 2-18. Critical Stress at Skin and J-Bolt Box Connection – Model AOS-025

where:

A	=	1.0 in.
t	=	0.05 in.
P	=	153 lbs.
σ	=	P / A * t = 153 (1.0 * 0.05) = 3.06 ksi
F	=	18.0 ksi
MS	=	(18.0 / 3.06) - 1 = 4.9

2.5.3.2.9.2 Mechanical Connector Stress Analysis – Model AOS-050

In the Model AOS-050 transport package, the critical stress is the bearing of a connector pin on a rib. For the bearing, use F = 40.0 ksi. (Refer to Figure 2-19.)

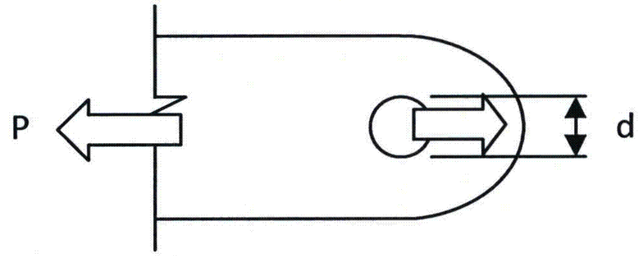


Figure 2-19. Critical Stress at Rib Connector Pin's Bearing – Models AOS-050 and AOS-100

where:

d	=	0.125 in.
t	=	0.09 in.
P	=	300 lbs.
A	=	d * t
σ	=	P / A = 300 / (0.125 * 0.09) = 26.7 ksi
F	=	40.0 ksi
MS	=	(40.0 / 26.7) - 1 = 0.50

2.5.3.2.9.3 Mechanical Connector Stress Analysis – Model AOS-100

In the Model AOS-100 transport package, the critical stress is the bearing of a connector pin on a rib. For the bearing, use F = 40.0 ksi. (Refer to Figure 2-19.)

where:

d	=	0.5 in.
t	=	0.125 in.
P	=	1,185 lbs.
A	=	d * t
σ	=	P / A = 1,185 (0.5 * 0.125) = 19.0 ksi
F	=	40.0 ksi
MS	=	(40.0 / 19.0) - 1 = 1.10

2.5.3.3 Analyses of Shielding Devices

2.5.3.3.1 Stress Analysis of Cavity Liner – Model AOS-025

The Model AOS-025's tungsten alloy cavity liner is analyzed for stress due to maximum accelerations under 9-m (30-ft.)-drop impact loadings.

Note: *The acceleration values used for this analysis envelopes the maximum accelerations.*

The following data is used in the analysis:

Longitudinal Acceleration	A_z =	2,072 g
Lateral Acceleration	A_y =	1,707 g
Elastic Modulus	E =	45.0×10^6 lb/in^2
Poisson's Ratio	ν =	0.3
Yield Stress	F_y =	94.0×10^3 lb/in^2
Density	ρ =	0.7 lb/in^3 (actual density is 0.655, rounded up to the more-conservative value, 0.7)

The cavity liner is analyzed using the LIBRA FEA program. The LIBRA model for this analysis is illustrated in Figure 2-20. The model contains 35,966 nodes and 30,400 elements, comprising 107,871 degrees of freedom. A 180° liner segment, with symmetry boundary conditions, is analyzed. The liner is analyzed separately for a 2,072 g longitudinal (Z direction) inertia loading, and a 1,707 g lateral (Y direction) inertia loading. For longitudinal loading, the cross-section at one end of the liner is fixed against longitudinal motion. For transverse loading, a longitudinal line of nodes is fixed against lateral motion. A small hole at the liner ends is included, to facilitate modeling. The LIBRA pre-conditioned conjugate gradient (PCG) solver is used.

The cavity liner equivalent (Von Mises) stress due to the longitudinal inertia loading is illustrated in Figure 2-21. The maximum equivalent stress for longitudinal loading is f_e = 8.83 ksi. The minimum margin of safety is then:

$$MS = F_y / f_e - 1 = 94.0 / 8.83 - 1 = 9.6$$

The cavity liner equivalent stress due to transverse inertia loading is illustrated in Figure 2-22. From Figure 2-22, the liner maximum equivalent stress under transverse inertia load is f_e = 16.2 ksi. The minimum margin of safety is then:

$$MS = F_y / f_e - 1 = 94.0 / 16.2 - 1 = 4.8$$

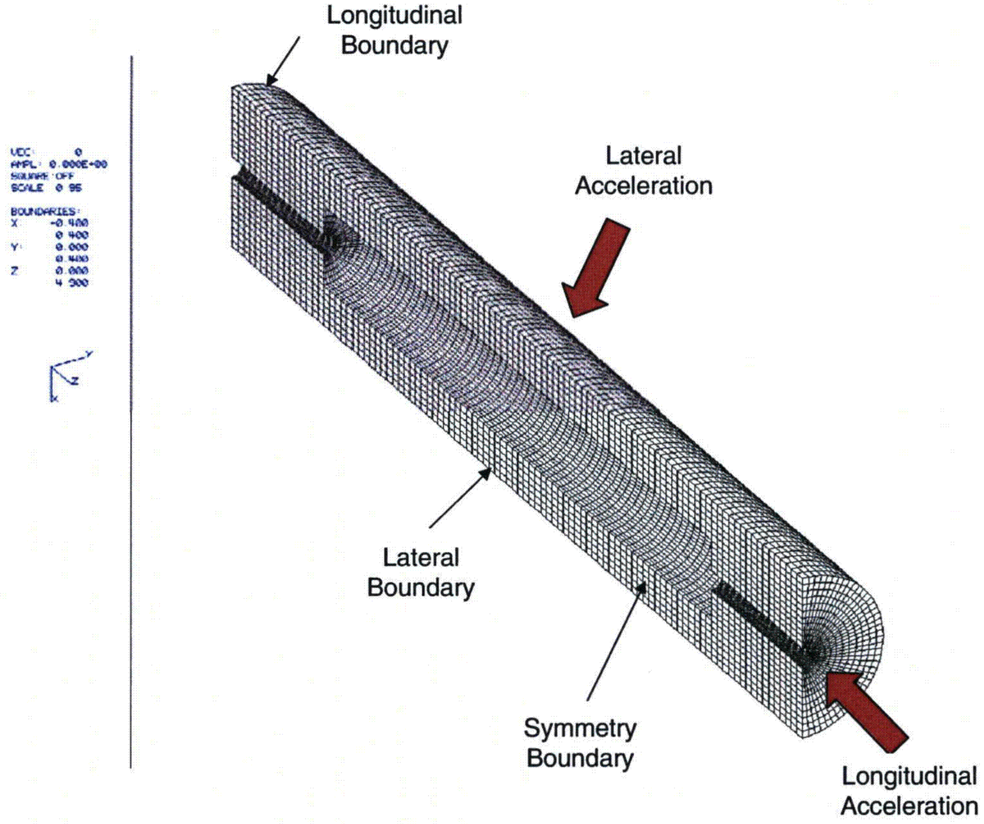


Figure 2-20. LIBRA Liner Model – Model AOS-025

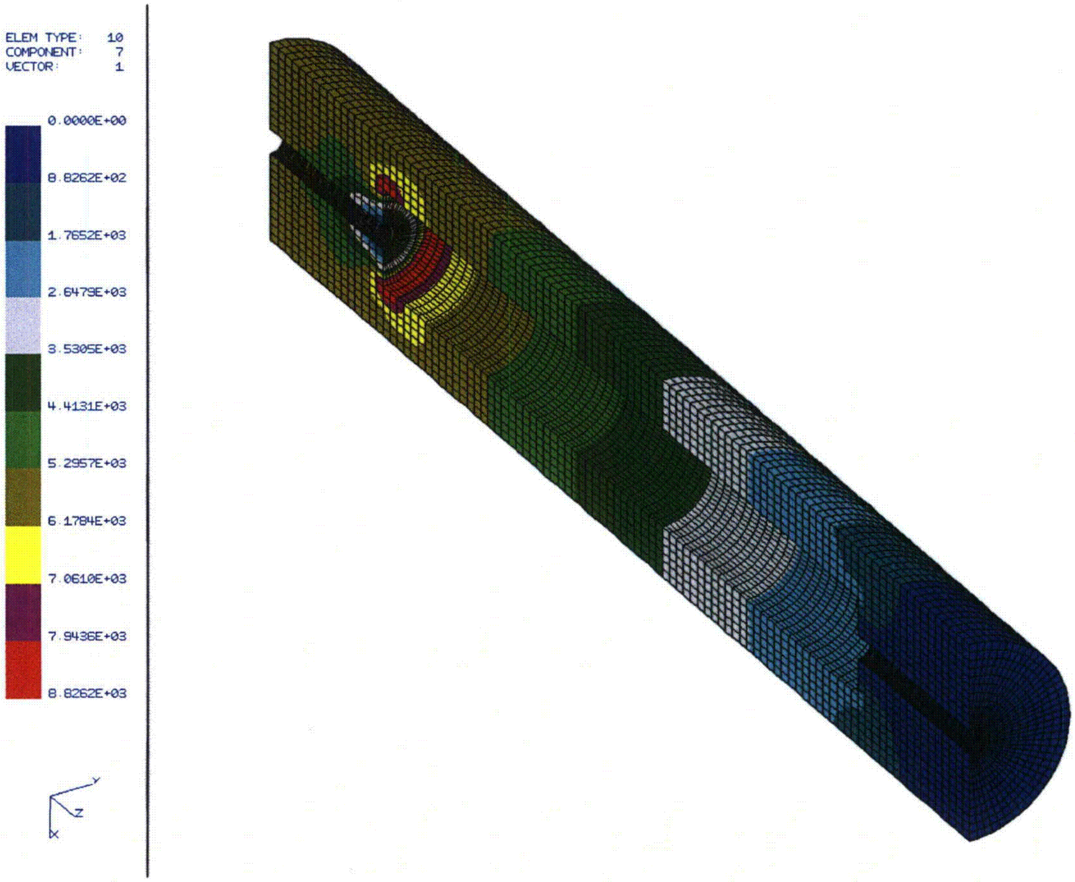


Figure 2-21. Equivalent Stress Due to Longitudinal Acceleration – Model AOS-025

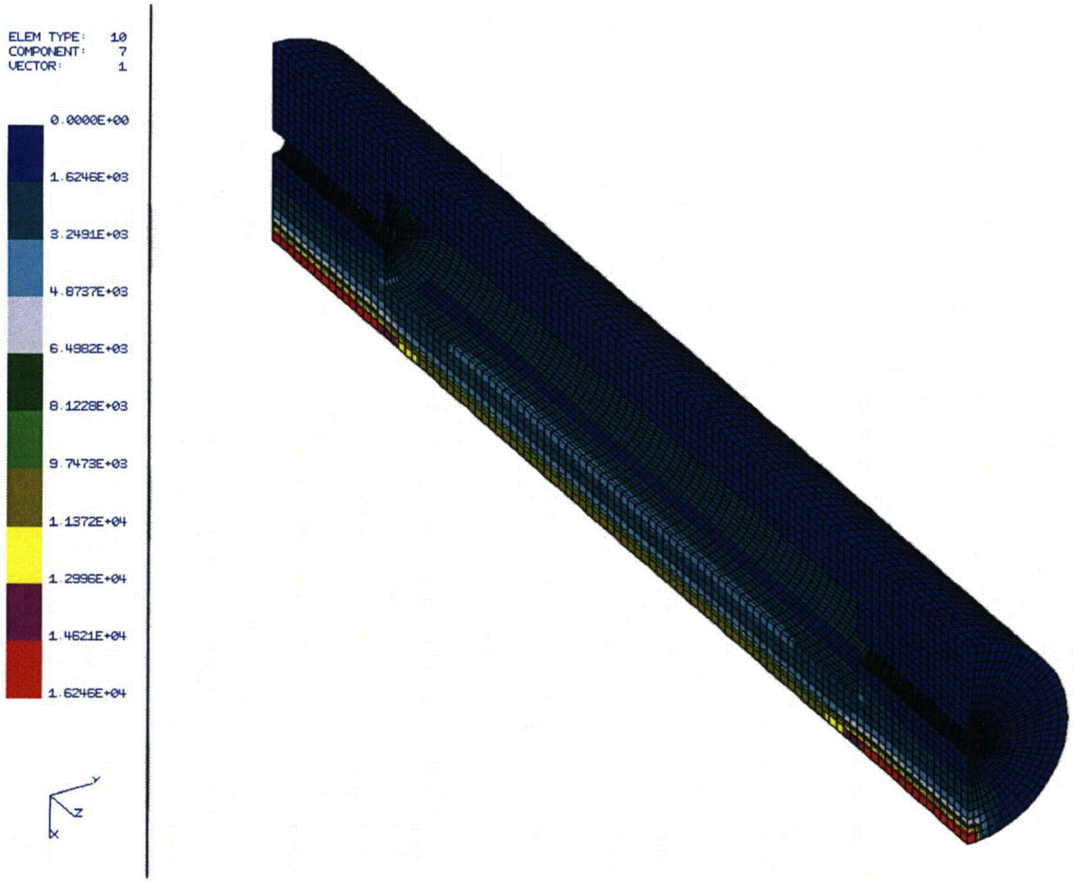


Figure 2-22. Equivalent Stress Due to Transverse Acceleration – Model AOS-025

2.5.3.3.2 Stress Analysis of Axial Shield Plate – Model AOS-100

The axial shield plate is a 15.24-cm (6-in.)-diameter, 3.81-cm (1.5-in.)-thick annular, tungsten alloy disk. For both Normal and Hypothetical Accident conditions of transport, the design load is a normal inertia loading. Under Normal conditions of transport, the plate is loaded by a 5 g inertia load. Under Hypothetical Accident conditions of transport, the plate is loaded by a 250 g inertia load.

The following data is used in the analysis:

Longitudinal Acceleration	A_z =	250 g
Elastic Modulus	E =	50.0×10^6 lb/in^2
Poisson's Ratio	ν =	0.3
Yield Stress	F_y =	75.0×10^3 lb/in^2
Density	ρ =	0.655 lb/in^3

The axial shield plate is analyzed by a LIBRA, axisymmetric analysis, using the model illustrated in Figure 2-23. The FEA model is composed entirely of Pian-Sumihara, mixed formulation, quad elements. The plate is assumed simply supported around the inside edge, and loaded with a 250 g inertia load in the negative Y direction.

Results of the FEA analysis are presented in Figure 2-23 and Figure 2-24. Figure 2-23 illustrates axial shield plate vertical (Y) displacements, and Figure 2-24 illustrates axial shield plate equivalent (Von Mises) stress. From Figure 2-23, it can be seen that under the 250 g inertia load, the maximum vertical displacement is 1.91×10^{-4} in. From Figure 2-24, it can be seen that under the 250 g inertia load, the maximum equivalent stress is 13.9 ksi:

$$MS = F_y / f_e - 1 = 75.0 / 13.9 - 1 = 4.4$$

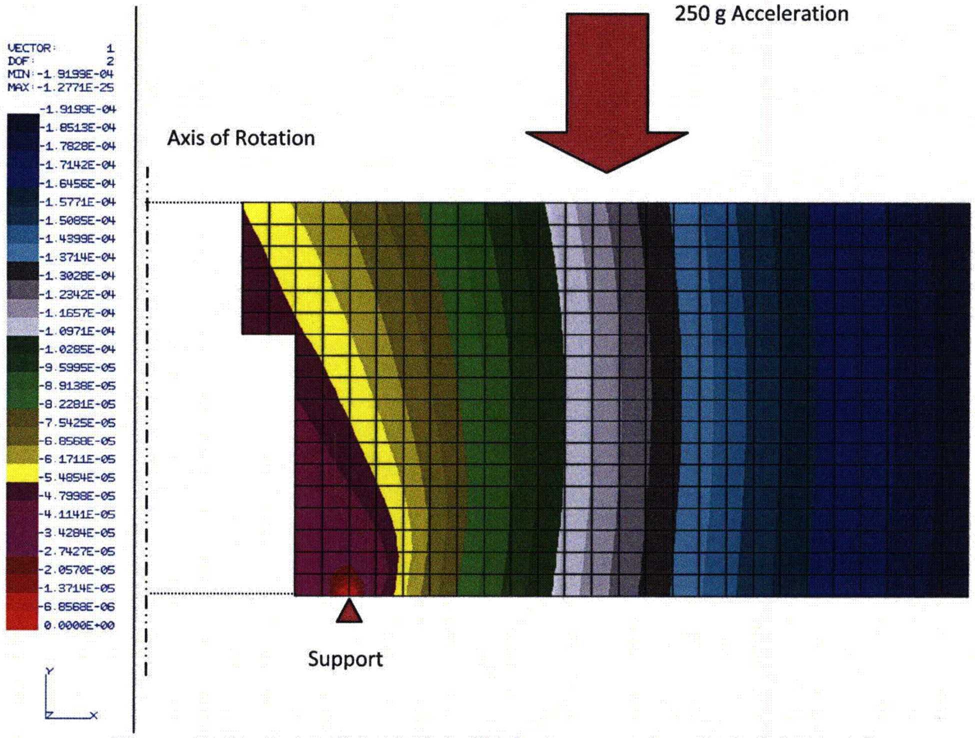


Figure 2-23. Axial Shield Plate Y-Displacements – Model AOS-100

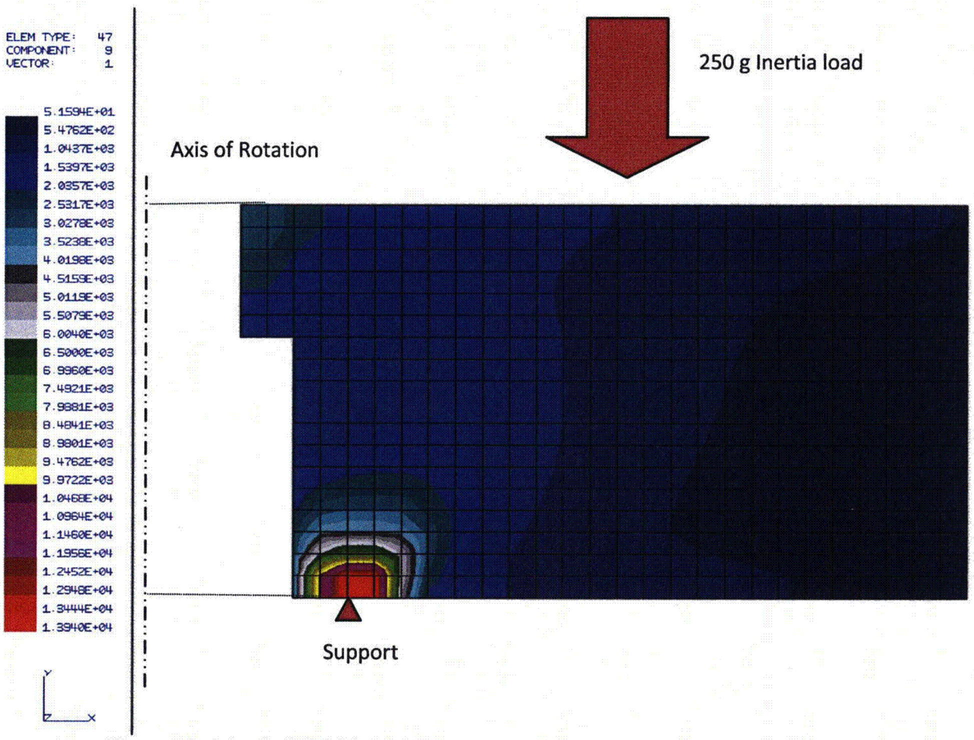


Figure 2-24. Axial Shield Plate Equivalent Stress – Model AOS-100

2.6 NORMAL CONDITIONS OF TRANSPORT

The AOS Transport Packaging System meets the requirements of Normal conditions of transport, as required in *10 CFR 71.71* **[2.1]** and *IAEA Standard* **[2.2]**.

Normal conditions of transport are evaluated using the LIBRA Finite Element computer program. The LIBRA program conducts both linear and non-linear, static and dynamic, structural analyses. The LIBRA element library contains more than 60 elements, which include beam, shell, and standard and hierarchical 2D and 3D elements. The program contains 20 solution algorithms. The principal solution algorithms are static analysis, modal analysis, direct and modal dynamic response analysis, and heat transfer. As discussed in Paragraph 2.1.2.4, three (3) Finite Element Analysis (FEA) analytical models are used in the evaluation.

Refer to Subsection 2.6.11 for a tabulation of the minimum Margin of Safety (MS) resulting from Normal conditions of transport.

2.6.1 Heat

The thermal evaluation for the heat condition is presented in Chapter 3, "Thermal Evaluation." The heat condition consists of exposing the cask to direct sunlight and 38°C (100°F) still air. Insolation of the package is specified in *10 CFR 71.71(c)(1)* **[2.1]**. An initial temperature field of 21°C (70°F) and a maximum internal heat of the respective model are used for the evaluation. In addition, the decay heat of the content must be accounted for in some of the required analyses. The seven (7) thermal conditions (analyses) required to satisfy the regulations are tabulated in Table 2-29.

The thermal loading temperature fields, Load Cases 101 through 106, 111, and 112, are taken directly from the heat transfer analyses, and applied to the stress models. The heat transfer and stress models are geometrically identical, with the same node numbering used in both analyses.

Table 2-29. Transport Package Thermal Environment Conditions – All Models

Condition	Thermal Environment
1	38°C (100°F) ambient with maximum decay heat and maximum solar load.
2	38°C (100°F) ambient with maximum decay heat.
3	Fire transient, t = 0 to 8.0 hours.
4	-40°C (-40°F) ambient with maximum decay heat.
5	-40°C (-40°F) ambient.
6	-29°C (-20°F) ambient with maximum decay heat.
7	-29°C (-20°F) ambient.

2.6.1.1 Summary of Pressures and Temperatures

Table 2-30 presents the maximum temperatures, throughout the transport package, resulting from Normal conditions of transport. The structural analyses are applied to the temperature field generated by the thermal analysis, to determine the thermal stresses.

Table 2-31 presents the pressure corresponding to the maximum temperature for each transport package model. This pressure value is based upon air at 100% relative humidity occupying the entire cavity volume. These pressures do not exceed the design pressure, which is also listed in Table 2-31. Therefore, the transport package can withstand pressures and temperatures in excess of those encountered in Normal conditions of transport.

Pressure-related Load Cases 201 through 204 are analyzed by the 2D cask model. Pressure is applied to the model's inside cask cavity wall or cask outside surface. The LIBRA LE -4[a] loading function is used to apply pressure loads. This function generates nodal forces in 2D models due to surface tractions along edge nodal lines. The nodal lines are defined by terminal nodes.

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a. *The LIBRA program's LE feature defines several types of edge and surface loadings. The first entry is a negative integer that distinguishes the type of loading. The types of loadings and nodal specifications are listed below, with former record types in parentheses.*

Options Available when Applying the "LE" Command

***Type -1** – General loading on nodes specified by numbering sequence.*

***Type -2** – General loading on arc defined by control points (LE1).*

***Type -3** – Surface pressure on arc defined by control points (LEP).*

***Type -4** – Linearly varying pressure on line specified by end nodes.*

***Type -5** – Linearly varying harmonic pressure on 3D model generated from a 2D model.*

Further Details for Types -4 and -5

***Type -4** – This command generates nodal loads corresponding to linearly varying surface tractions along a line on a 2D model. The line is specified by the two (2) terminal nodes, and loads are applied to all nodes within a specified distance of the line. The linearly varying pressure is specified by the terminal values.*

***Type -5** – This command generates nodal loads corresponding to surface tractions over a 3D model generated from an axisymmetric (2D) model. The tractions may vary linearly along a radial line, and circumferentially as a Fourier harmonic. The loaded nodes are identified by specifying the two (2) terminal nodes on the zero meridian. The linearly varying pressure is specified by the corresponding terminal values on the zero meridian.*

Table 2-30. Temperature Summary of Normal Conditions of Transport – All Models

Package Component	Maximum Temperatures, by Model							
	AOS-025A		AOS-050A		AOS-100A AOS-100A-S		AOS-100B	
	°C	°F	°C	°F	°C	°F	°C	°F
Cask Cavity	125	257	147	296	155	312	156	312
Shielding Material	124	256	142	288	148	298	148	298
Cask Lid Seal Area	124	255	141	286	145	293	145	293
Cask Vent Port	124	255	140	284	143	290	143	290
Cask Drain Port	124	255	141	286	144	291	144	291
Test Port	124	255	141	286	145	293	145	293
Cask Vent Port Pipe Plug	124	255	140	285	143	290	143	290
Cask Drain Port Pipe Plug	124	255	141	286	144	292	144	292
Cask Vent Port Conical Seal	124	255	141	286	145	293	145	293
Cask Drain Port Conical Seal	124	255	142	288	147	296	147	297
Cask Outside Surface	124	256	142	287	146	295	146	295
Impact Limiter, Foam Materials	94	202	117	242	111	231	111	231
Accessible Outside Surface	48	119	45	113	41	106	41	106

Table 2-31. Maximum Cask Cavity Pressure Due to Normal Conditions of Transport – All Models

Model	Temperature		Pressure[a]			Design Pressure[b]	
	°C	°F	kPa	psia		kPa	psia
AOS-025A	125	257	135	20	<	207	30
AOS-050A	147	296	142	21	<	414	60
AOS-100A AOS-100A-S	155	312	145	21	<	1,930	280
AOS-100B	156	312	145	21	<	1,930	280

a. *Pressure calculation is based upon the ideal gas law illustrated in Table 4-6, "Maximum Cask Cavity Pressure Due to Normal Conditions of Transport – All Models," footnote a.*

b. ***Model AOS-100 transport package** – Pressure value is based upon projected operating conditions.*

2.6.1.2 Differential Thermal Expansion

The effects of thermal gradients on the AOS Transport Packaging System are included in the LIBRA Finite Element analyses. Therefore, these effects are also included in the Load Combination procedure, where maximum stress and stress margins are calculated. Refer to Table 2-37 and Table 2-56 for Normal and Hypothetical Accident conditions of transport, respectively.

2.6.1.3 Stress Calculations

This paragraph describes the effects of the following:

- Thermal Stresses (stresses induced within a structure when some or all of the parts are not free to expand nor contract in response to temperature changes)
- Design Pressure Stresses (stresses induced by pressure differentials)
- Fabrication Stresses (stresses resulting from welding operations)

2.6.1.3.1 Thermal Stresses

The thermal loading temperature fields, Load Cases 101 through 106, 111, and 112, are taken directly from the heat transfer analyses, and applied to the stress models. The heat transfer and stress models are geometrically identical, with the same node numbering used in both analyses.

2.6.1.3.2 Design Pressure Stresses

Pressure-related Load Cases 201 through 204 are analyzed by the 2D cask model. Pressure is applied to the model's inside cask cavity wall, or cask outside surface. The LIBRA LE -4[a] loading function is used to apply pressure loads. This function generates nodal forces in 2D models due to surface tractions along edge nodal lines, and the nodal lines are defined by terminal nodes.

2.6.1.3.3 Fabrication Stresses

Fabrication stress loading is a displacement field modeling cask deformation due to welding. The displacement field produces bending at the weld cross-section, as illustrated in Figure 2-25. A configuration of the weld is also shown for clarification. Dimensions provided in the weld sketch are those for the Model AOS-100. Equal and opposite displacements are applied to the inside surface of the cask cavity shell upper ring, and cask outer shell, and produce a prying load upon the dog-leg section of the inside shell. The dog-leg section is one of the most highly stressed locations within the cask. The magnitude of the applied displacement is based upon observed welding deformation. For the Model AOS-025, the applied displacement is 0.003175 mm (0.000125 in.). For the Model AOS-050 and AOS-100, the applied displacement is 0.0127 mm (0.0005 in.).

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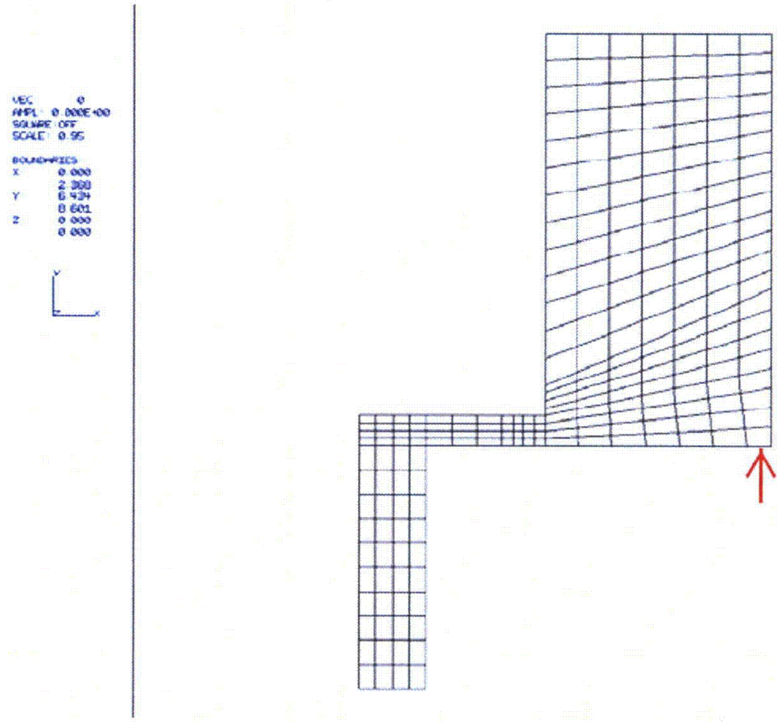
a. *Ibid (refer to previous LIBRA LE -4 footnote a).*



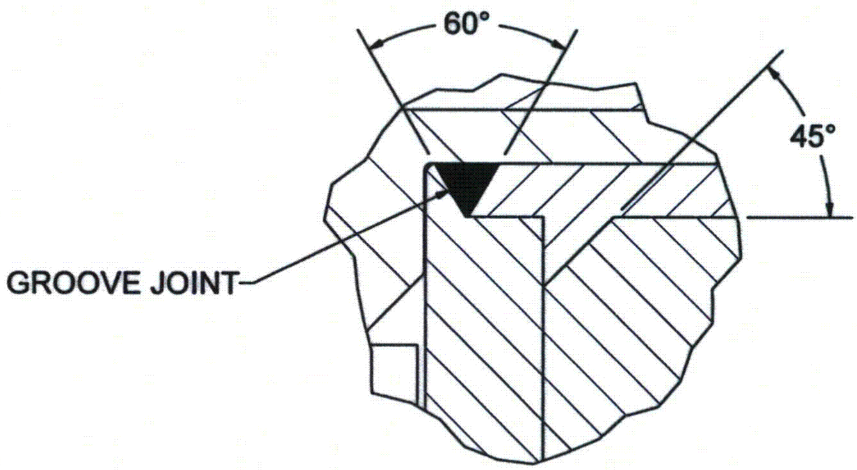


Figure 2-25. Typical Corner Cask Cavity Shell Weld Joint Configuration – All Models

2.6.1.4 Comparison with Allowable Stresses

Load Combinations 101 and 106 account for Heat Environment conditions of the Load Cases defined in Table 2-33. (The referenced tables for each model are located in Appendix 2.12.2, "Structural Evaluation Results – Models AOS-025, AOS-050, and AOS-100," within their respective paragraphs.)

Table 2-32. Stresses Resulting from Load Combinations Associated with Heat Environment under Normal Conditions of Transport – All Models

Load Combinations	Load Cases	Description	Data, by Model			
			AOS-025A	AOS-050A	AOS-100A AOS_100A-S	AOS-100B
101	102, 201, 211	Hot Environment	Table 2-84	Table 2-153	Table 2-222	Table 2-290
106	101, 201, 203, 211	Maximum Pressure, Hot Environment	Table 2-89	Table 2-158	Table 2-227	Table 2-295

2.6.2 Cold

The transport package must be able to withstand an ambient temperature of -40°C and -29°C (-40°F and -20°F, respectively), in still air and in the shade. Load Combinations 102, 105, and 107 account for Cold Environment conditions of the Load Cases defined in Table 2-33. (The referenced tables for each model are located in Appendix 2.12.2, "Structural Evaluation Results – Models AOS-025, AOS-050, and AOS-100," within their respective paragraphs.) For details regarding the specific conditions related to each of the listed Load Cases and Load Combinations, refer to Table 2-36 and Table 2-37, respectively.

Low-temperature service does not affect the AOS Transport Packaging System, because the majority of structural components are fabricated of SS300, a material that does not undergo ductile-to-brittle transition in the temperature range of interest, down to -40°C (-40°F). For the cask lid attachment bolt material – nickel alloy ASME SB-637, UNS N07718 – brittle failure is not a consideration per *paragraph NB-2311(a)(7)*, in Reference **[2.26]**, and the General Plastics FR-3700 series foam material has an operating temperature range down to -54°C (-65°F).

Table 2-33. Stresses Resulting from Load Combinations Associated with Cold Environment under Normal Conditions of Transport – All Models

Load Combinations	Load Cases	Description	Data, by Model			
			AOS-025A	AOS-050A	AOS-100A AOS_100A-S	AOS-100B
102	104, 201, 211	Cold Environment	Table 2-85	Table 2-154	Table 2-223	Table 2-291
105	105, 201, 202, 211	Cold Environment with Maximum Decay Heat	Table 2-88	Table 2-157	Table 2-226	Table 2-294
107	105, 201, 203, 211	Maximum Pressure, Cold Environment	Table 2-90	Table 2-159	Table 2-228	Table 2-296

2.6.3 Reduced External Pressure

Pressure-related Load Cases 201 through 204 are analyzed by the 2D cask model. Pressure is applied to the model's inside cask cavity wall or cask outside surface. The LIBRA LE -4[a] loading function is used to apply pressure loads. This function generates nodal forces in 2D models due to surface tractions along edge nodal lines. The nodal lines are defined by terminal nodes.

Load Cases 201 through 204 include the greatest pressure difference between the inside and outside of the transport package, as well as the inside and outside of the containment system, and are used to evaluate this condition in combination with the maximum normal operating pressure.

2.6.4 Increased External Pressure

The analysis for this condition is conducted in a similar manner as in Subsection 2.6.3. Pressure-related Load Cases 201 through 204 are analyzed by the 2D cask model. Pressure is applied to the model's inside cask cavity wall or cask outside surface. The LIBRA LE -4 loading function is used to apply pressure loads. This function generates nodal forces in 2D models due to surface tractions along edge nodal lines. The nodal lines are defined by terminal nodes.

Load Cases 201 through 204 include the greatest pressure difference between the inside and outside of the package, as well as the inside and outside of the containment system, and are used to evaluate this condition in combination with the maximum design operating pressure.

2.6.5 Vibration

Vibration and shock loads are analyzed using the 3D model in three (3) separate analyses. The vibration and shock loads are, conservatively, assumed to be:

- **Load Case 221** – Forward 10g Vibration Inertia Load
- **Load Case 222** – Lateral 5g Vibration Inertia Load
- **Load Case 223** – Vertical 2g Vibration Inertia Load

In each analysis, displacements are fixed at the trunnions, and vertical displacement is fixed along the cask and truck bed contact line. The fixed nodes are illustrated in Figure 2-26. The inertia loads are applied as body forces.

The analytical procedure applied to the cask lid attachment bolts of the AOS Transport Packaging System account for fatigue and vibration loads, in addition to preload, pressure, and temperature loads. Procedure setup provides infinite life service (1×10^6 cycles), based upon the ASME Code, Reference **[2.14]**. (Refer to Appendix 4.5.2, "Fortran Program Used to Analyze Cask Lid Attachment Bolts (Reference [4.6])," for details.)

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a. *Ibid (refer to previous LIBRA LE -4 footnote a).*

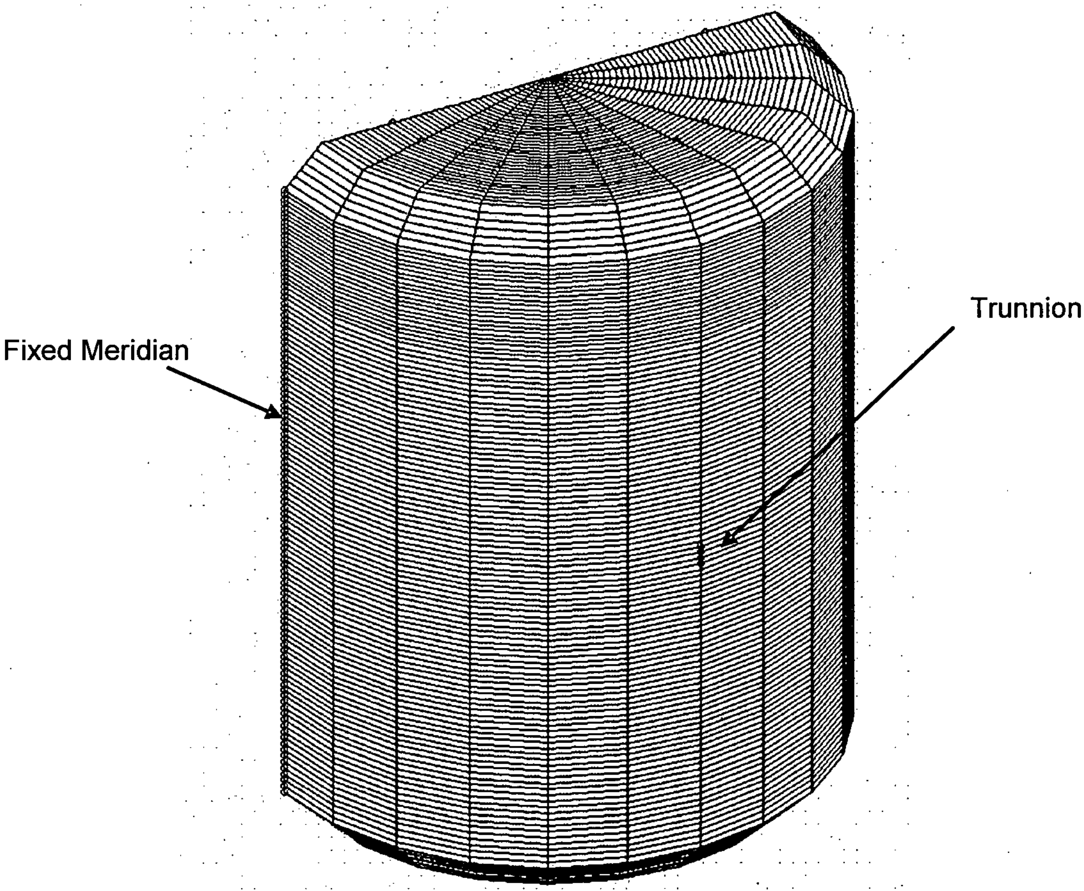

Figure 2-26. Fixed Points for Shock and Vibration Analyses

2.6.6 Water Spray

The containment capabilities of the AOS Transport Packaging System are not compromised by water spray, because all external surfaces are comprised of stainless steel, and the closure seal is impervious to water. Furthermore, it is shown that the containment boundary of the AOS Transport Packaging System cask component is leak-tight, thus preventing water from entering the cask cavity. Refer to Chapter 4, "Containment," for a description of the containment boundary and its capability to prevent leakage.

2.6.7 Free Drop

Each AOS Transport Packaging System model was analyzed to the effect of a free drop, using the LIBRA code. The transport package models were evaluated for a drop distance, based upon the model's weight, as listed in Table 2-34. The Drop condition evaluation is based upon the energy displacement curves developed by the 30-ft. drop analysis. The maximum displacements are determined from the energy displacement curves, and are listed in Table 2-35.

The analyses conducted consider three (3) orientations, as illustrated in Figure 2-27. The orientation that produced the most stress upon the cask component of the AOS Transport Packaging System was used as the load condition to be included in the Load Combination procedure.

Table 2-34. Free-Drop Distance – All Models

	Maximum Authorized Package Weight[a]		Free-Drop Distance	
Model	kg	lbs.	m	ft.
AOS-025A	100	220	1.2	4
AOS-050A	681	1,500	1.2	4
AOS-100A	5,675	12,500	0.9	3
AOS-100B	4,994	11,000		
AOS-100A-S	5,675	12,500		

a. The weights that comprise the maximum authorized package weight are defined in Table 2-7.

Table 2-35. Maximum Displacements in Free Drops, Normal Conditions of Transport – All Models

	Drop		Head-On		Side		Cg/Corner	
Model	cm	in.	cm	in.	cm	in.	cm	in.
AOS-025	121.9	48.0	1.52	0.60	0.96	0.38	2.54	1.00
AOS-050	121.9	48.0	3.81	1.50	3.05	1.20	6.73	2.65
AOS-100	91.4	36.0	6.60	2.60	5.08	2.00	12.19	4.80

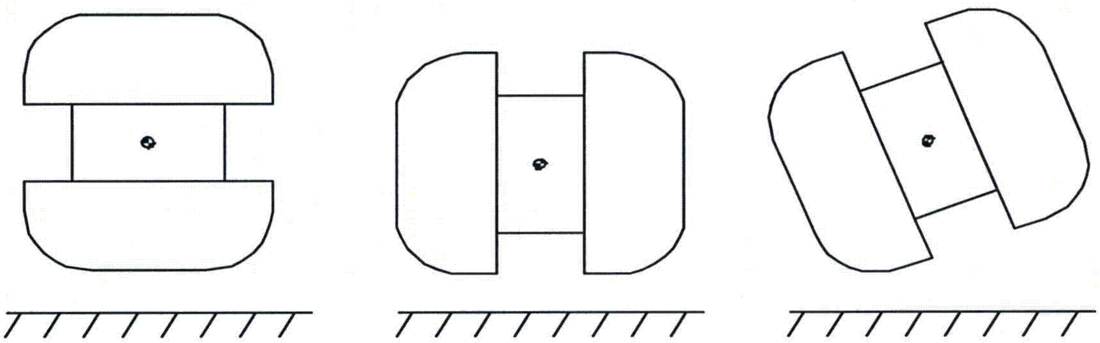

Figure 2-27. Head-On, Side, and Slap-Down Free-Drop Orientations

2.6.8 Corner Drop

Not applicable. This requirement applies only to fiberboard, wood, or fissile material rectangular packages not exceeding 50 kg (110 lbs.) and fiberboard, wood, or fissile materials not exceeding 100 kg (220 lbs.).

2.6.9 Compression

The compression load of five times (5x) the cask weight is applied to the cask under Load Case 215. This analysis uses the 2D model. The compression force is applied to the top of the cask as a pressure loading, using the LE -4 load function.

2.6.10 Penetration

The regulations for Normal conditions of transport stipulate that the transport package must be capable of withstanding the impact of the hemispherical end of a vertical steel cylinder, that:

- Weighs 6 kg (13.23 lbs.)
- Has a 3.2-cm (1.26-in.) diameter
- Is dropped from a height of 1 m (40 in.), normally onto the exposed surface of the package that is expected to be the most vulnerable to puncture

The impact of a rod falling onto the cask, Load Case 216, was analyzed by a direct integration, dynamic analysis. The cask was modeled by the 2D model illustrated in Figure 2-28. The cask was assumed fixed at the base, and an impulse corresponding to the momentum impacting rod was applied at the top of the cask. Displacement at the impact point was monitored, as illustrated in Figure 2-29. The stress state at the time of maximum displacement was used for stress evaluation.

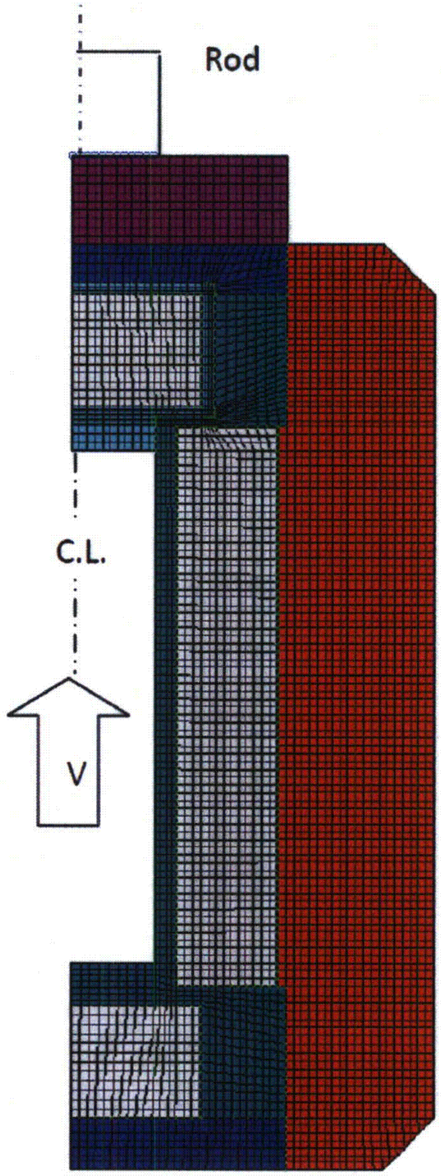

Figure 2-28. Rod Impact Analysis Load Distribution – Model AOS-100

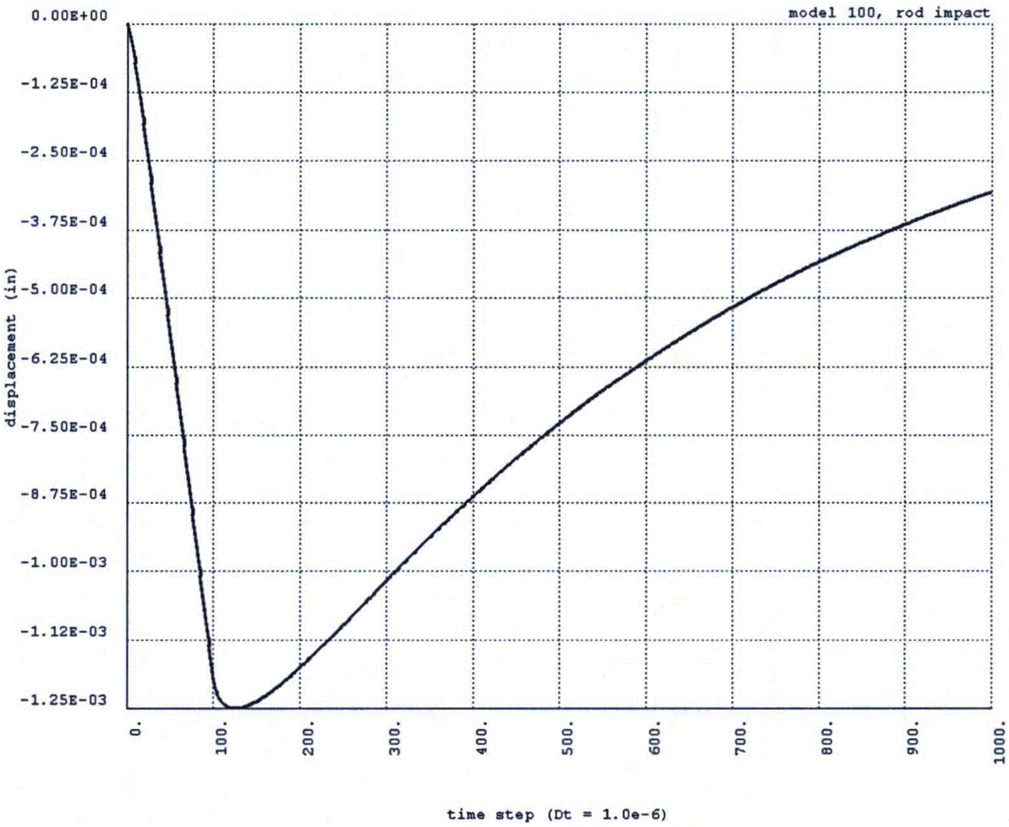

Figure 2-29. Rod Impact Time History Displacement at Impact Node – Model AOS-100