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 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 pair of elastomeric O-Rings captured within one (1) or two (2) SS300 series flat rings, or metallic double "C" cross-section arrangement. 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.

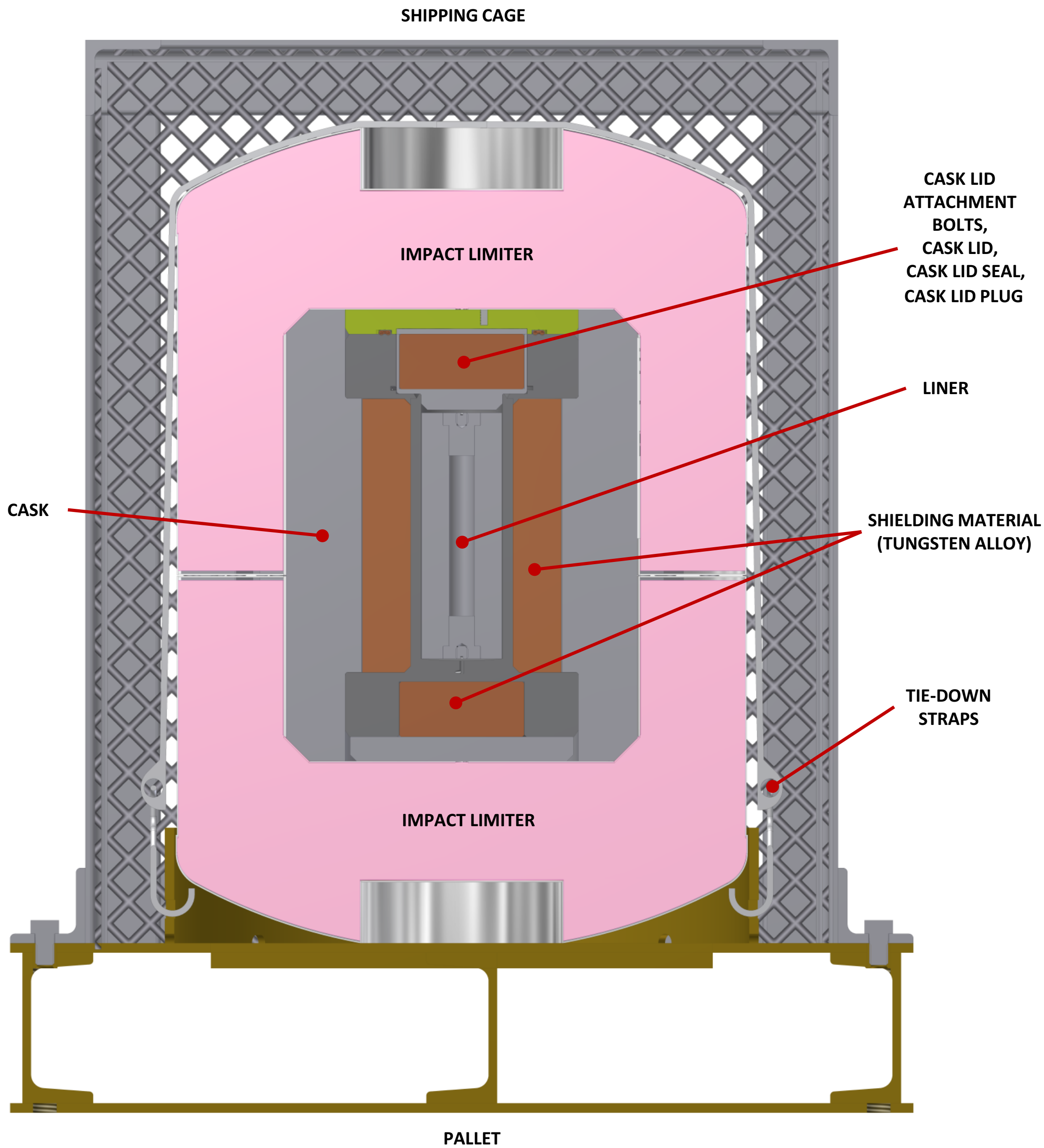

Figure 2-1. Assembled Transport Package Cutaway – Model AOS-025A

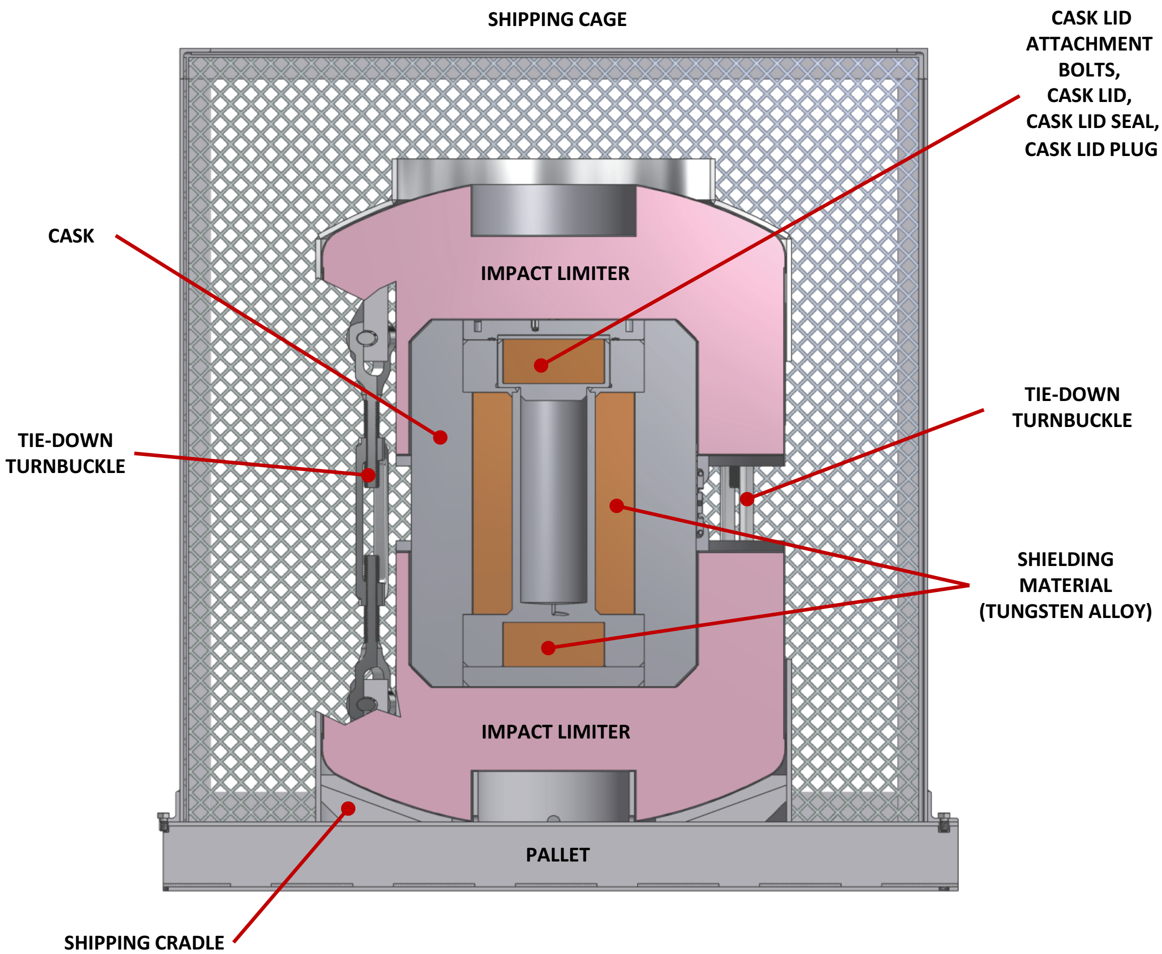

Figure 2-2. Assembled Transport Package Cutaway – Model AOS-050A

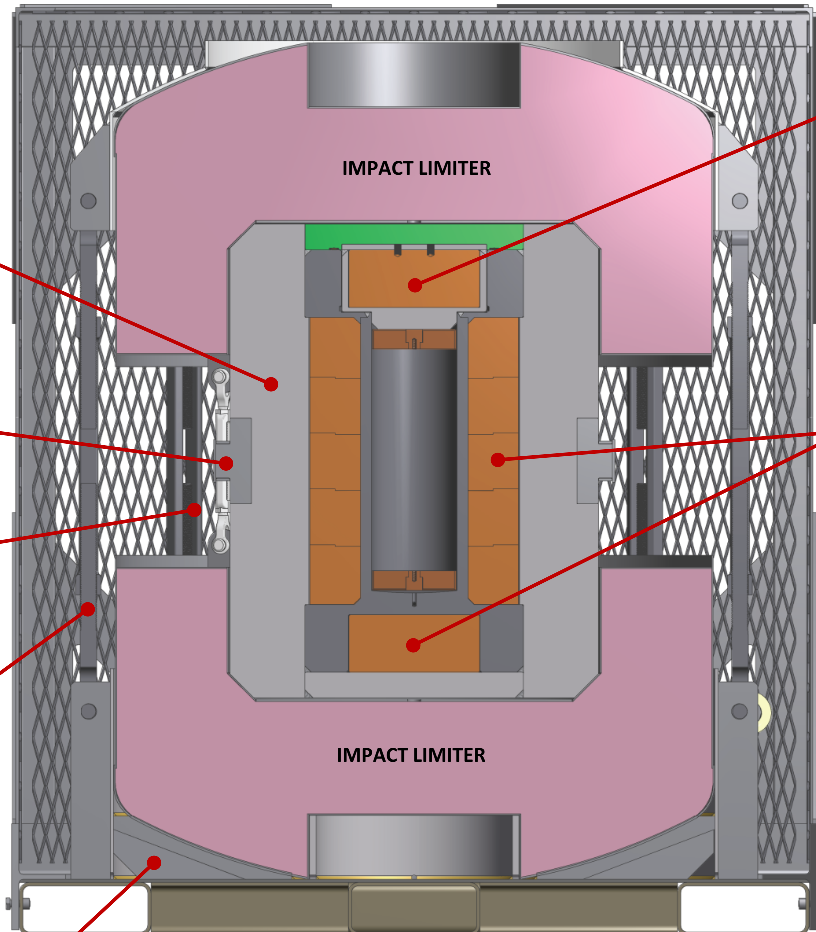

Figure 2-3. Assembled Transport Package Cutaway – Models AOS-100A and AOS-100B

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

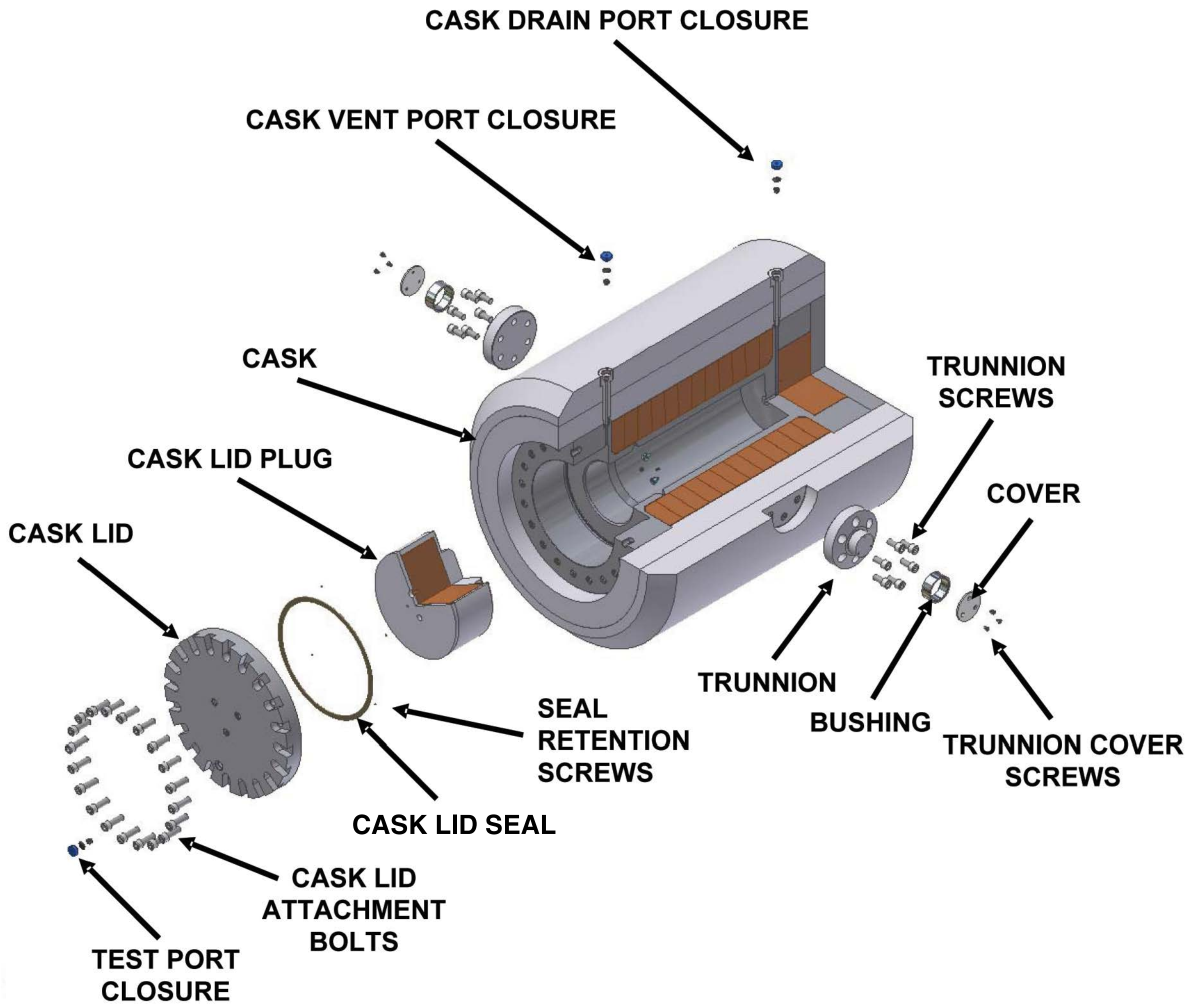

Figure 2-4. Isometric View – Typical Cask

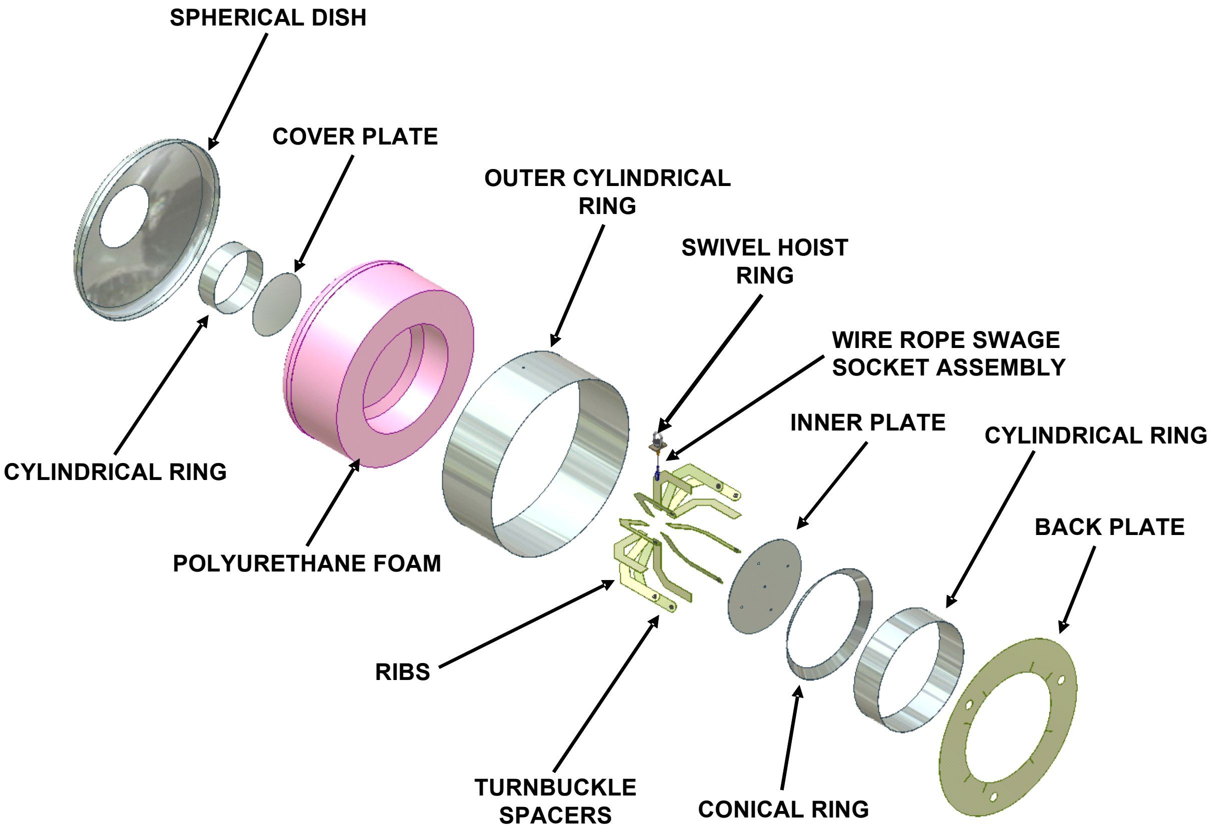

Figure 2-5. Isometric View – Typical Impact Limiter

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.

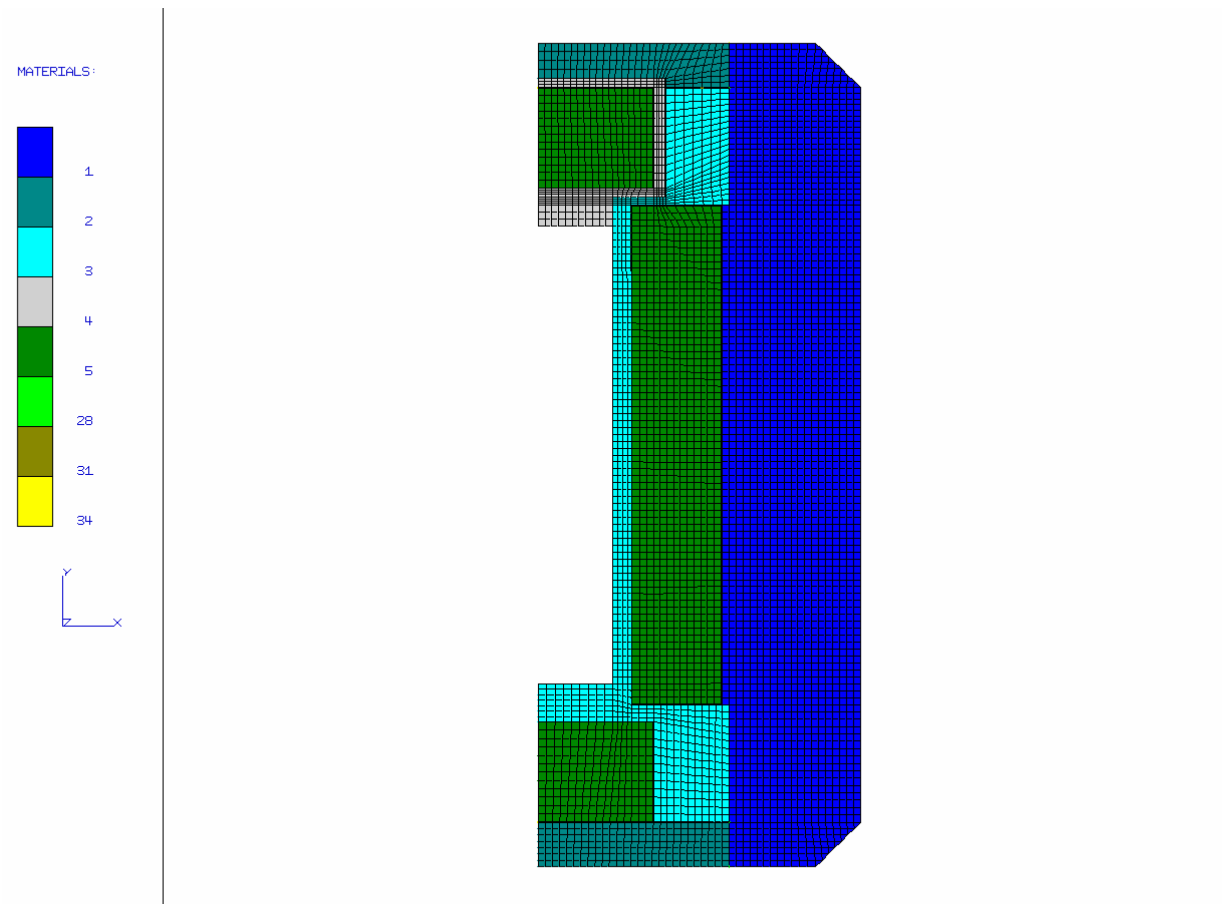

Figure 2-6. Axisymmetric (2D) Model – Models AOS-025, AOS-050, and AOS-100

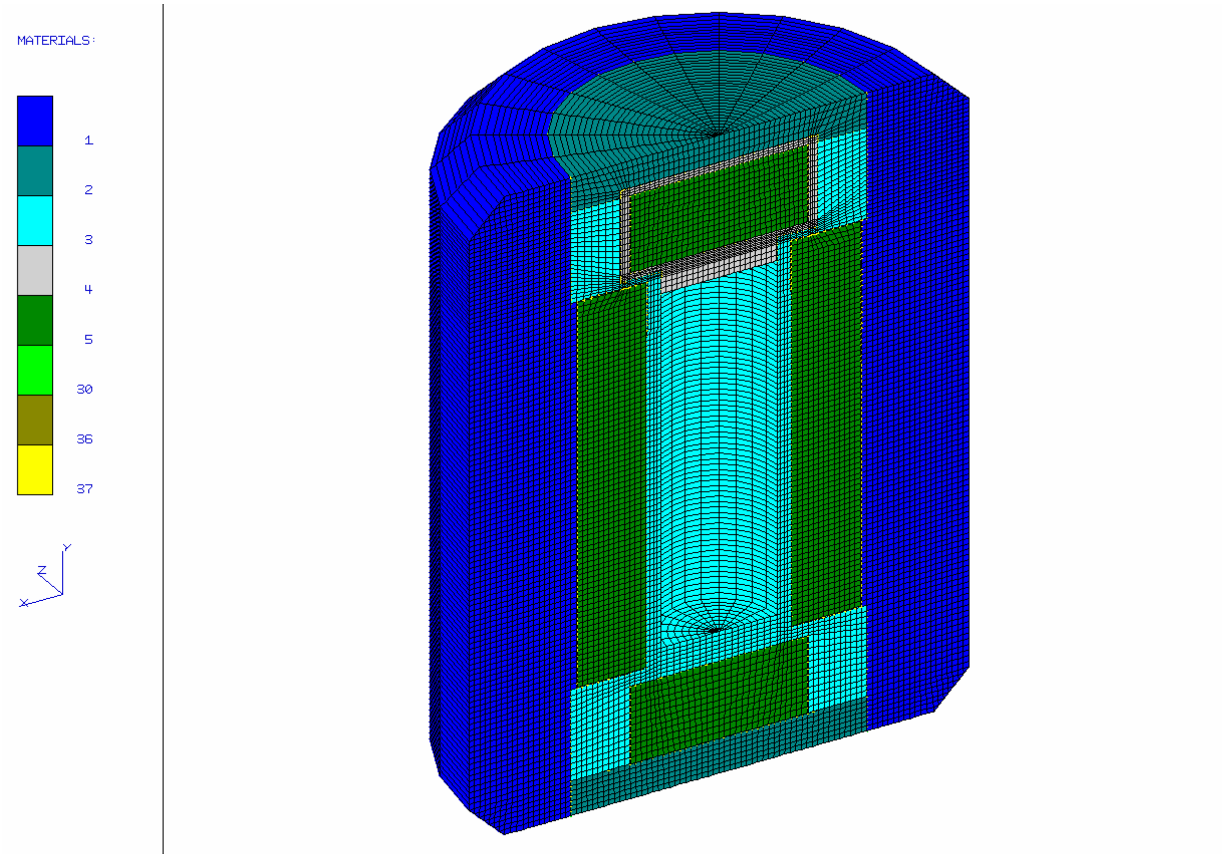

Figure 2-7. 3D Model – Models AOS-025, AOS-050, and AOS-100

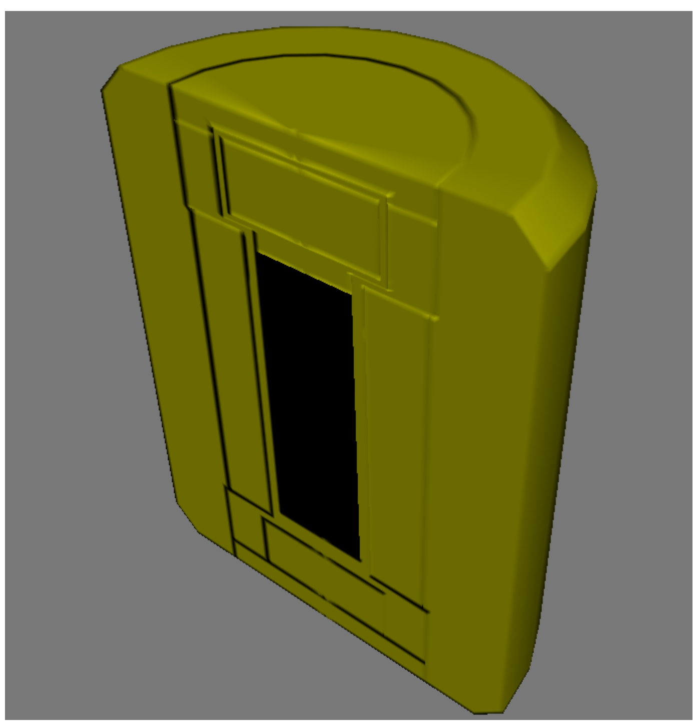

Figure 2-8. 3D Rendered Model – Models AOS-025, AOS-050, and AOS-100

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.

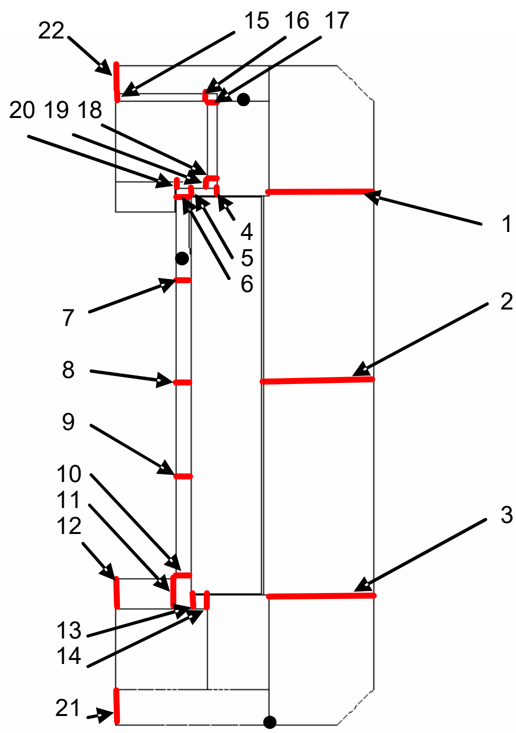

Figure 2-9. P_m and P_b Stress Monitoring Points – All Models

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

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

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 – 4-ft. Head-On Drop, Normal Conditions • Model AOS-050 – 4-ft. Head-On Drop, Normal Conditions • Model AOS-100 – 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 – 4-ft. Drop at Cold Temperature • Model AOS-050 – 4-ft. Drop at Cold Temperature • Model AOS-100 – 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	26.97	22.86
		220	28	140	10	55	7.50	10.62	9.00
AOS-050A	I	681	56	480	27	135.2	45.41	46.22	41.57
		1,500	123	1,058	60	298	17.88	18.20	16.37
AOS-100A	I	5,675	467	3,850	227	1,685.1	77.39	87.68	77.39
		12,500	1,029	8,481	xxx500	3,715	30.47	34.52	30.47
AOS-100B	II	4,994	467	3,192	227	1,685.1	77.39	87.68	77.39
		11,000	1,029	7,030	500	3,715	30.47	34.52	30.47
AOS-100A-S	I	5,675	467	3,850	227	1,685.1	77.39	87.68	77.39
		12,500	1,029	8,481	500	3,715	30.47	34.52	30.47

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.

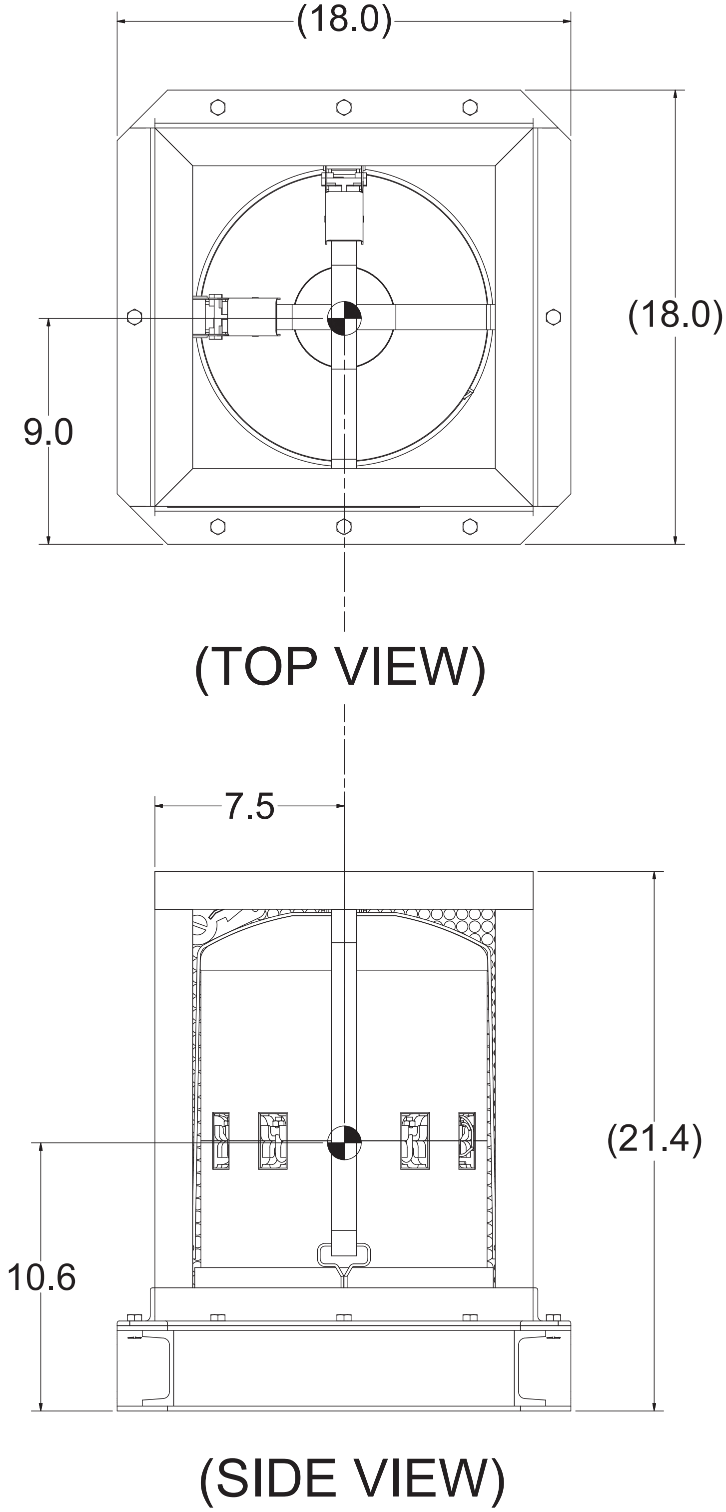

Figure 2-10. Center of Gravity – Model AOS-025

Note: *Dimensions are in inches.*

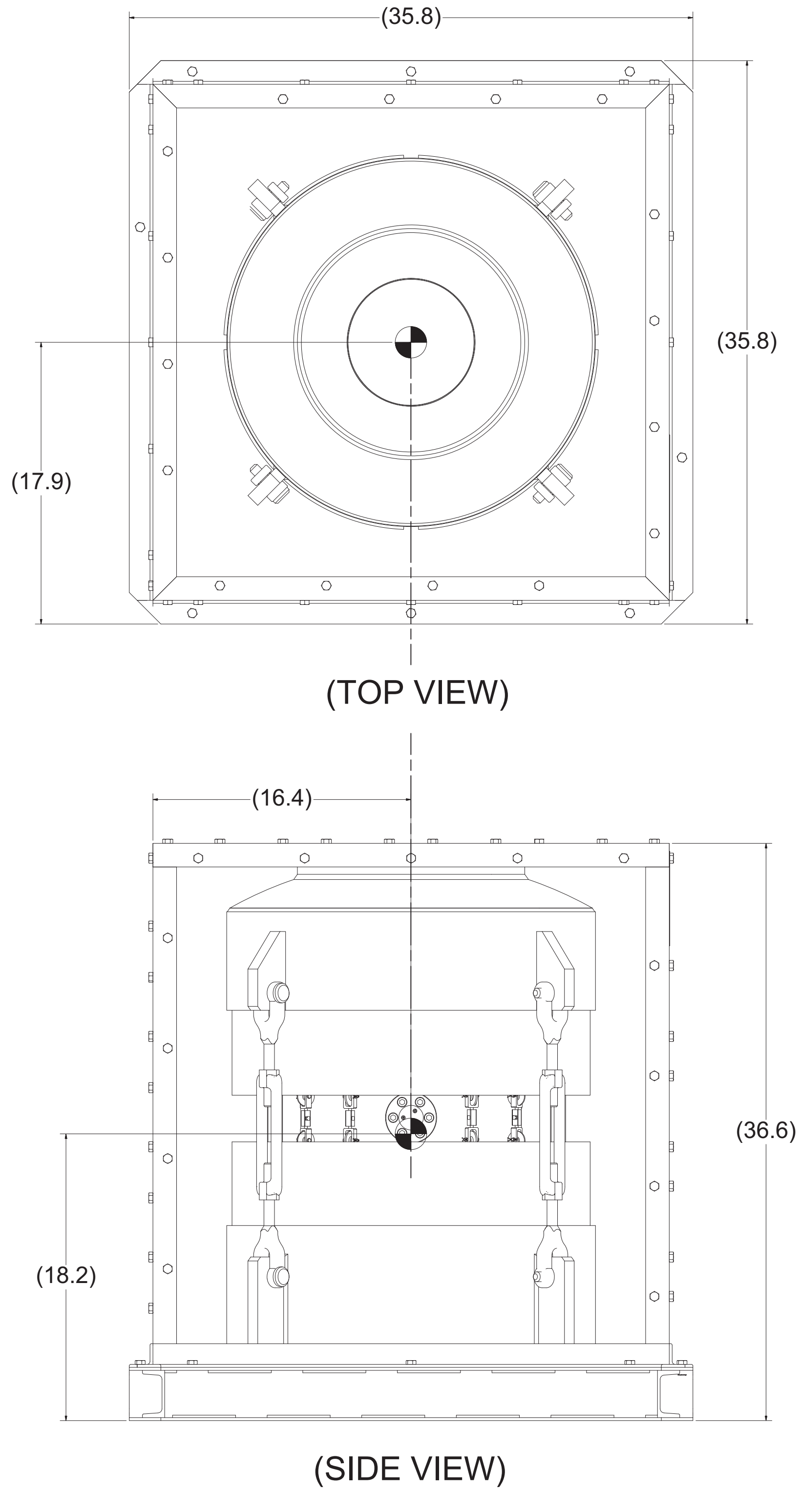

Figure 2-11. Center of Gravity – Model AOS-050

Note: *Dimensions are in inches.*

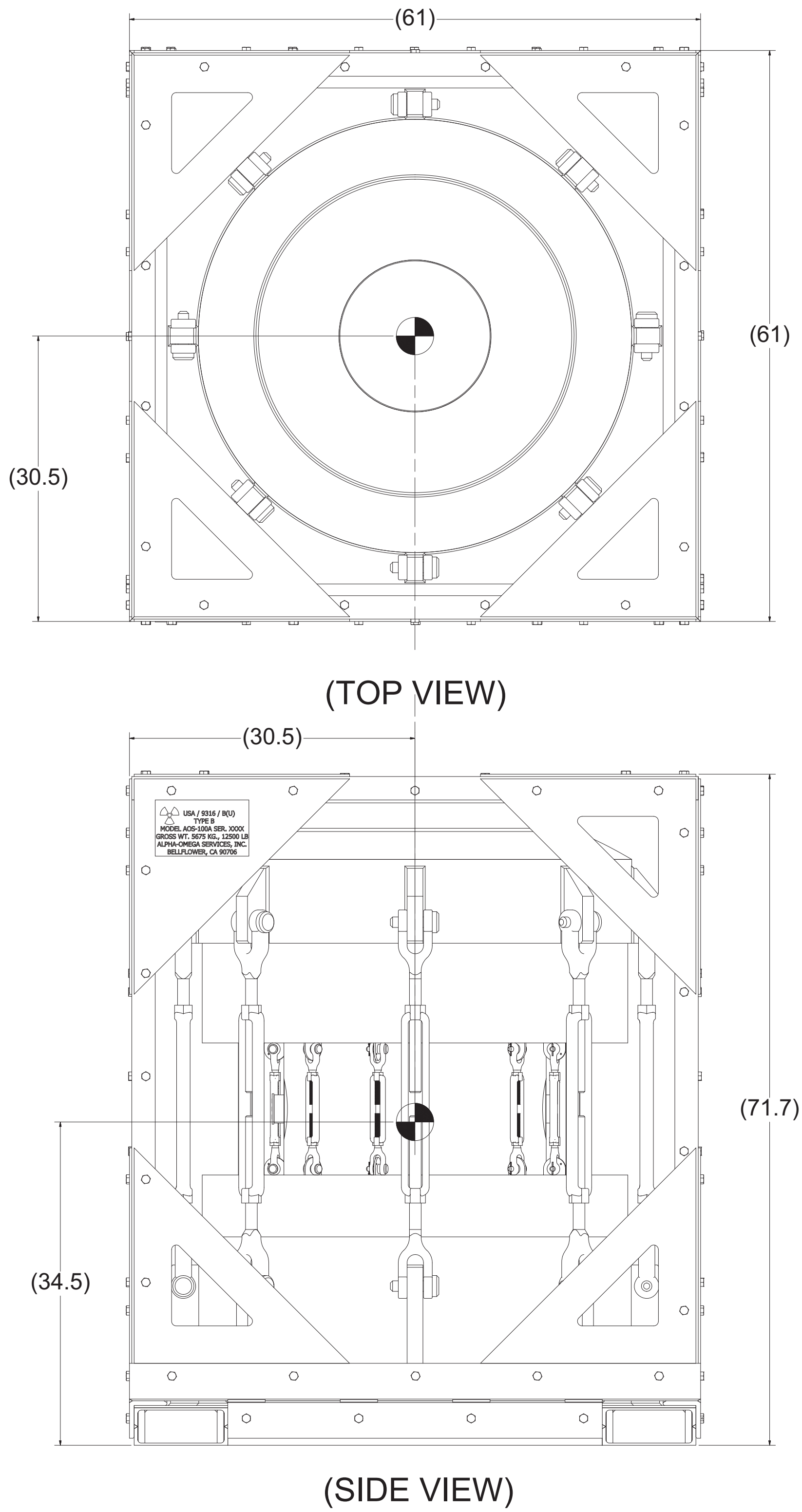

Figure 2-12. Center of Gravity – Model AOS-100

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]).*

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

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		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	–	105E9712	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-6112*, Section III, and *ANSI N14.5*, Section 7.3.	Pneumatic and Leakage test, per Reference **[2.11]**.
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.

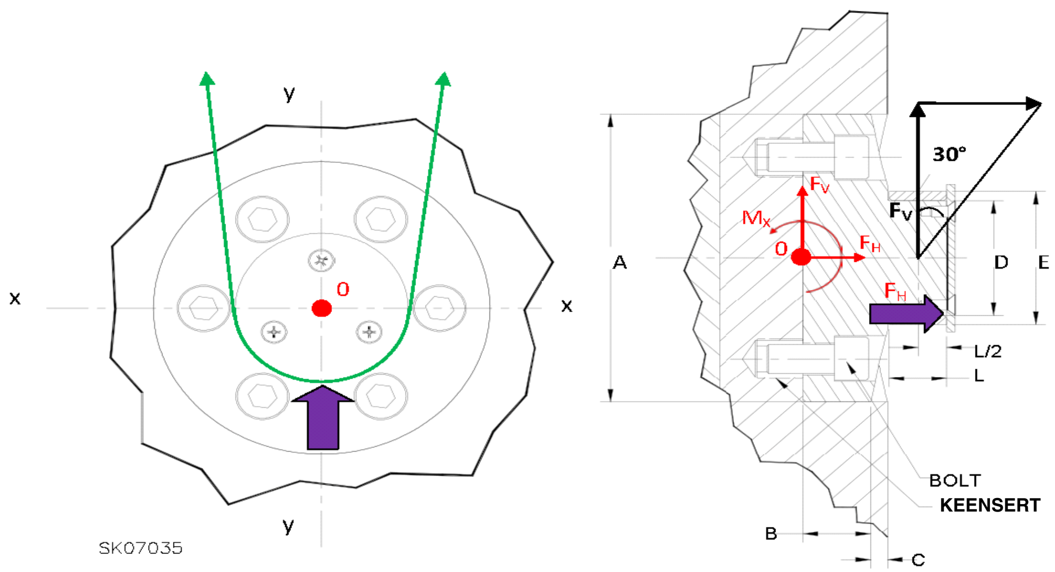


Figure 2-13. Trunnion Area Cross-Section and Force Diagram Associated with Lifting Loads

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
$I_{x\text{-}x\ per\ unit\ area}$[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
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
I	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

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

Item	Units		Model					
			AOS-025		AOS-050		AOS-100	
			Metric	English	Metric	English	Metric	English
P	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:

$$Area = A * B$$

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 1-4 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 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.

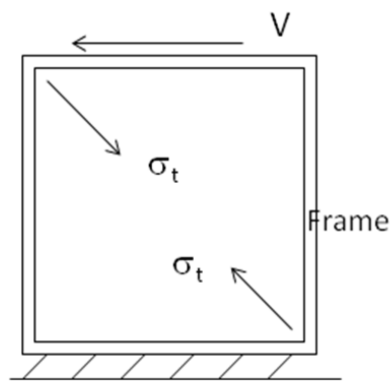


Figure 2-14. Mesh Diagonal Tension

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 $\rho = 0.28\ \text{lb/in}^3$ 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

The Model AOS-025 shipping cage sits on top of the transport pallet with screws that pass vertically through flanges on four (4) sides of the shipping cage. There are three (3) screws on each side of the shipping cage and one (1) each on its front and back (total of eight (8)). The shipping cage is made with five (5) frames covered with expandable metal screens. The frames are made with 1.5 in. x 1.5 in. aluminum angles with a thickness of 0.19 in. The actual shipping cage dimensions are used in the analysis. The shipping cage is 15 in. long by 15 in. wide by 18 in. high. Fastener properties are in accordance with ASME SA-193/ASTM A193, GRADE B6 (UNS S41000), –or– an alternate material, ASTM A193 Grade B8S (Nitronic 60). The calculations use the lesser yield strength of the two (2) materials.

Shipping Cage Mass

Vertical Frame

w = Density of aluminum = 0.1 lb/in^3

W_1 = 2 * (18 + 15) * (1.5 + 1.5) * 0.19 * 0.1 = 3.8 lbs.

H_1 = 9 in.

Top Frame

W_2 = 4 * 15 * (1.5 + 1.5) * 0.19 * 0.1 = 3.4 lbs.

H_2 = 18 in.

Vertical Screen

w = Unit weight of screen = 2.0 lb/ft^2

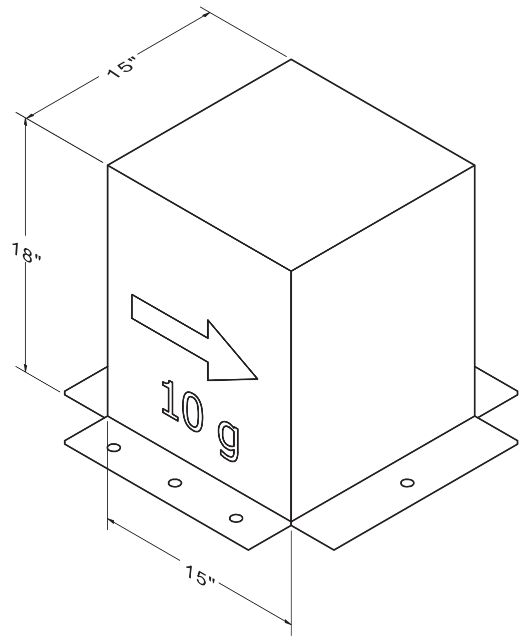
W_3 = 15/12 * 18/12 * 2.0 = 3.8 lbs.

H_3 = H_1 = 9 in.

Top Screen

W_4 = 15/12 * 15/12 * 2.0 = 3.1 lbs.

H_4 = H_2 = 18 in.



Maximum Inertia Force

G = 10.0g

Total Weight of Shipping Cage

W = 4W_1 +W_2 + 4W_3 + W_4 = 36.9 lbs.

Fastener Properties

3/8-16 UNC screws, quantity of eight (8), per ASME SA-193/ASTM A193, GRADE B6 –or– NITRONIC 60 PER ASME SA-193/ASTM A193, GRADE B8S (UNS S21800)

A_s = Stress Area = 0.0775 in^2

F_y = 85 ksi (UNS S41000)

–or–

F_y = 50 ksi (evaluate Nitronic 60 as an optional material)

Yield Stress in shear = $S_y = 0.58 * F_y$ = 29 ksi

Fastener Shear Stress

$\tau = (G * W) / (8 * A_s) = (10 * 36.9) / (8 * 0.0775) = 595.2$ psi

Fastener Axial Stress

Shipping cage's tipping moment is assumed to be resisted by three (3) screws along the back edge.

M = Tipping Moment = $(G * (4W_1 + 4W_3) * H_1) + (G * (W_2 + W_4) * H_2)$ = 3,906 in-lb

L = Moment Arm = 15 + 2 * 1.5 - 0.69 = 17.3 in.

$\sigma = M / (L * 3 * A_s) = 971.1$ psi

Equivalent Stress

$\sigma_e = \sqrt{(\sigma^2 + 3\tau^2)} = 1{,}416.3$ psi

Margin of Safety

$MS = F_y / \sigma_e - 1 = 29{,}000 / 1{,}416.3 - 1 = 19.5$

2.5.3.1.3 Analysis of Shipping Cage Fasteners – Model AOS-050

The Model AOS-050 shipping cage has the same geometry as the Model AOS-025 shipping cage, but is 32.75 in. long by 32.75 in. wide by 33.25 in. high.

Shipping Cage Mass

Vertical Frame

w = Density of aluminum = 0.1 lb/in^3

W_1 = 2 * (32.75 + 33.25) * (1.5 + 1.5) * 0.19 * 0.1 = 7.5 lbs.

H_1 = 16.6 in.

Top Frame

W_2 = 4 * 32.75 * (1.5 + 1.5) * 0.19 * 0.1 = 7.5 lbs.

H_2 = 33.25 in.

Vertical Screen

w = Unit weight of screen = 2.0 lb/ft^2

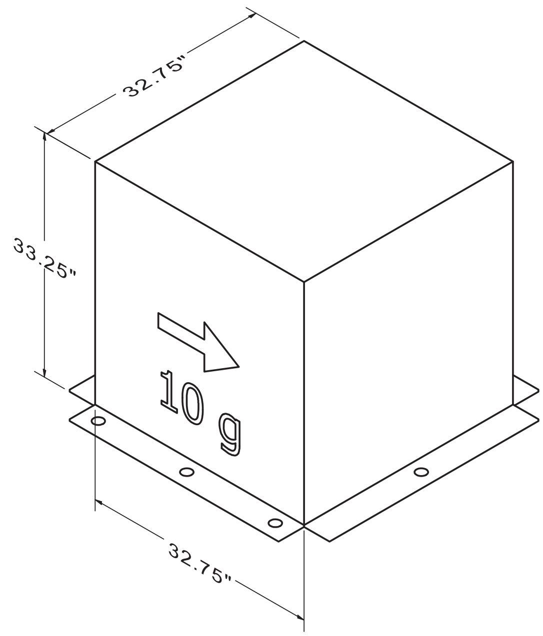
W_3 = 32.75/12 * 33.25/12 *2.0 = 15.1 lbs.

$H_3 = H_1$ = 16.6 in.

Top Screen

W_4 = 32.75/12 * 32.75/12 *2.0 = 14.9 lbs.

$H_4 = H_2$ = 33.25 in.



Optional Shipping Cage Lifting Bar

The Lifting Bar is made from a T-section 2 in. by 2 in. by 0.25 inch thick.

W_5 = 32.75 * (2.0 + 2.0) * 0.25 * 0.1 = 3.3 lbs.

$H_5 = H_2$ = 33.25 in.

Total Weight of Shipping Cage

$W = 4W_1 + W_2 + 4W_3 + W_4 + W_5$ = 116.2 lbs.

Maximum Inertia Force

G = 10.0g

Fastener Properties

3/8-16 UNC screws, quantity of eight (8), per ASME SA-193/ASTM A193, GRADE B6 –or– NITRONIC 60 PER ASME SA-193/ASTM A193, GRADE B8S (UNS S21800)

A_s = Stress Area = 0.0775 in^2

F_y = 85 ksi (UNS S41000)

–or–

F_y = 50 ksi (evaluate Nitronic 60 as an optional material)

Yield Stress in shear = $S_y = 0.58 * F_y = 29$ ksi

Fastener Shear Stress

$\tau = (G * W) / (8 * A_s) = (10 * 116.2) / (8 * 0.0775) = 1874.2$ psi

Fastener Axial Stress

Shipping cage's tipping moment is assumed to be resisted by three (3) screws along the back edge.

M = Tipping Moment = $(G * 4 * (W_1 + W_3) * H_1) + (G * (W_2 + W_4) * H_2) + (G * W_5 * H_5) = 23{,}551.6$ in-lb

L = Moment Arm = 32.75 + 2 x 1.5 - 0.69 = 35.06 in.

$\sigma = M / (L * 3 * A_s) = 2{,}889.3$ psi

Equivalent Stress

$\sigma_e = \sqrt{(\sigma^2 + 3\tau^2)} = 4{,}345.8$ psi

Margin of Safety

$MS = F_y / \sigma_e - 1 = 29{,}000 / 4{,}345.8 - 1 = 5.7$

2.5.3.1.4 Analysis of Shipping Cage Fasteners – Model AOS-100

The Model AOS-100 shipping cage configuration is different from that of the Model AOS-025 and AOS-050 shipping cages. The shipping cage has vertical flanges that straddle the transport pallet, and the screws pass horizontally through the flanges. Because the transport pallet is captured within these flanges, the screws do not resist forward or sideways movement of the shipping cage. The screws only need to resist tipping of the shipping cage. The relevant parameters and calculations are provided below.

Shipping Cage Center of Gravity

H_1 = 46.6 in.

Shipping Cage Mass

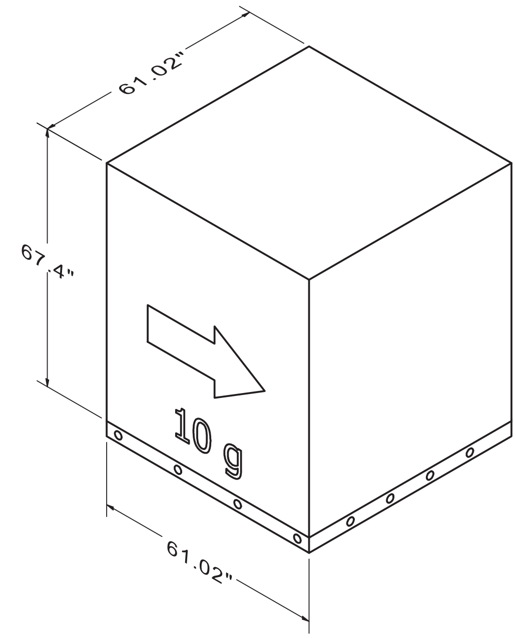
W = 450 lbs.

Shipping Cage Length

L = 61.02 in.

Acceleration

G = 10.0g



Fastener Properties and Stress

1/2-13 UNC screws, quantity of 16, per ASME SA-193/ASTM A193, GRADE B6 –or– NITRONIC 60 PER ASME SA-193/ASTM A193, GRADE B8S (UNS S21800)

A = Tensile Stress Area = 0.142 in^2

The 10.0-g acceleration tends to tip the shipping cage about one edge.

M = Tipping Moment = $W * G * H_1 = 450 * 10 * 46.6 = 209{,}700$ in-lb

Shipping cage's tipping is conservatively assumed to be resisted by only four (4) screws in shear. Total force on the screws is:

F = M / L = 209,700 / 61.02 = 3,436.6 lbs.

The shear stress in each screw is:

$\tau = F / 4A_s = 3{,}436.6 / (4 * 0.142) = 6{,}050.3$ psi

Margin of Safety

$MS = F_y / \tau - 1 = 29{,}000 / 6{,}050.3 - 1 = 3.8$

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.

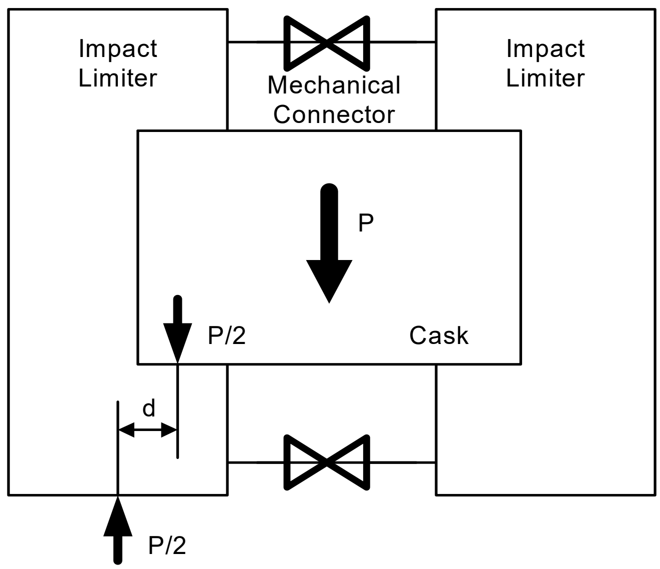


Figure 2-15. Side Drop Impact Forces

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.

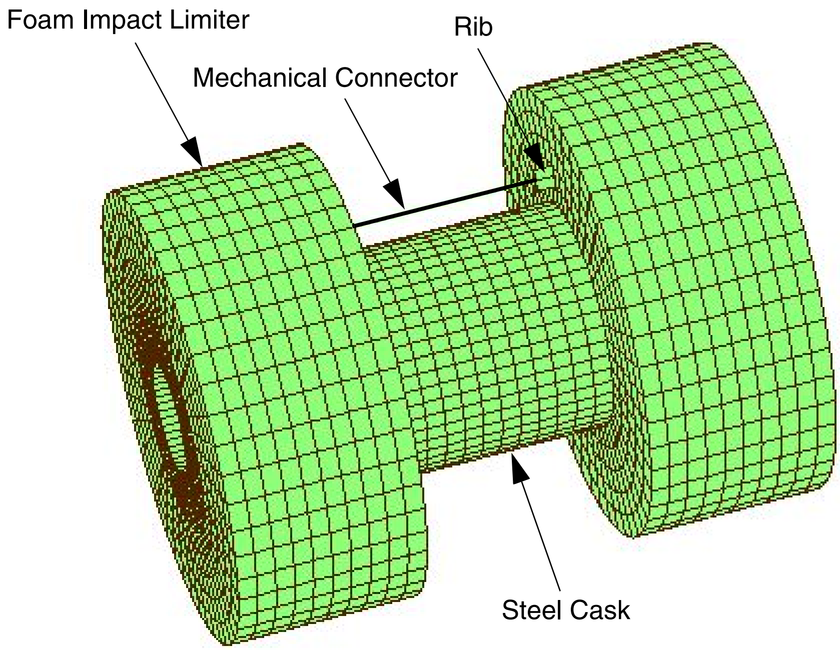


Figure 2-16. Cask and Impact Limiter FEA Model – Model AOS-100

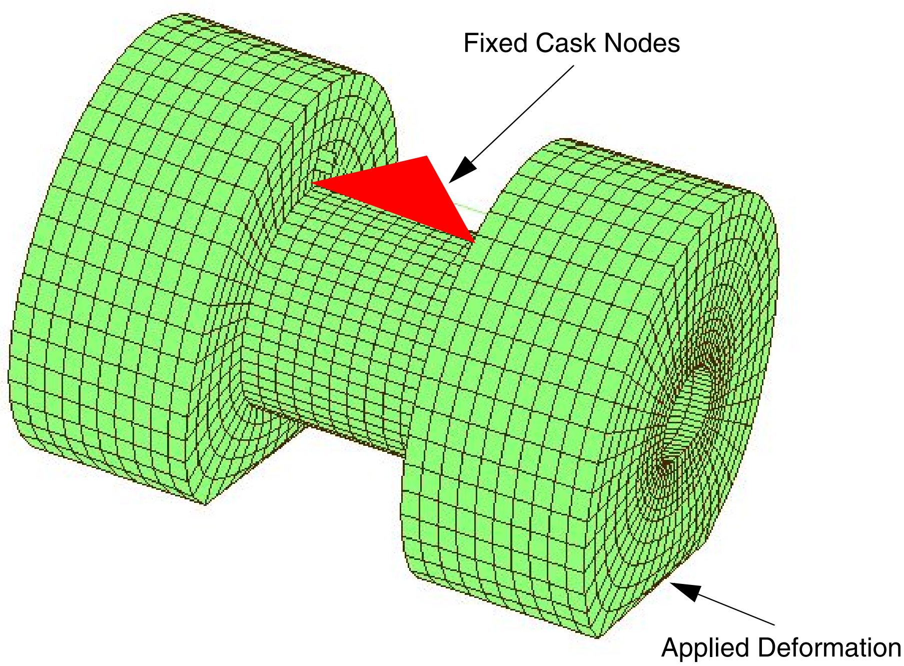


Figure 2-17. Cask and Impact Limiter Deformed FEA Model – Model AOS-100

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 $\times$ 10^5 lbs. Thus, the applied loading of 1.861 $\times$ 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

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

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

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

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

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

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.)

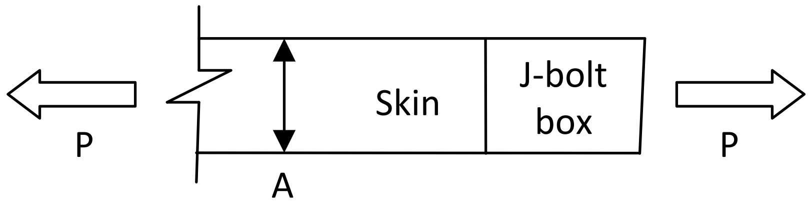


Figure 2-18. Critical Stress at Skin and J-Bolt Box Connection – Model AOS-025

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.)

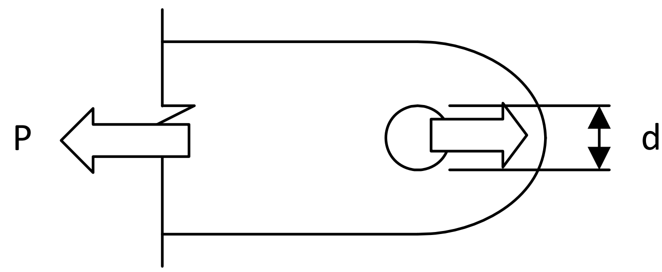


Figure 2-19. Critical Stress at Rib Connector Pin's Bearing – Models AOS-050 and AOS-100

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

Note: *Analyses of the axial shielding plates (Models AOS-050A, AOS-100A, and AOS-100A-S) and cavity spacer plates (Models AOS-100A and AOS-100A-S) are provided in Appendix 2.12.15.*

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:

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

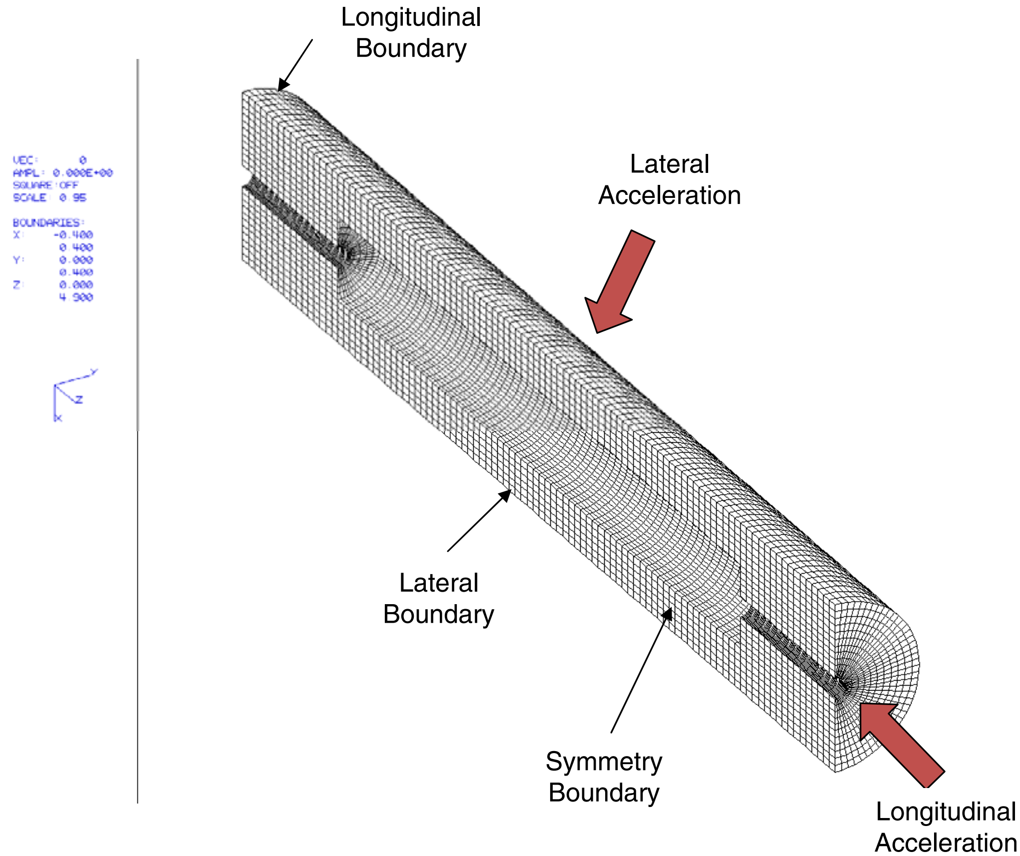


Figure 2-20. LIBRA Liner Model – Model AOS-025

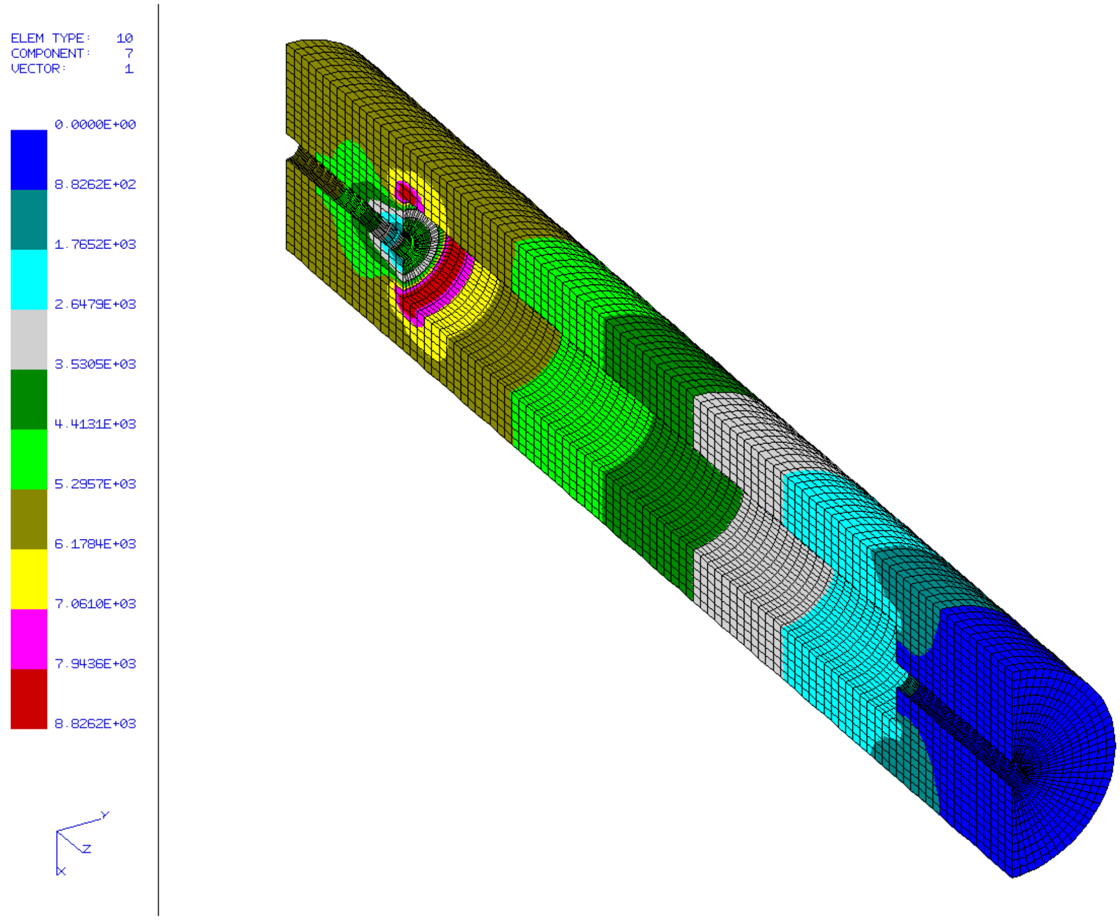


Figure 2-21. Equivalent Stress Due to Longitudinal Acceleration – Model AOS-025

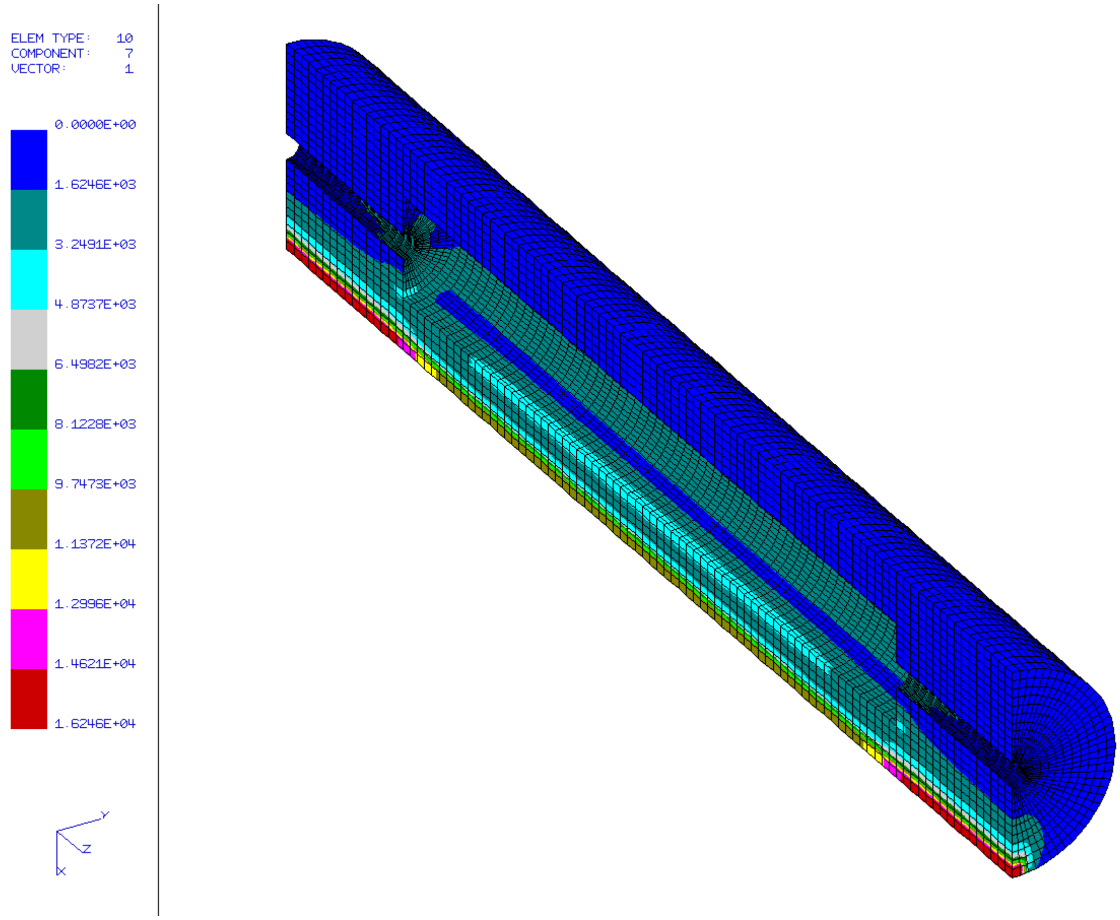


Figure 2-22. Equivalent Stress Due to Transverse Acceleration – Model AOS-025

2.5.3.3.2 DELETED

CONTENT DELETED – Refer to Paragraph 2.12.15.5.

Figure 2-23. DELETED

Figure 2-24. DELETED

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.

---

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.

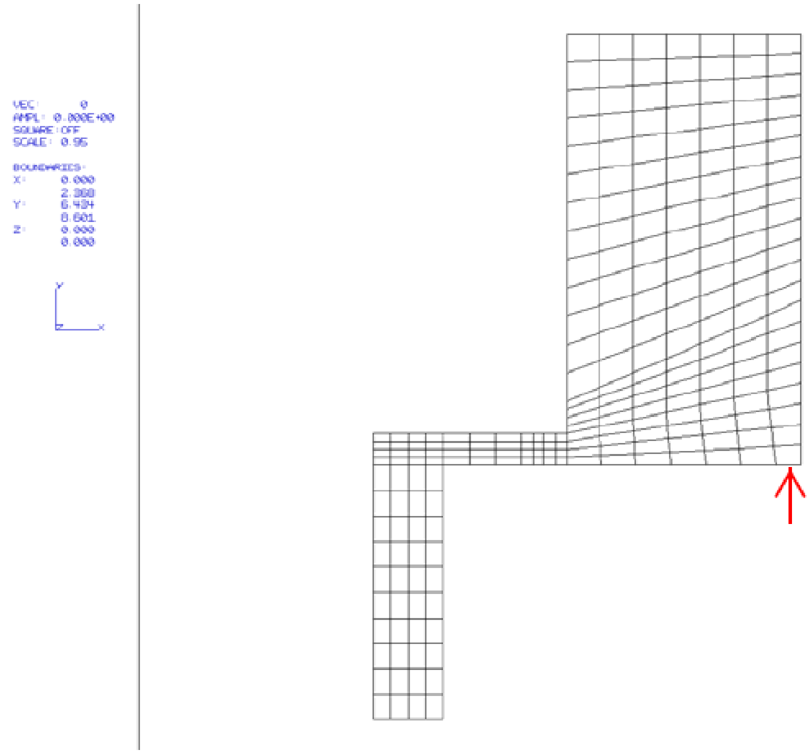
2.6.1.3.2 Design Pressure Stresses

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.).

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



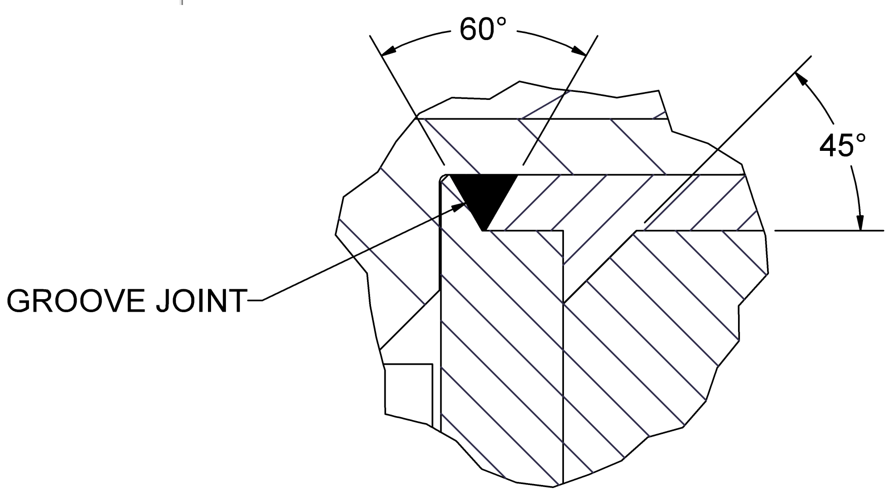


Figure 2-25. Typical Corner Cask Cavity Shell Weld Joint Configuration – All Models

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.

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

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.)

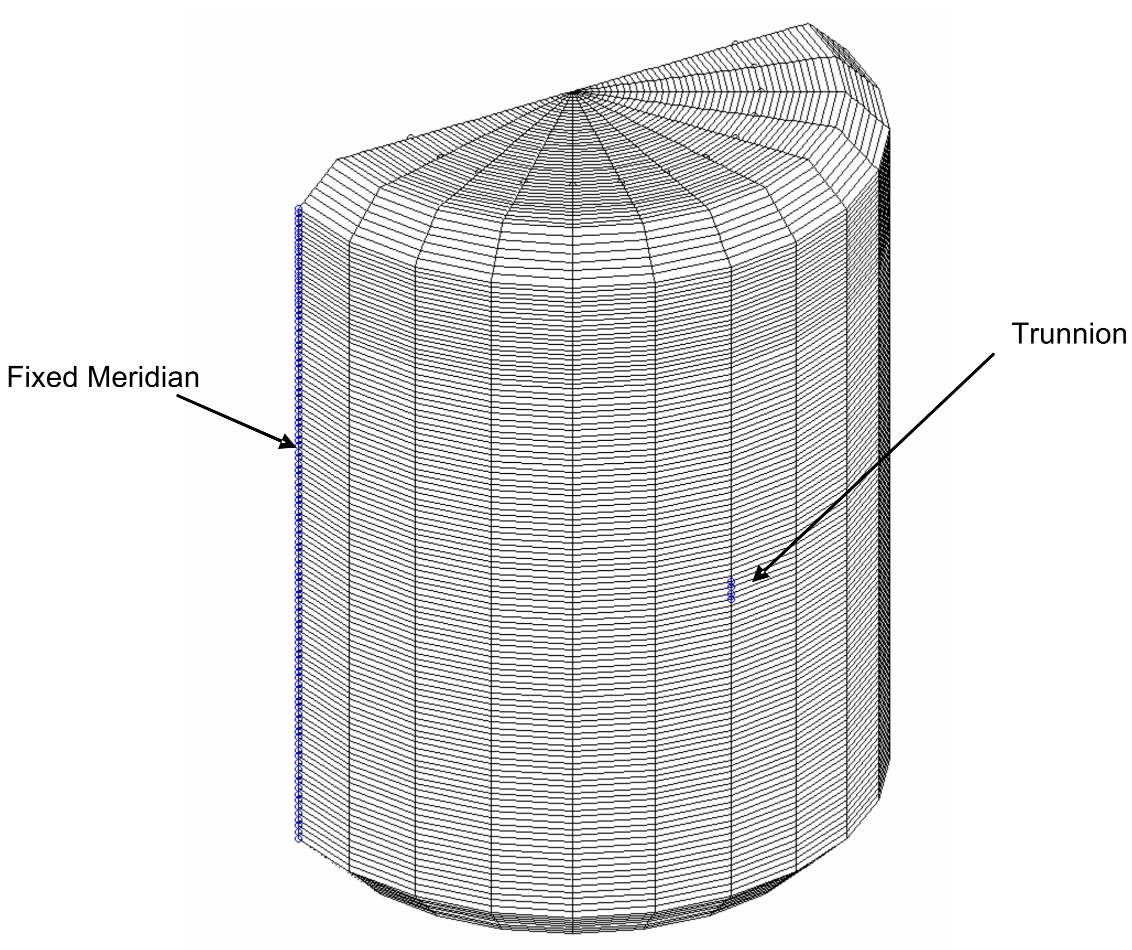


Figure 2-26. Fixed Points for Shock and Vibration Analyses

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

Model	Maximum Authorized Package Weight[a]		Free-Drop Distance	
	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

Model	Drop		Head-On		Side		Cg/Corner	
	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

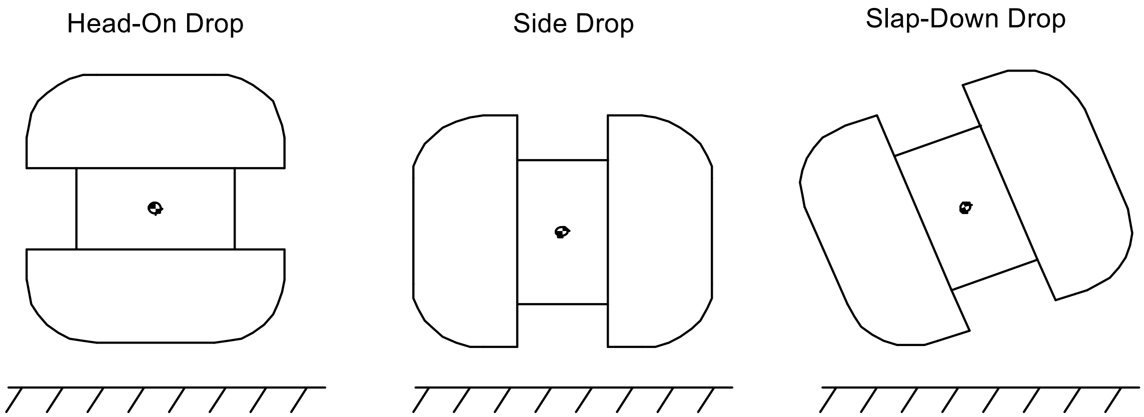


Figure 2-27. Head-On, Side, and Slap-Down Free-Drop Orientations

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.

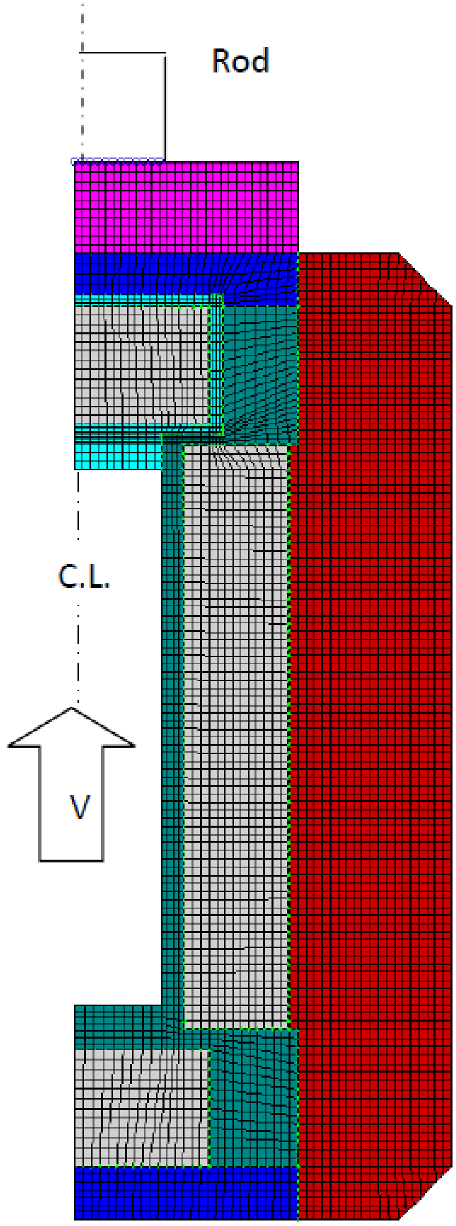


Figure 2-28. Rod Impact Analysis Load Distribution – Model AOS-100

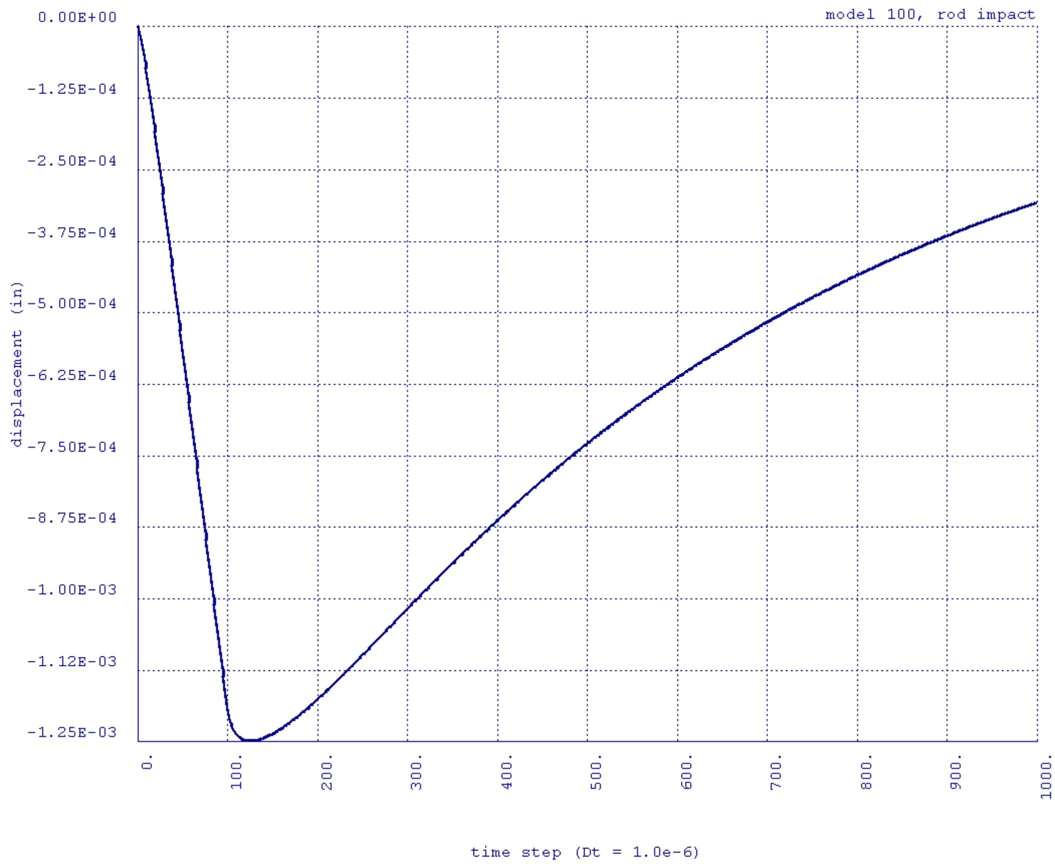


Figure 2-29. Rod Impact Time History Displacement at Impact Node – Model AOS-100

2.6.11 Structural Evaluation Results Summary and Minimum Margins of Safety under Normal Conditions of Transport

In this subsection, the resulting stresses from analyses for Normal conditions of transport are combined, following Reference **[2.4]** guidelines.

Table 2-36 and Table 2-37 identify the particular table in which the resulting stresses are reported for each AOS Transport Packaging System model, for all Normal conditions of transport Load Cases and Load Combinations, respectively. 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.

Paragraph 2.6.11.1 provides the Minimum Margin of Safety (MS) obtained for each Load Combination and System model, under Normal conditions of transport.

This data shows that the AOS Transport Packaging System has the capacity to endure all Normal conditions of transport, without affecting its ability to contain and shield the radioactive material payload from undue risk to the public.

Table 2-36. Load Cases under Normal Conditions of Transport Structural Evaluation Results – All Models

Load Case	Description	Data, by Model			
		AOS-025A	AOS-050A	AOS-100A AOS-100A-S	AOS-100B
101	100°F Ambient, Maximum Decay Heat	Table 2-66	Table 2-135	Table 2-204	Table 2-272
102	100°F Ambient, Maximum Decay Heat, Maximum Insolation	Table 2-67	Table 2-136	Table 2-205	Table 2-273
103	-20°F Ambient, Zero Decay Heat, Zero Insolation	Table 2-68	Table 2-137	Table 2-206	Table 2-274
104	-40°F Ambient, Zero Decay Heat, Zero Insolation	Table 2-69	Table 2-138	Table 2-207	Table 2-275
105	-40°F Ambient, Maximum Decay Heat	Table 2-70	Table 2-139	Table 2-208	Table 2-276
106	-20°F Ambient, Maximum Decay Heat	Table 2-71	Table 2-140	Table 2-209	Table 2-277
201	Internal Design Pressure	Table 2-72	Table 2-141	Table 2-210	Table 2-278
202	Minimum External Pressure, 24 kPa (3.5 psia)	Table 2-73	Table 2-142	Table 2-211	Table 2-279
203	Maximum Increased External Pressure, 140 kPa (20 psia)	Table 2-74	Table 2-143	Table 2-212	Table 2-280
204	Additional Increased External Pressure, 2 MPa (290 psia)	Table 2-75	Table 2-144	Table 2-213	Table 2-281
211	Fabrication Stress	Table 2-76	Table 2-145	Table 2-214	Table 2-282
215	Compression Load (5x weight)	Table 2-77	Table 2-146	Table 2-215	Table 2-283
216	Rod Drop onto Cask	Table 2-78	Table 2-147	Table 2-216	Table 2-284
221	Forward 10g Vibration Inertia Load	Table 2-79	Table 2-148	Table 2-217	Table 2-285
222	Lateral 5g Vibration Inertia Load	Table 2-80	Table 2-149	Table 2-218	Table 2-286
223	Vertical 2g Vibration Inertia Load	Table 2-81	Table 2-150	Table 2-219	Table 2-287
231	3- or 4-ft. Head-On Drop	Table 2-82	Table 2-151	Table 2-220	Table 2-288
232	30-ft. Head-On Drop Impact Test, Normal Conditions	Table 2-83	Table 2-152	Table 2-221	Table 2-289

Table 2-37. Load Combinations under Normal Conditions of Transport Structural Evaluation Results – All Models

Load Combination	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
102	104, 201, 211	Cold Environment	Table 2-85	Table 2-154	Table 2-223	Table 2-291
103	103, 202, 211	Increased External Pressure	Table 2-86	Table 2-155	Table 2-224	Table 2-292
104	101, 201, 202, 211	Minimum External Pressure	Table 2-87	Table 2-156	Table 2-225	Table 2-293
105	105, 201, 202, 211	Cold Environment with Maximum Decay Heat	Table 2-88	Table 2-157	Table 2-226	Table 2-294
106	101, 201, 203, 211	Maximum Pressure, Hot Environment	Table 2-89	Table 2-158	Table 2-227	Table 2-295
107	105, 201, 203, 211	Maximum Pressure, Cold Environment	Table 2-90	Table 2-159	Table 2-228	Table 2-296
215	215, 101, 201, 211	Compression Load	Table 2-91	Table 2-160	Table 2-229	Table 2-297
216	216, 101, 201, 211	Rod Drop	Table 2-92	Table 2-161	Table 2-230	Table 2-298
217	216, 104, 201, 211	Rod Drop, Cold Environment	Table 2-93	Table 2-162	Table 2-231	Table 2-299
221	221, 101, 201, 211	Forward Vibration	Table 2-94	Table 2-163	Table 2-232	Table 2-300
222	222, 101, 201, 211	Lateral Vibration	Table 2-95	Table 2-164	Table 2-233	Table 2-301
223	223, 101, 201, 211	Vertical Vibration	Table 2-96	Table 2-165	Table 2-234	Table 2-302
224	221, 103, 201, 211	Forward Vibration at Cold Temperature	Table 2-97	Table 2-166	Table 2-235	Table 2-303
225	222, 103, 201, 211	Lateral Vibration at Cold Temperature	Table 2-98	Table 2-167	Table 2-236	Table 2-304
226	223, 103, 201, 211	Vertical Vibration at Cold Temperature	Table 2-99	Table 2-168	Table 2-237	Table 2-305

Table 2-37. Load Combinations under Normal Conditions of Transport Structural Evaluation Results – All Models (Continued)

Load Combination	Load Cases	Description	Data, by Model			
			AOS-025A	AOS-050A	AOS-100A AOS-100A-S	AOS-100B
231	231, 102, 201, 211	3- or 4-ft. Head-On Drop, Normal Conditions	Table 2-100	Table 2-169	Table 2-238	Table 2-306
232[a]	232, 102, 201, 211	30-ft. Head-On Drop, Normal Conditions (Impact Test)	Table 2-101	Table 2-170	–	–
233	231, 103, 211	3- or 4-ft. Drop at Cold Temperature	Table 2-102	Table 2-171	Table 2-239	Table 2-307

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]***).*

2.6.11.1 Minimum Margins of Safety

Table 2-38 through Table 2-41 provide the Minimum Margin of Safety (MS) obtained for each Load Combination and Transport Packaging System model, under Normal conditions of transport.

Table 2-38. Min MS for Normal Conditions of Transport – Model AOS-025A

Ld_Cmb	Load_Cases					Min_MS	Loc	Str_Cmb
101	102	201	211	0	0	5.630E+00	20	Pm+Pb
102	104	201	211	0	0	2.146E+00	5	Pm+Pb+Q
103	103	202	211	0	0	2.841E+00	5	Pm+Pb+Q
104	101	201	202	211	0	2.943E+00	20	Pm+Pb
105	105	201	202	211	0	2.943E+00	20	Pm+Pb
106	101	201	203	211	0	2.889E+00	20	Pm+Pb
107	105	201	203	211	0	2.889E+00	20	Pm+Pb
215	215	101	201	211	0	5.457E+00	20	Pm+Pb
216	216	101	201	211	0	3.306E-01	15	Pm
217	216	104	201	211	0	3.306E-01	15	Pm
221	221	101	201	211	0	5.612E+00	20	Pm+Pb
222	222	101	201	211	0	5.567E+00	20	Pm+Pb
223	223	101	201	211	0	5.505E+00	20	Pm+Pb
224	221	103	201	211	0	2.717E+00	5	Pm+Pb+Q
225	222	103	201	211	0	2.704E+00	5	Pm+Pb+Q
226	223	103	201	211	0	2.686E+00	5	Pm+Pb+Q
231	231	102	201	211	0	2.821E+00	4	Pm+Pb
232	232	102	201	211	0	2.354E+00	4	Pm+Pb
233	231	103	211	0	0	2.678E+00	5	Pm+Pb+Q

Table 2-39. Min MS for Normal Conditions of Transport – Model AOS-050A

Ld_Cmb	Load_Cases					Min_MS	Loc	Str_Cmb
101	102	201	211	0	0	5.819E+00	4	Pm+Pb
102	104	201	211	0	0	2.164E+00	5	Pm+Pb+Q
103	103	202	211	0	0	2.771E+00	5	Pm+Pb+Q
104	101	201	202	211	0	5.535E+00	4	Pm+Pb
105	105	201	202	211	0	5.535E+00	4	Pm+Pb
106	101	201	203	211	0	4.918E+00	4	Pm+Pb
107	105	201	203	211	0	4.918E+00	4	Pm+Pb
215	215	101	201	211	0	4.990E+00	4	Pm+Pb
216	216	101	201	211	0	1.285E+00	15	Pm
217	216	104	201	211	0	1.285E+00	15	Pm
221	221	101	201	211	0	5.732E+00	4	Pm+Pb
222	222	101	201	211	0	5.775E+00	4	Pm+Pb
223	223	101	201	211	0	5.816E+00	4	Pm+Pb
224	221	103	201	211	0	2.681E+00	5	Pm+Pb+Q
225	222	103	201	211	0	2.684E+00	5	Pm+Pb+Q
226	223	103	201	211	0	2.686E+00	5	Pm+Pb+Q
231	231	102	201	211	0	3.266E+00	4	Pm+Pb
232	232	102	201	211	0	1.032E+00	4	Pm+Pb
233	231	103	211	0	0	2.454E+00	5	Pm+Pb+Q

Table 2-40. Min MS for Normal Conditions of Transport – Model AOS-100A and AOS-100A-S

Ld_Cmb	Load_Cases					Min_MS	Loc	Str_Cmb
101	102	201	211	0	0	1.196E+00	4	Pm+Pb
102	104	201	211	0	0	1.196E+00	4	Pm+Pb
103	103	202	211	0	0	5.387E+00	5	Pm+Pb+Q
104	101	201	202	211	0	1.146E+00	4	Pm+Pb
105	105	201	202	211	0	1.146E+00	4	Pm+Pb
106	101	201	203	211	0	1.087E+00	4	Pm+Pb
107	105	201	203	211	0	1.087E+00	4	Pm+Pb
215	215	101	201	211	0	9.375E-01	4	Pm+Pb
216	216	101	201	211	0	1.128E+00	15	Pm+Pb
217	216	104	201	211	0	1.128E+00	15	Pm+Pb
221	221	101	201	211	0	1.068E+00	4	Pm+Pb
222	222	101	201	211	0	1.176E+00	4	Pm+Pb
223	223	101	201	211	0	1.191E+00	4	Pm+Pb
224	221	103	201	211	0	1.068E+00	4	Pm+Pb
225	222	103	201	211	0	1.176E+00	4	Pm+Pb
226	223	103	201	211	0	1.191E+00	4	Pm+Pb
231	231	102	201	211	0	1.127E+00	4	Pm+Pb
233	231	103	211	0	0	5.347E+00	5	Pm+Pb+Q

Table 2-41. Min MS for Normal Conditions of Transport – Model AOS-100B

Ld_Cmb	Load_Cases					Min_MS	Loc	Str_Cmb
101	102	201	211	0	0	1.196E+00	4	Pm+Pb
102	104	201	211	0	0	1.196E+00	4	Pm+Pb
103	103	202	211	0	0	1.101E+01	4	Pm+Pb
104	101	201	202	211	0	1.146E+00	4	Pm+Pb
105	105	201	202	211	0	1.146E+00	4	Pm+Pb
106	101	201	203	211	0	1.087E+00	4	Pm+Pb
107	105	201	203	211	0	1.087E+00	4	Pm+Pb
215	215	101	201	211	0	9.375E-01	4	Pm+Pb
216	216	101	201	211	0	1.128E+00	15	Pm+Pb
217	216	104	201	211	0	1.128E+00	15	Pm+Pb
221	221	101	201	211	0	1.068E+00	4	Pm+Pb
222	222	101	201	211	0	1.176E+00	4	Pm+Pb
223	223	101	201	211	0	1.191E+00	4	Pm+Pb
224	221	103	201	211	0	1.068E+00	4	Pm+Pb
225	222	103	201	211	0	1.176E+00	4	Pm+Pb
226	223	103	201	211	0	1.191E+00	4	Pm+Pb
231	231	102	201	211	0	1.127E+00	4	Pm+Pb
233	231	103	211	0	0	1.043E+01	4	Pm+Pb

2.7 HYPOTHETICAL ACCIDENT CONDITIONS

The AOS Transport Packaging System, when subjected to the Hypothetical Accident conditions of transport specified in *10 CFR 71.73*, meets the performance requirements specified in *10 CFR 71* **[2.1]**, Subpart E. This is demonstrated within this section where the Hypothetical Accident conditions of transport are addressed and shown to meet the applicable design criteria provided in Subsection 2.1.2, "Design Criteria."

The engineering evaluation for these regulatory conditions was conducted by using the LIBRA Finite Element program. The analytical model used was verified by a Free-Drop test of a 165% scaled-up version of the Model AOS-100A, referred to as "AOS-165A" and/or "prototype" in the discussions. The testing conducted and results are also briefly discussed within this section; however, the complete test report is included in Appendix 2.12.6.

The scaled-up Free-Drop test was conducted at General Electric ("GE Hitachi Nuclear Energy" at the time of this publication), Vallecitos Nuclear Center, Sunol, California, for Alpha-Omega Services, Inc., of Bellflower, California. In addition, Alpha-Omega Services contracted CSA Engineering, Inc., of Mountain View, California, to instrument and record the test results, and RANOR, Inc., of Westminster, Massachusetts, to fabricate the prototype packaging. GE Hitachi Nuclear Energy contracted RANOR, Inc. to perform pre- and post-dimensional inspections. A copy of the Dimensional Inspection report is included in Appendix 2.12.7.

For Free Drop evaluation, three orientations were analyzed:

- Head-On Drop
- Side Drop, including Slap-Down
- Cg/Corner Drop

The first two drop orientations were correlated to the Free-Drop test data, for validation of the analytical model and procedure used. The correlation work is also included in this section.

2.7.1 Free Drop

The AOS Transport Packaging System is described in Subsection 2.1.1, "Discussion." As discussed in that subsection, the cask component is covered at both ends by the impact limiter. The impact limiter is designed to absorb the energy developed during the drop, mitigating the drop's effect on the cask. The analysis presented in this subsection consists of two (2) parts:

- To identify the load onto the cask, by conducting a pseudo-static collapse analysis of the impact limiter, and
- To impose this resulting load onto the cask in the stress analysis

Hypothetical Accident conditions of transport are provided in Appendix 2.12.2.

The AOS Transport Packaging System has an axisymmetric geometry. The Head-On Drop is oriented with the cask lid facing down, to produce the maximum damage on the cask lid seal joint. For the Side Drop, the cask is oriented to produce maximum side loading. The Slap-Down Drop is oriented to produce the maximum slap-down loading. The Cg/Corner Drop is oriented such that impact occurs on a line through the cask center of gravity.

Notes: *The Cg/Corner Drop loading condition was not one of the orientations tested. This condition does not produce as critical a load as the Slap-Down loading. Additionally, the design has a recessed cask lid, which protects the cask lid seal and cask lid attachment bolts.*

The foam properties used in the free drop analysis are those presented in Appendix 2.12.5 **[2.19]** *for the foam density values of 20, 10, and 12 pcf. for the Model AOS-025, AOS-050, and AOS-100, respectively.*

The Impact (Free-Drop) test is conducted to obtain data to demonstrate the adequacy of analytical methods used for qualifying the transport packages, both at the size tested and scaled-down versions. The AOS-165A was selected for this test because it is the largest package, in terms of size and weight. These analytical methods are used to show that the impact limiters are capable of limiting impact loads on the payload to an acceptable level.

Appendix 2.12.6 presents the Free-Drop Test report, which includes a detailed description of the test procedure. Appendix 2.12.7 presents the Dimensional Inspection report of the impact limiter and cask components, taken throughout the Free-Drop test. Appendix 2.12.13 presents the Certificate of Conformance for the General Plastics LAST-A-FOAM FR-3720 foam used in the AOS-165A prototype.

A 9-m (30-ft.) Drop test is conducted on a 165% scaled-up version of the Model AOS-100A, the AOS-165A prototype. The test article weighs approximately 18,144 kg (40,000 lbs.). Three (3) free drops, each with the package at a different orientation, are conducted as part of the test:

- **End (Head-On orientation)** – Package axis is vertically oriented
- **Side (Side orientation)** – Package axis is horizontally oriented
- **Slap-Down** – Package axis is oriented at a pre-determined angle with the impact plane to cause maximum slap-down load

Figure 2-30 illustrates the three (3) free drop orientations and test setup. The test sequence listed above can be changed during the tests. High-speed cameras from two (2) orthogonal directions were used to document the orientation prior to each drop. (Refer to Figure 2-31 for camera positioning.)

Acceleration time history data is recorded during the test, using accelerometers located inside the cask and on the impact limiter. A total of 10 sensors are used. One triaxial accelerometer is mounted on the impact limiter, at a location determined by CSA Engineering, Inc. (the company contracted to conduct the test). Two (2) triaxial accelerometers are mounted inside the payload cavity, one on each end of the dummy mass. Each triaxial accelerometer senses in the radial, tangential, and axial directions. The tenth sensor is a uniaxial accelerometer sensing in the vertical direction for the drop.

The impact force distribution on the cask surface is estimated using a pressure-sensing film applied prior to each drop and removed immediately afterward. The film is used on the top and curved surfaces of the cask, enclosed by the impact limiters.

In addition, a series of dimensional inspections of the cask and impact limiter are conducted before and after each drop, to establish the drop's resulting deformation pattern.

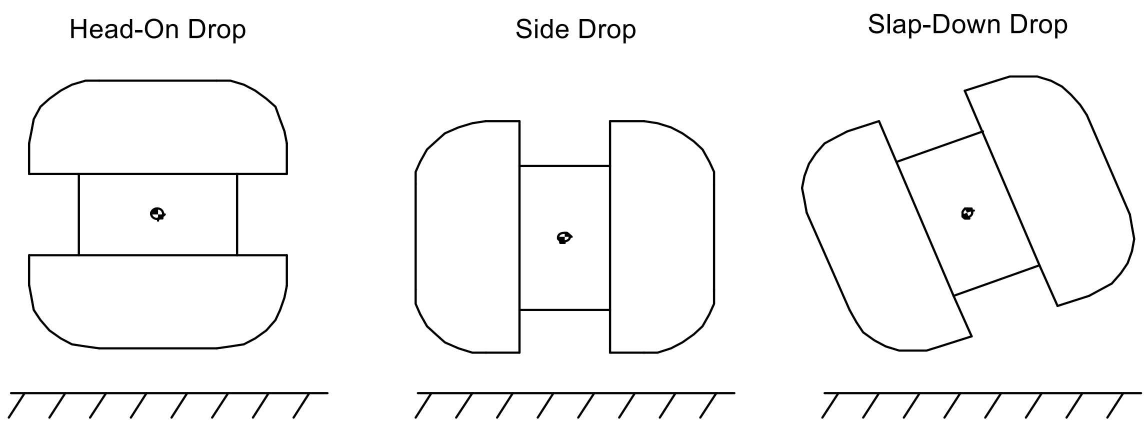


Figure 2-30. Head-On, Side, and Slap-Down Free-Drop Orientations

A portable 90-ton hydraulic crane is used to position the package at the proper height of 9m (30 ft.) or greater, above the impact surface. To prevent crane boom backlash after the load is released, the crane hook must be connected to two (2) dead weights by wire rope slings. This maintains the load on the crane after the package is released. (Refer to Figure 2-31.)

A quick-release (air-actuated, pneumatic) mechanism is used to release the package and allow it to fall freely. The mechanism is attached to the crane hook and package holding gear [3.7-m (12-ft.) wire rope sling]. The only connections to the package during the drop are the light instrumentation cables. The cables are arranged so that they do not interfere with the free-fall path of the package. Attached to the slings is a 3-gallon air accumulator tank and fast-acting, electrically triggered diaphragm valve mounted close to the quick-release mechanism.

Drop height is determined by means of a light, graduated chain or measuring tape, hanging from the lowest point of the package to the ground. After the drop height is verified, the graduated chain or measuring tape is removed prior to the drop.

The primary pass-fail criterion for the test is based upon a Leak Rate test, conducted upon the transport package's cask component before and after the Drop tests. Subsection 8.1.4, "Leakage Tests," details the Leak test methodology. An acceptable leak rate is less than 2.96×10^{-7} cm^3/sec (helium), at a differential pressure of 1 atmosphere.

Note: *For the transport package to be judged acceptable, the measured leak rate must be less than this amount, both before and after the Drop tests.*

The secondary criterion relates to external transport package dimensions. These must not have changed by any amount that would prevent or endanger the transport package's performance of its primary functions – containment and shielding.

Figure 2-31. Test Setup (Head-On Orientation Shown) – AOS-165A Prototype

2.7.1.1 End Drop

2.7.1.1.1 Head-On Free-Drop Impact Limiter Analysis – Model AOS-100

The Model AOS-100 transport package's impact limiter structure is composed of General Plastics LAST-A-FOAM FR-3712 foam and 12-gauge (2.7 mm / 0.105 in.) stainless steel cladding. The entire assembly consists of two (2) impact limiters connected by eight (8) turnbuckles. Each impact limiter is approximately 116 cm (45.65 in.) in diameter by 62.5 cm (24.6 in.) in height. There is an uncovered cask length of approximately 56 cm (22 in.) between the impact limiters. The impact limiter end is a spherical, dish shell. In addition, the ends contain a recessed, cylindrical section of approximately 41 cm (16.2 in.) in diameter by 12.4 cm (5.0 in.) in depth.

The foam material accounts for most of the impact limiter's energy absorbing capability. The energy absorbed by the cladding is small and not included in this analysis. Also, not included in the analytical models are the eight (8) structural ribs that are part of the impact limiter structure because they have little effect on the behavior of the impact limiter due to the free drop load. The omission of the ribs are justified by the analysis presented in Appendix 2.12.10. The impact limiter foam is analyzed by static, 3D, large displacement, finite element analyses. The foam is modeled by solid elements with Piola-Kirchhoff stress tensors, and FR-3712 foam constitutive behavior. Strain energy developed in the foam is determined for a sequence of applied displacement fields corresponding to the impact of the cask on a rigid plane. Displacements are applied in 0.25 mm (0.01 in.) increments for both head-on and side drop configurations, until the strain energy developed in the foam equals the potential energy of a 9-m (30-ft.) drop. The configuration corresponding to the maximum slap-down impact is determined from a series of dynamic analyses with different cask impact orientations and side-drop impact properties. The orientation producing maximum impact force is selected as the slap-down configuration.

Figure 2-32 shows the FEA model used in the drop analyses. The model represents a 180° section of the impact limiter and contains 2,835 nodes, 2,220 elements, and 8,496 degrees of freedom. A small, artificial hole is modeled at the axis of rotation of the impact limiter, to restrict the model to 8-node solid elements. Radial degrees of freedom are fixed at the hole. Foam element constitutive properties are taken from Table 2-14 and Table 2-15.

The interaction between the content and cask lid due to the free drop load is provided in Appendix 2.12.8.

In the impact analysis, a series of displacement fields simulating the head-on impact of the impact limiter onto a rigid surface was applied. The displacement steps correspond to 0.25 mm (0.01 in.) displacements of the rigid surface. The geometric and constitutive element properties were updated after each displacement step. Figure 2-33 illustrates the strain energy developed in the foam, and total force at the rigid surface, as a function of surface displacement. For a 180° model, and 9,510-lb. weight (Model AOS-100 is used for reference), the maximum displacement corresponds to the strain energy.

$$U = 9{,}510 * 360 = 3.42 \times 10^6 \text{ in.-lb.}$$

From Figure 2-33, the corresponding displacement is 15.5 cm (6.1 in.), the total force is 1.42×10^6 lbs., and the maximum acceleration is:

$$a = 1.42 \times 10^6 / 9{,}510 = 149.3g$$

Figure 2-34 shows longitudinal foam displacements, where the displacement contours are plotted on the deformed geometry. The equivalent stress at maximum displacement is plotted in Figure 2-35.

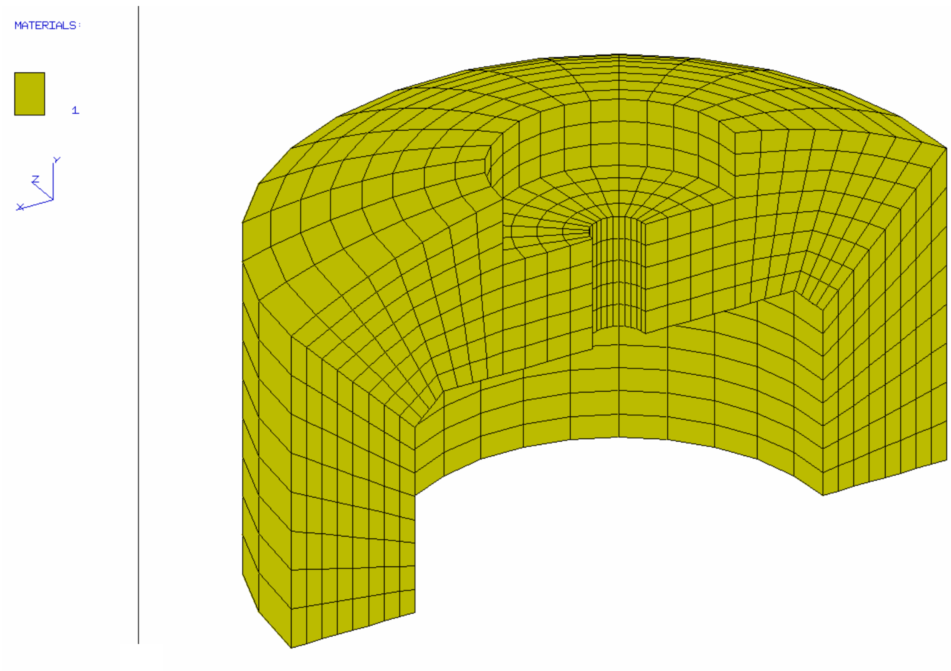


Figure 2-32. Finite Element Model of Impact Limiter – Model AOS-100

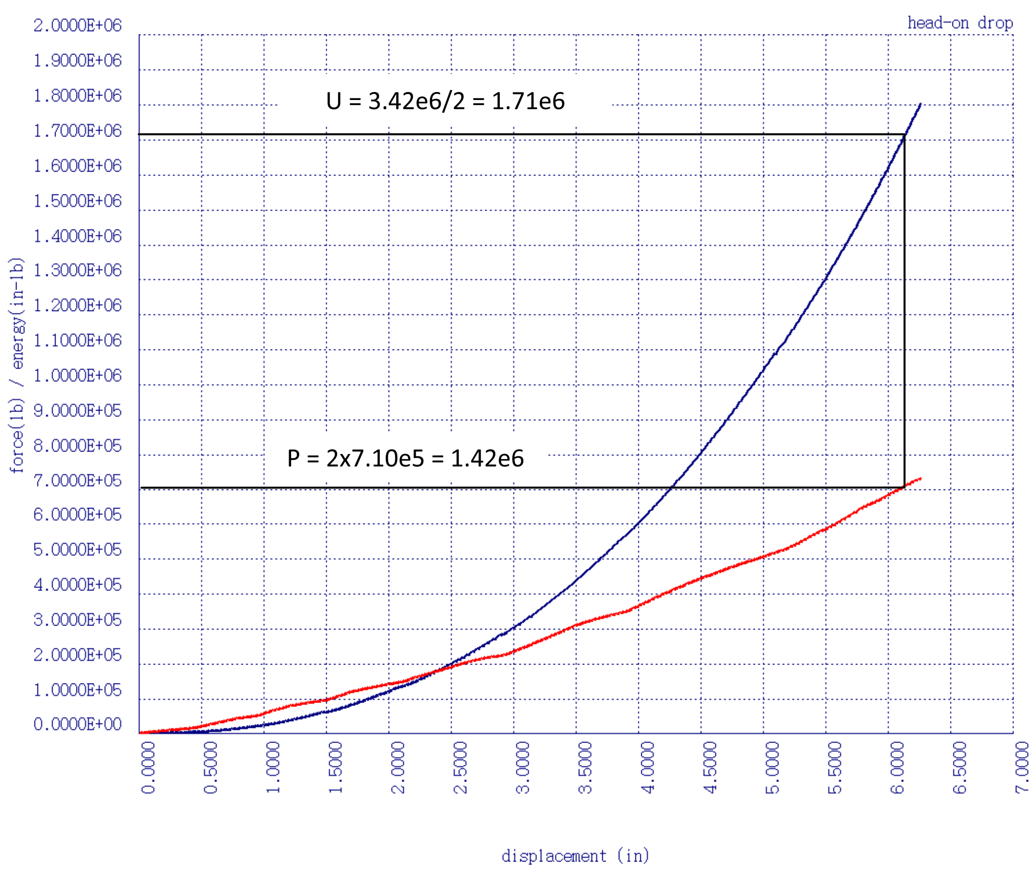


Figure 2-33. Head-On Drop Force and Energy – Model AOS-100

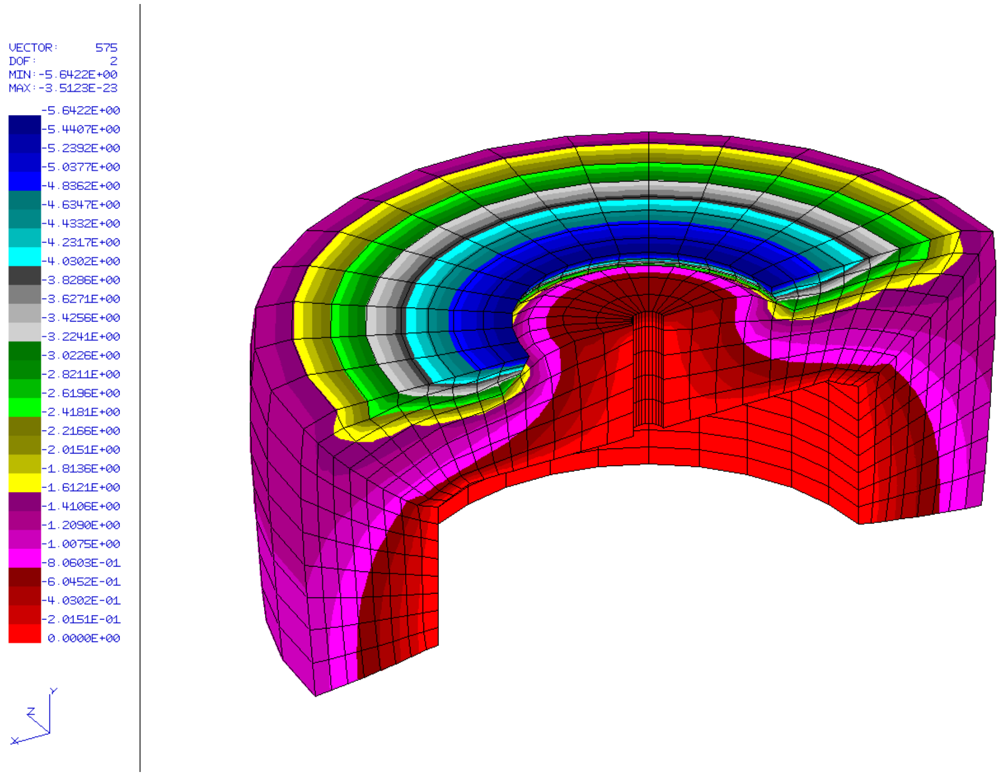


Figure 2-34. Head-On Drop, Maximum Foam Displacement (Deformed Model) – Model AOS-100

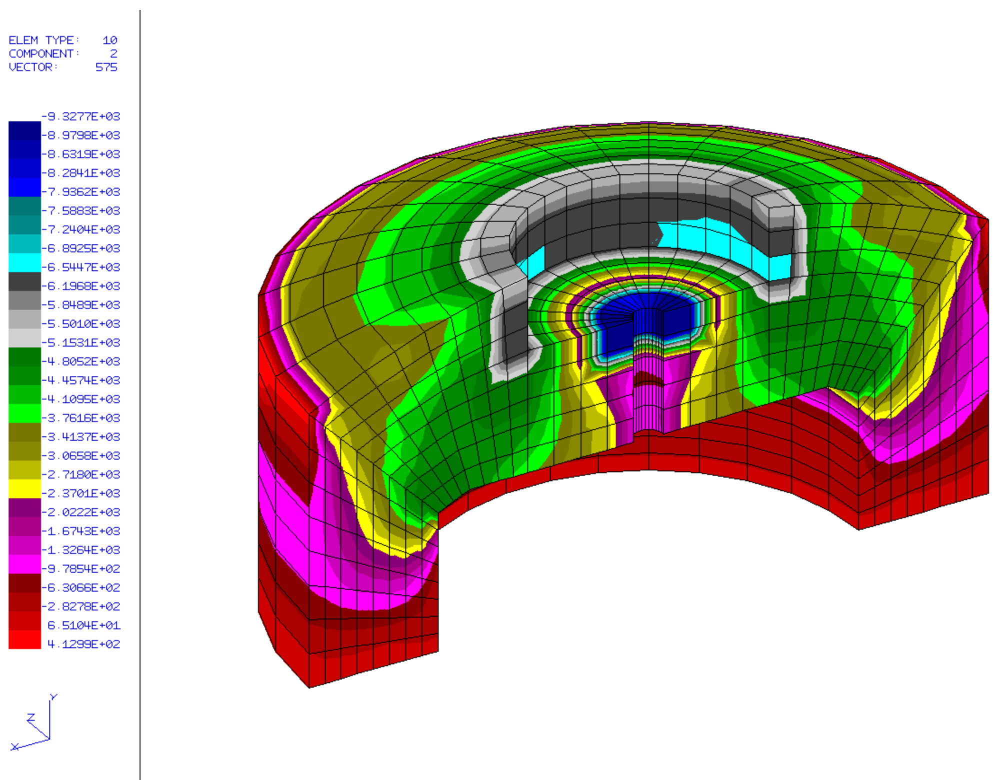


Figure 2-35. Head-On Drop, Maximum Equivalent Stress in Foam – Model AOS-100

2.7.1.1.2 Head-On Free-Drop Cask Analysis

A net force due to a 30-ft. head-on drop, Load Case 301, is determined from the impact limiter analysis presented in Paragraph 2.7.1.1.1. Stress due to head-on drop loads was analyzed by the 2D cask model. Figure 2-36 shows the assumed impact load distribution. With reference to Figure 2-36, for a total impact force P, the load intensity is given by:

$$q = P / \pi (R_1^2 - R_2^2)$$

Over section L, the load intensity in the *x* and *y* directions is:

$$q_x = q_y = q * \sin(45°)$$

The LIBRA LE -4[a] loading function is used to apply pressure load q. In addition to the impact load, an opposing inertia body force is applied to the cask. Displacements are fixed along the cask base to account for the small non-equilibrium of pressure and inertia forces.

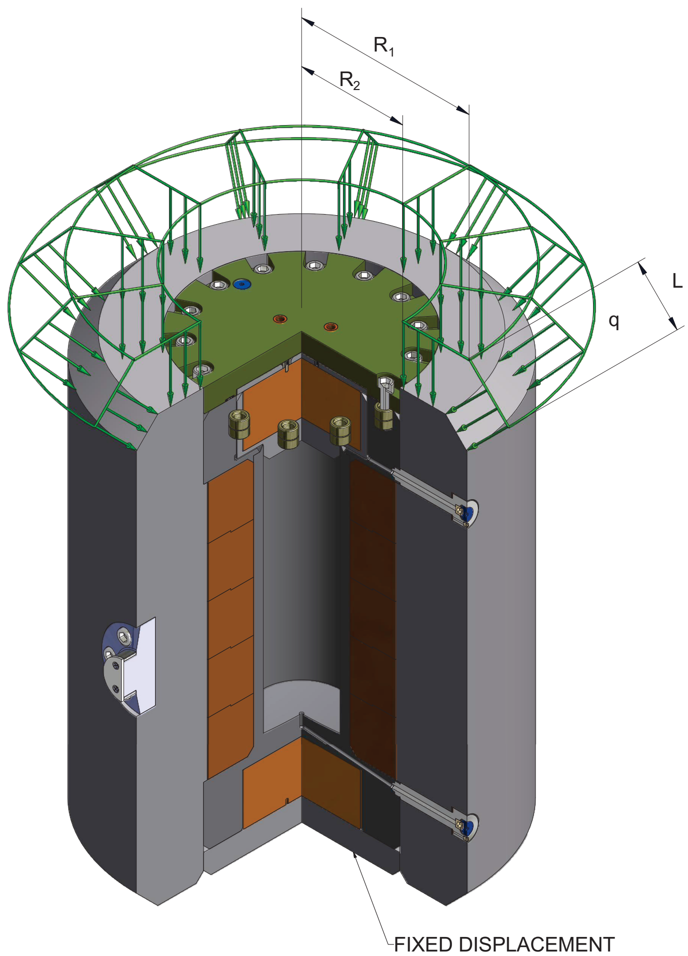


Figure 2-36. Head-On Drop Analysis Load Distribution – All Models

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

2.7.1.1.3 Correlation of Head-On Drop Analysis and Test

In the Drop test, a 165% scaled-up version of the Model AOS-100A (referred to as “AOS-165A” and/or “prototype” in the discussions) was used. A single cask component of the prototype with multiple impact limiters was subjected to three (3), 9.14-m (30-ft.) Drop tests:

- Head-On Drop
- Side Drop
- Slap-Down Drop

In the Slap-Down Drop test, the cask was oriented with one end offset 25.4 cm (10 in.) above the other. Following all three (3) tests, the cask showed no measurable deformation, and passed all Leak tests. The only notable structural problem encountered in the Drop tests was the failure of a turnbuckle pin in the Side Drop test. A larger-diameter pin was successfully used in the subsequent Slap-Down Drop test.

Four (4) types of data were gathered before, during, and after each drop test:

- Acceleration data from three (3) accelerometers
- Laser dimensional readings
- High-speed photographs at 1-ms intervals during impact
- Photographs of the sectioned, deformed impact limiters

The Dimensional Inspection report, presented in Appendix 2.12.7, for the Head-On Drop test, does not provide a direct correlation with the LIBRA analysis, because the laser readings are of the cladding, and the cladding at the center of the impact limiter significantly separated from the foam. A correlation of analysis and test displacement results is obtained from the photo of the sectioned impact limiter, shown in Figure 2-37. This photo provides a measurement of the compressed impact limiter height that can be directly compared to analysis. In Figure 2-37, Dimension A is used to scale the photo measures to design dimensions, and Dimension B is the overall height.

Design Dimensions	A	=	46.6 in.
	B	=	39.0 in.
Photo Dimensions	a	=	4.85 in.
	b	=	3.60 in.
Scale Factor	X	=	A / a = 46.6 in. / 4.85 in. = 9.61 in.
Compressed Height from Photo	B'	=	X * b = 9.61 in. * 3.60 in. = 34.6 in.
Deflection, δ	B - B'	=	39.0 in. - 34.6 in. = 4.4 in.

The deflection, δ, corresponds to a displacement of 5.5 in. for a cask weight of 37,500 lbs., in Figure 2-44. The analysis and measured values differ by 25%.

In addition to correlating maximum displacements, a qualitative comparison of overall displacements is provided by Figure 2-38 and Figure 2-39. Figure 2-38 is a photo of the deformed impact limiter. Figure 2-39 is a LIBRA-rendered plot of the deformed model. A comparison of these figures shows that the LIBRA deformed model qualitatively compares well with the deformed structure.

The test accelerometer data is dominated by ringing due to vibration of tungsten alloy cylinders, rendering it unsuitable for correlation with the analytical results. A comparison of analytical and test results for head-on, rigid body cask deceleration is obtained using the time to achieve maximum displacement shown on the high-speed photographs, some of which are shown in Figure 2-40. In the Drop Test report, presented in Appendix 2.12.6, the time to achieve maximum displacement is given as 0.021 sec. This time can be calculated by considering the cask and impact limiter to be a single degree of freedom spring-mass system, where the spring is approximated from Figure 2-33, and the mass is the total cask plus impact limiter mass. The period for cask impact limiter, undamped spring-mass system is:

$$k = 5.6 \times 10^6 / 6.2 = 0.90 \times 10^6 \text{ lb/in}$$
$$m = 37{,}500 / 386.4 = 96.3 \text{ lb-sec/in}^2$$
$$f = (k / m)^{0.5} = 96.7 \text{ rad/sec} = 15.4 \text{ Hz}$$
$$T = 1 / f = 0.065 \text{ sec}$$

Due to the foam, the cask experienced high damping during impact. The amount of damping is given by the height of the cask rebound. From the Drop Test report (Appendix 2.12.6), the rebound height was approximately 0.9m (3 ft.), 10% of the drop height, indicating that 90% of the kinetic energy was damped. A series of LIBRA-AGS analyses were conducted, to determine the critical damping coefficient corresponding to a 90% energy loss. As illustrated in Figure 2-42, a critical damping coefficient of $\xi = 0.60$ corresponds approximately to a 90% energy loss. The damped period is then:

$$T' = T / (1 - \xi^2)^{0.5} = 0.065 / 0.80 = 0.0813 \text{ sec}$$

The impact duration is half the period, T'/2 = 0.041 sec, and corresponds to the time at which the cask separates form the ground. From Figure 2-40, separation time is seen to be approximately 0.042 sec, which corresponds well to T'/2. In addition, the maximum displacement occurs at T'/4 (0.023 sec.), which correlates well with the time observed in the test, 0.021 sec.

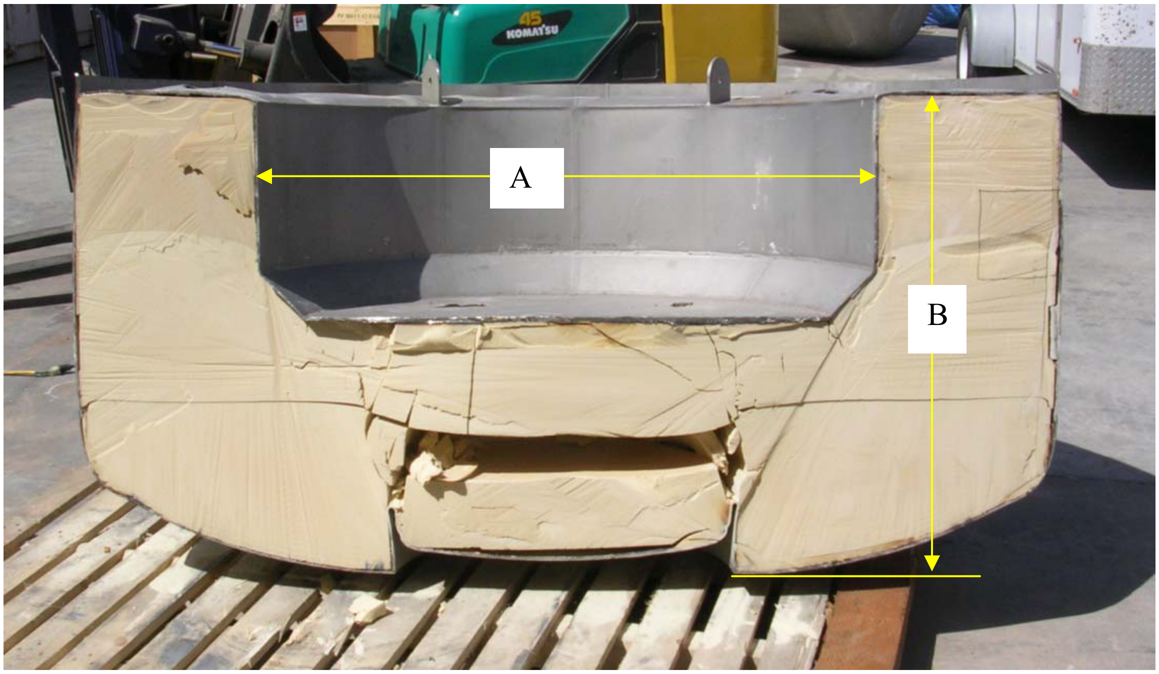


Figure 2-37. Sectioned Impact Limiter Used in Head-On Drop – AOS-165A Prototype

Figure 2-38. Impact Limiter after Head-On Drop – AOS-165A Prototype

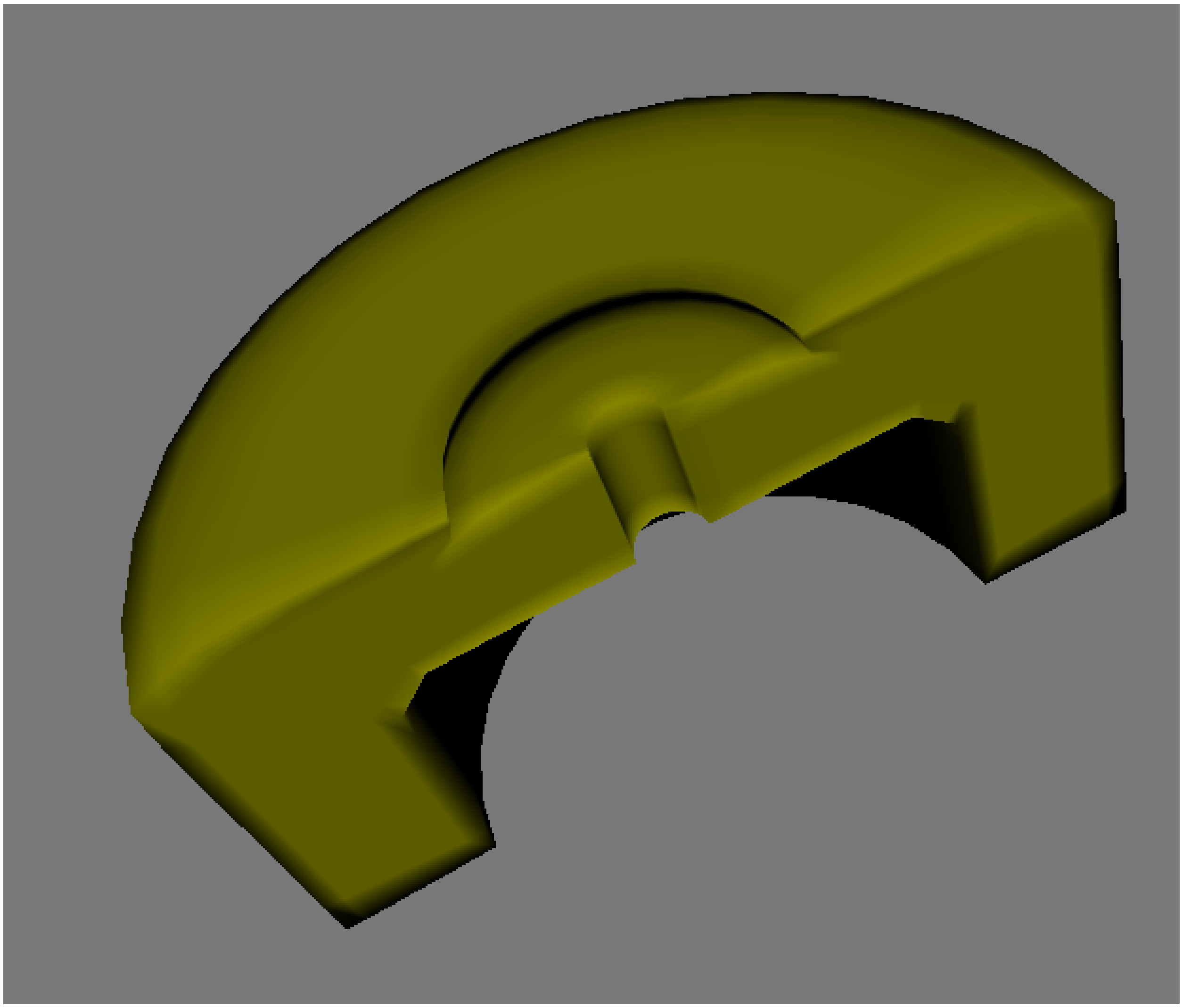


Figure 2-39. Rendered LIBRA Deformed Head-On Drop – AOS-165A Prototype

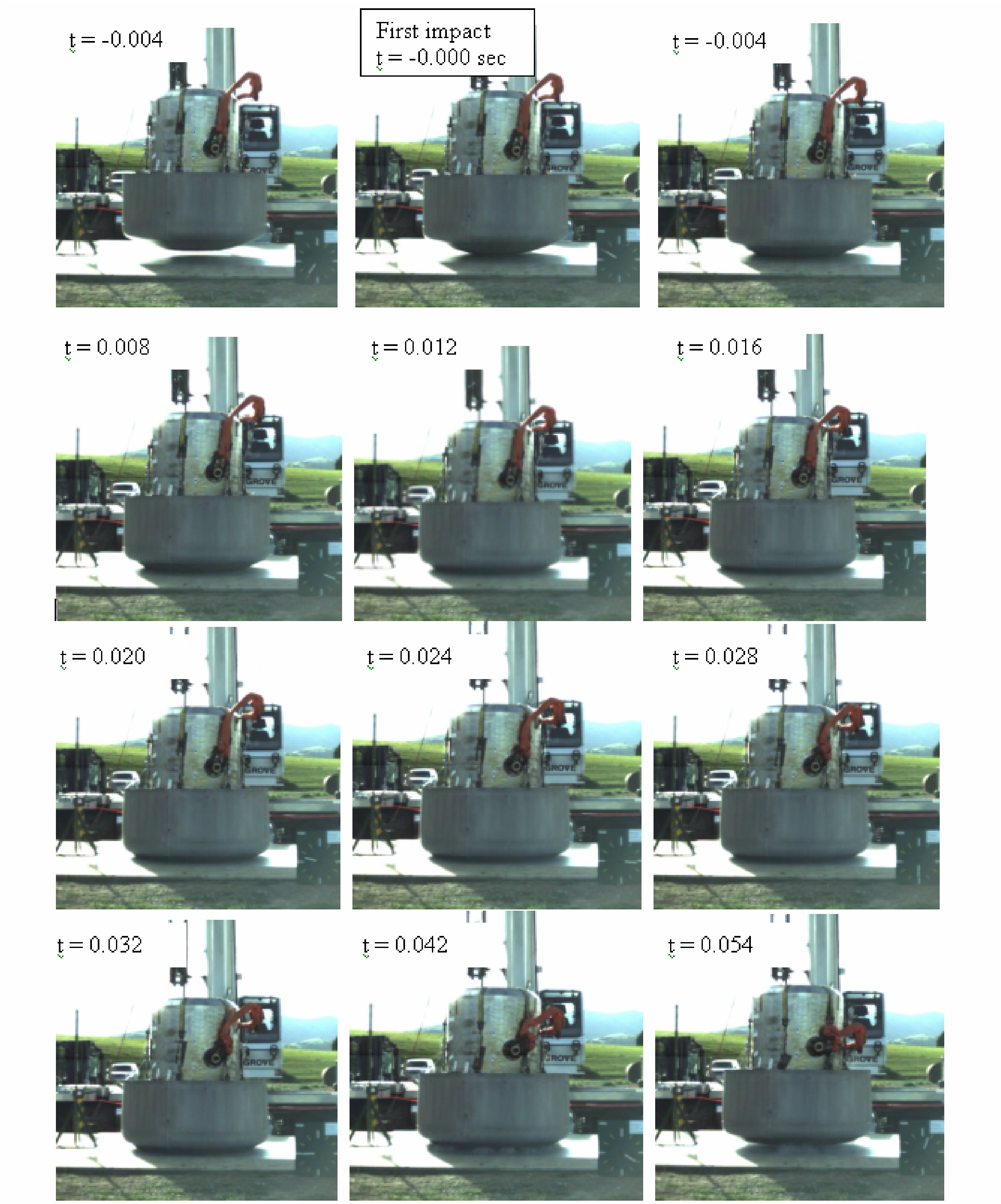


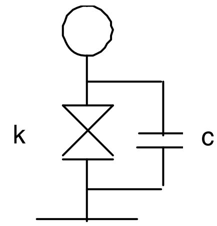
Figure 2-40. Photograph Frames from High-Speed Video of Head-On Drop – AOS-165A Prototype

```
ti   damping analysis
sc   300000,1.0E-6,   0,0.0114,   0,0,0
nd   1,90.0
,    2,1
el   1,1,1,2
pr   1,1.0E6
bc   2
iv   1,527
mo   1,1
end
```

$\omega = \sqrt{k/m} = 105.4$

$\xi = 0.06$

$\beta = 2 * \xi / \omega = 0.0114$



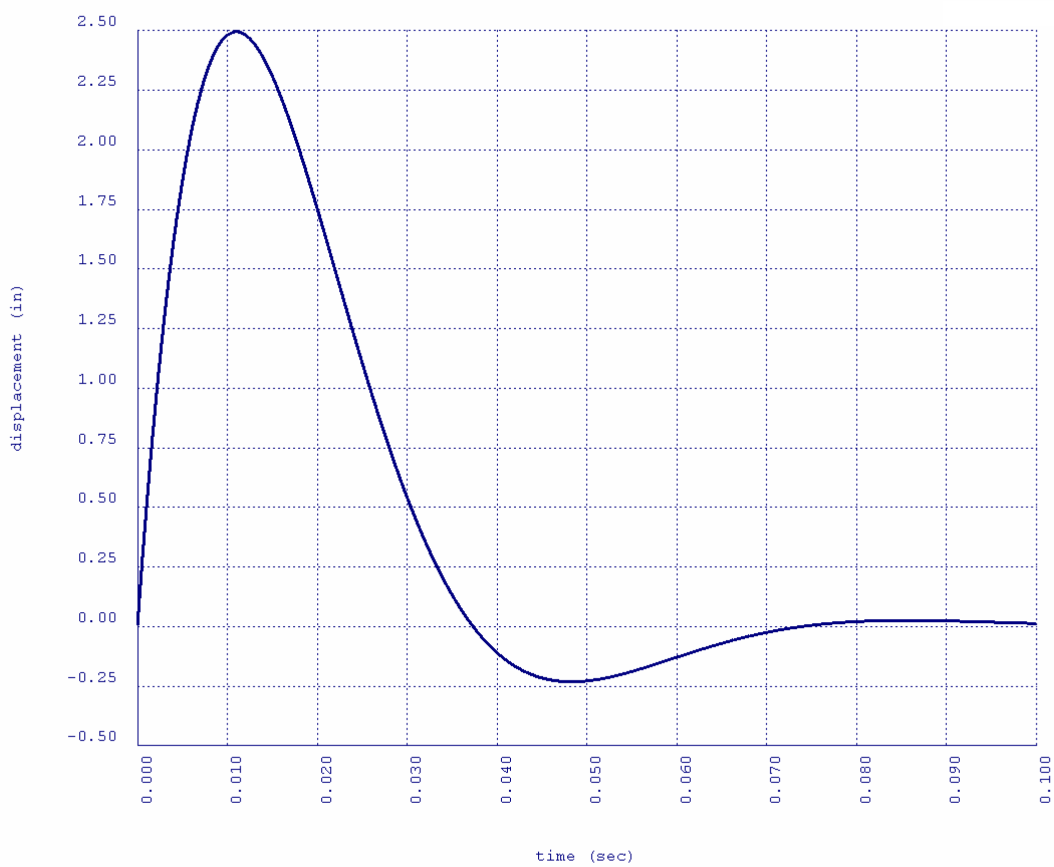


Figure 2-41. Impact Response for Damping, ξ = 0.06 – AOS-165A Prototype

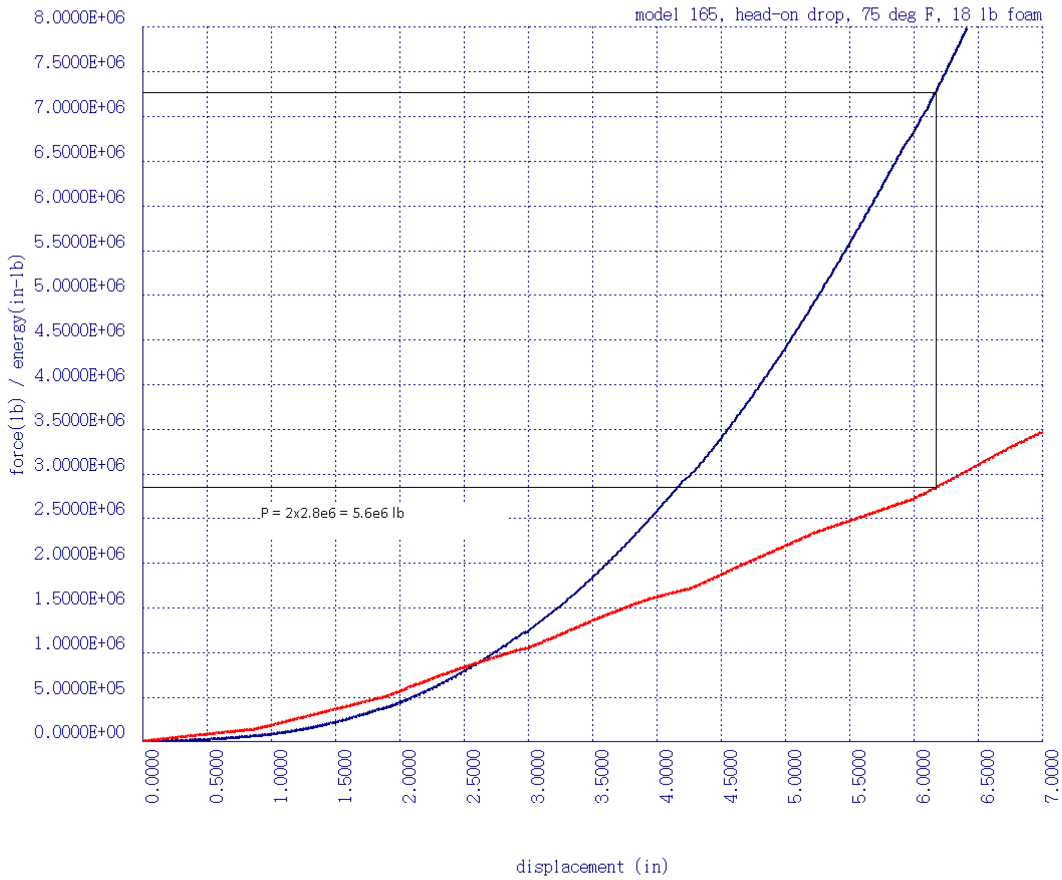


Figure 2-42. Head-On Drop Force and Energy – AOS-165A Prototype

2.7.1.2 Side Drop

2.7.1.2.1 Side Drop Impact Limiter Analysis

The FEA model shown in Figure 2-32 is also used for the Side Drop configuration. As in the head-on drop analysis, a series of displacement fields, simulating the side impact of the impact limiter onto a rigid surface, is applied, with displacement steps corresponding to 0.25 mm (0.01 in.) displacements of the rigid surface, and geometric and constitutive element properties updated after each displacement step. Figure 2-43 illustrates the strain energy and total force developed in the foam due to the rigid surface displacements. For the 180° section of one impact limiter and an 9,510-lb. cask weight, the maximum displacement corresponds to the strain energy:

$$U = 9{,}510 * 360 = 3.42 \times 10^6 \text{ in.-lb.}$$

From Figure 2-43, the corresponding displacement is 14.5 cm (5.7 in.), the total force is 1.36×10^6 lbs., and the maximum acceleration is:

$$a = 1.36 \times 10^6 / 9{,}510 = 143.0g$$

Figure 2-44 illustrates the lateral foam displacements, where the displacement contours are plotted on the deformed geometry. The equivalent stress and strain at maximum displacement are plotted in Figure 2-45 and Figure 2-46, respectively.

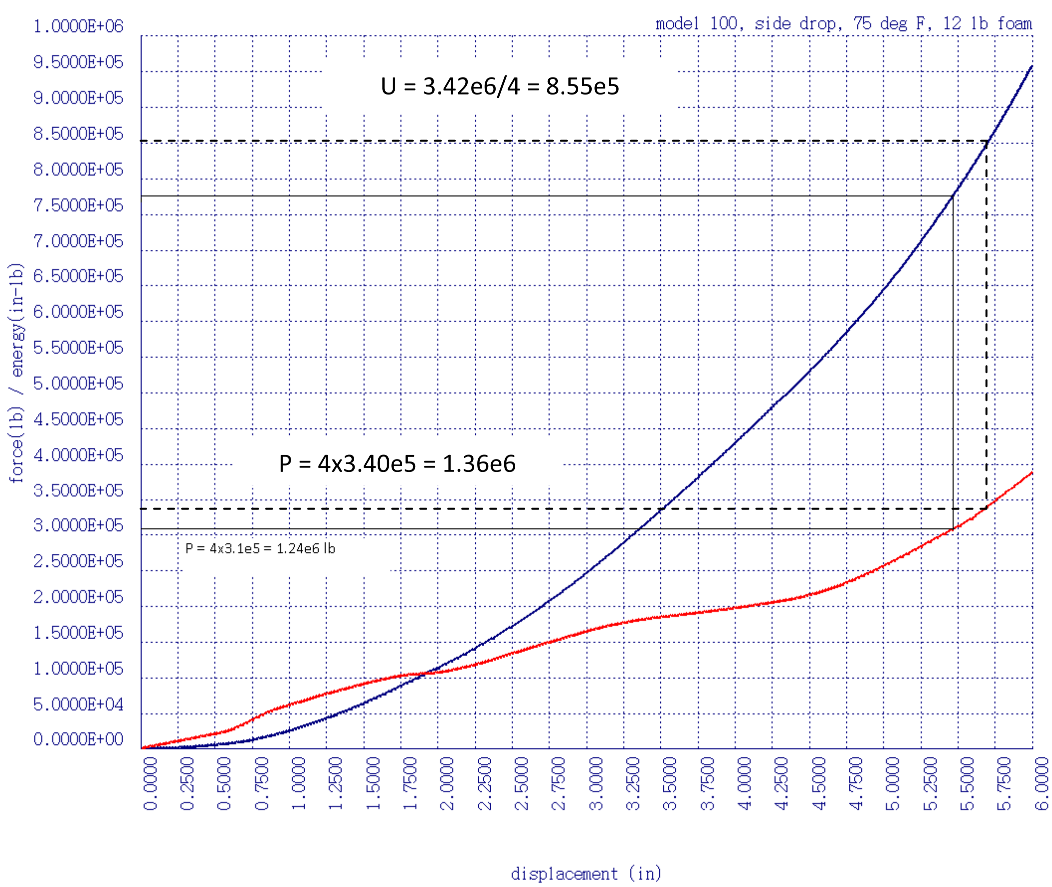


Figure 2-43. Side Drop Force and Energy – Model AOS-100

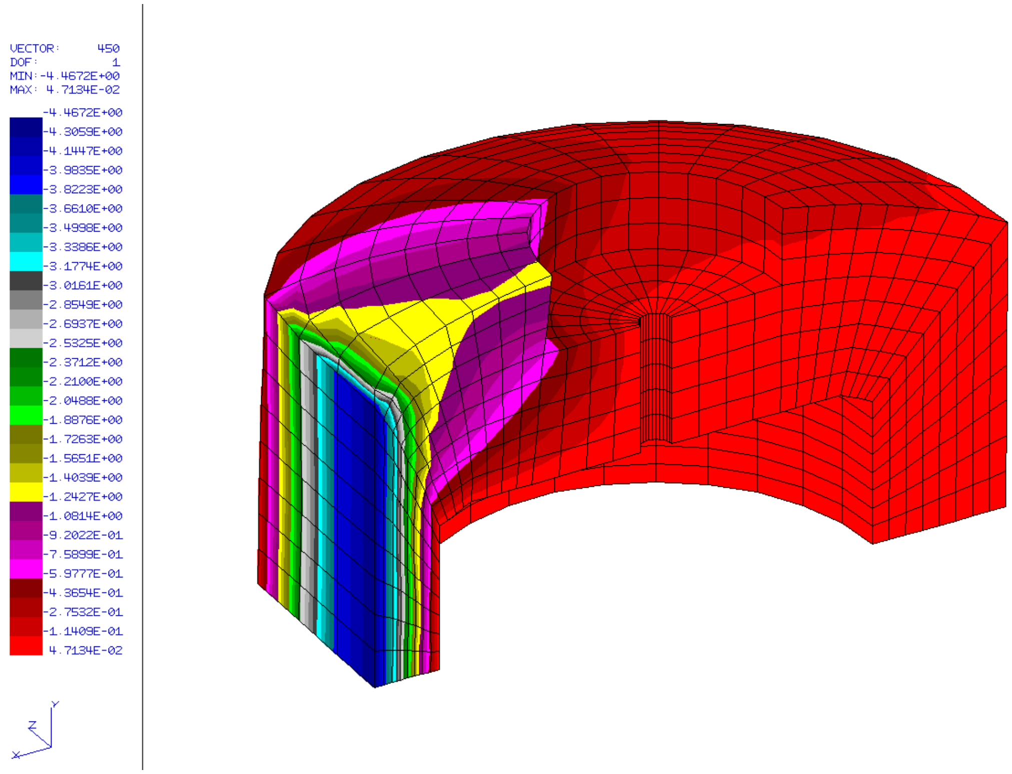


Figure 2-44. Side Drop, Maximum Foam Displacement (Deformed Model) – Model AOS-100

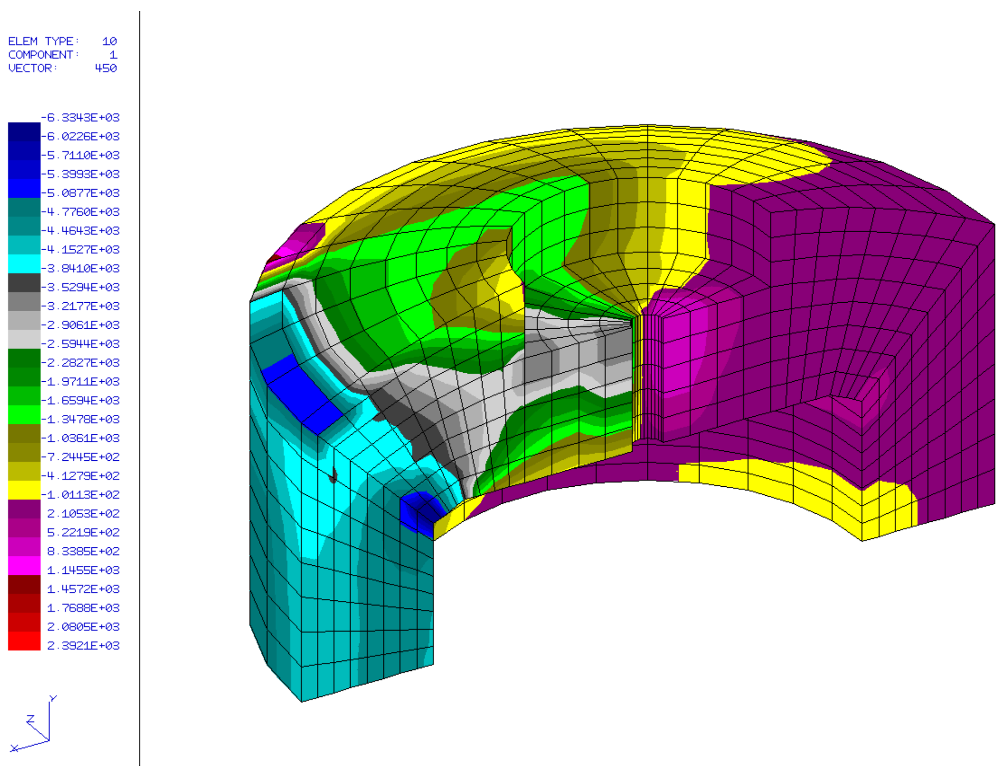


Figure 2-45. Side Drop, Maximum Equivalent Stress in Foam – Model AOS-100

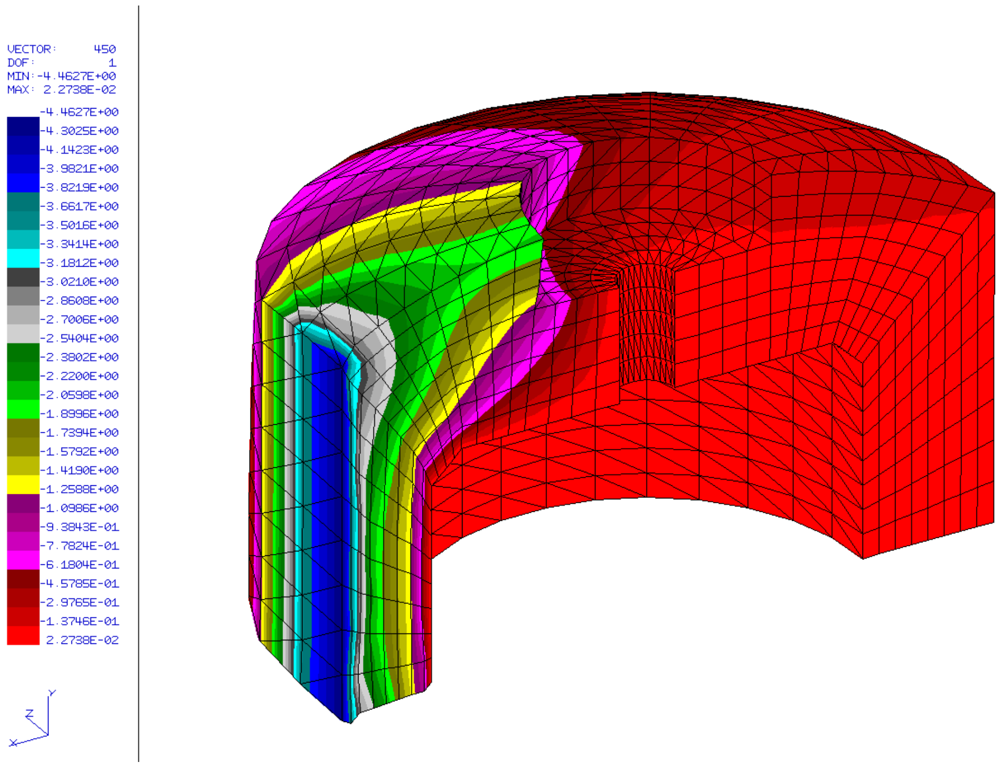


Figure 2-46. Side Drop, Maximum Principal Strain in Foam – Model AOS-100

2.7.1.2.2 Side Drop Cask Analysis

Net force due to a 30-ft. side drop plus slap-down, Load Case 302, is determined from the impact limiter analysis presented in Paragraph 2.7.1.2.1. Figure 2-47 illustrates the assumed impact load distribution. For impact force P, the load intensity distribution, as a function of the circumferential angle, is assumed to be:

$$q_x = -q * \cos^2\theta$$
$$q_z = q * \sin\theta * \cos\theta$$

$$P = 2L \int_{-\pi/2}^{\pi/2} -q * \cos^2\theta * r * d\theta$$

$$P = \pi * R * L * q$$
$$q = P / (\pi * R * L)$$

The LIBRA loading function, LE -5[a], applies impact traction q. This function applies surface tractions in 3D models generated from 2D models. Tractions are applied along nodal lines of the 2D model. The tractions can vary linearly along the 2D nodal lines, and as a sine or cosine harmonic in the circumferential direction. The above tractions, q_x and q_z, are applied with LE -5, using the trigonometric identities:

$$q_x * \cos^2\theta = 1/2 * q_x * (1 + \cos 2\theta)$$
$$q_z * \sin\theta * \cos\theta = 1/2 * q_z * \sin 2\theta$$

In addition to the impact load, an opposing inertia body force is applied to the cask. Radial displacements are fixed along the cask meridian 180° from center of loading, to account for non-equilibrium of pressure and inertia forces.

a. *Ibid (refer to previous LIBRA LE -5 footnote a).*

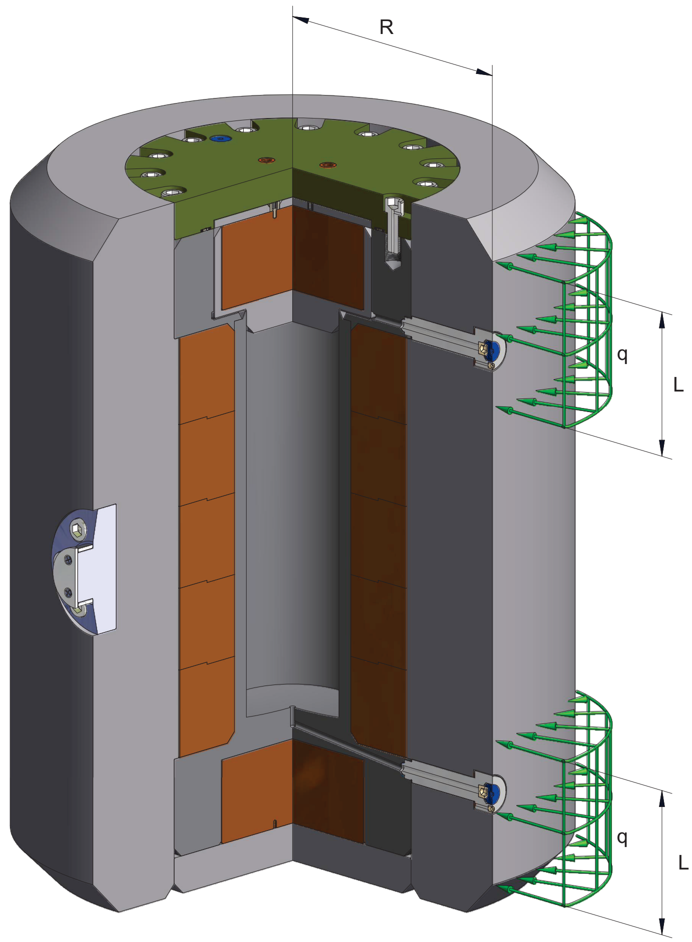


Figure 2-47. Side Drop Analysis Load Distribution – All Models

2.7.1.2.3 Correlation of Side-Drop Analysis and Test

In the side drop, there is not a significant separation of foam and cladding. (Refer to Figure 2-44.) As a result, the dimensional inspection results are used to correlate test and analysis results. In the analysis, a uniform radial displacement is applied along the impact limiter structure. In the side-drop test, the impact limiter experienced small rotation, producing differences in radial displacement along the impact limiter. Consequently, the net average test radial displacement in each impact limiter is compared to the uniform analysis displacement. For the AOS-165A prototype, the net average test radial displacements at the two (2) impact limiters are provided in Table 2-42 from the Dimensional Inspection report, presented in Appendix 2.12.7.

The average of displacements is determined at three (3) locations along the impact limiter:

- **Point 1** – At the impact limiter base
- **Point 2** – Approximately halfway between the impact limiter base and crown
- **Point 3** – At the impact limiter crown

The net displacement – the sum of all displacements, at the inside and outside of the impact limiter – is used at each point.

The average radial displacement at Impact Limiter 1 is 8.91794 cm (3.511 in.). The average radial displacement at Impact Limiter 2 is 7.56666 cm (2.979 in.). From Figure 2-43, the average analytical radial displacement is 10.5156 cm (4.14 in.). This analytical value includes a 1.15 slap-down factor.

Table 2-42. Side-Drop Analysis and Test, Radial Displacement at Impact Limiters 1 and 2 – AOS-165A Prototype

Impact Limiter 1 (in.)				Impact Limiter 2 (in.)			
Area	Base	Mid	Crown	Area	Base	Mid	Crown
Outside	3.969	2.239	2.080	Outside	4.027	2.057	1.892
Inside	0.547	1.247	0.451	Inside	0.000	0.650	0.311
Total	4.516	3.486	2.531	Total	4.027	2.707	2.203

2.7.1.2.4 Side Drop Slap-Down Analysis

The Slap-Down drop analysis is used to determine the cask orientation that produces maximum side impact. The impact force is determined by a series of direct integration, dynamic analyses involving different offset values, and the FEA model used for these analyses is shown in Figure 2-48. This model consists of a uniform block, and two (2) linear springs connected to the block by gap elements. Block geometry, total mass, and moment of inertia approximate the cask values. The spring stiffness values approximate stiffness of the impact limiter when subjected to a side drop. In each analysis, a null gap is modeled at one spring, and a gap equal to the offset is modeled at the other spring. The approximate, linear stiffness used for the impact limiter is 0.85×10^6.

Figure 2-49 and Figure 2-50 graphically present the direct integration, dynamic analyses results for the AOS-165A prototype:

- Figure 2-49 presents the spring displacement, plotted as a function of support offset.
- Figure 2-50 presents the displacements at both springs, plotted as functions of time for an offset of approximately 25.4 cm (10 in.), the offset used in the drop test.

  Maximum values from Figure 2-50 are presented in Table 2-43.

Table 2-43. Support Displacements – AOS-165A Prototype

Support	Maximum Displacement	
	cm	in.
1	8.89	3.500
2	10.82	4.260

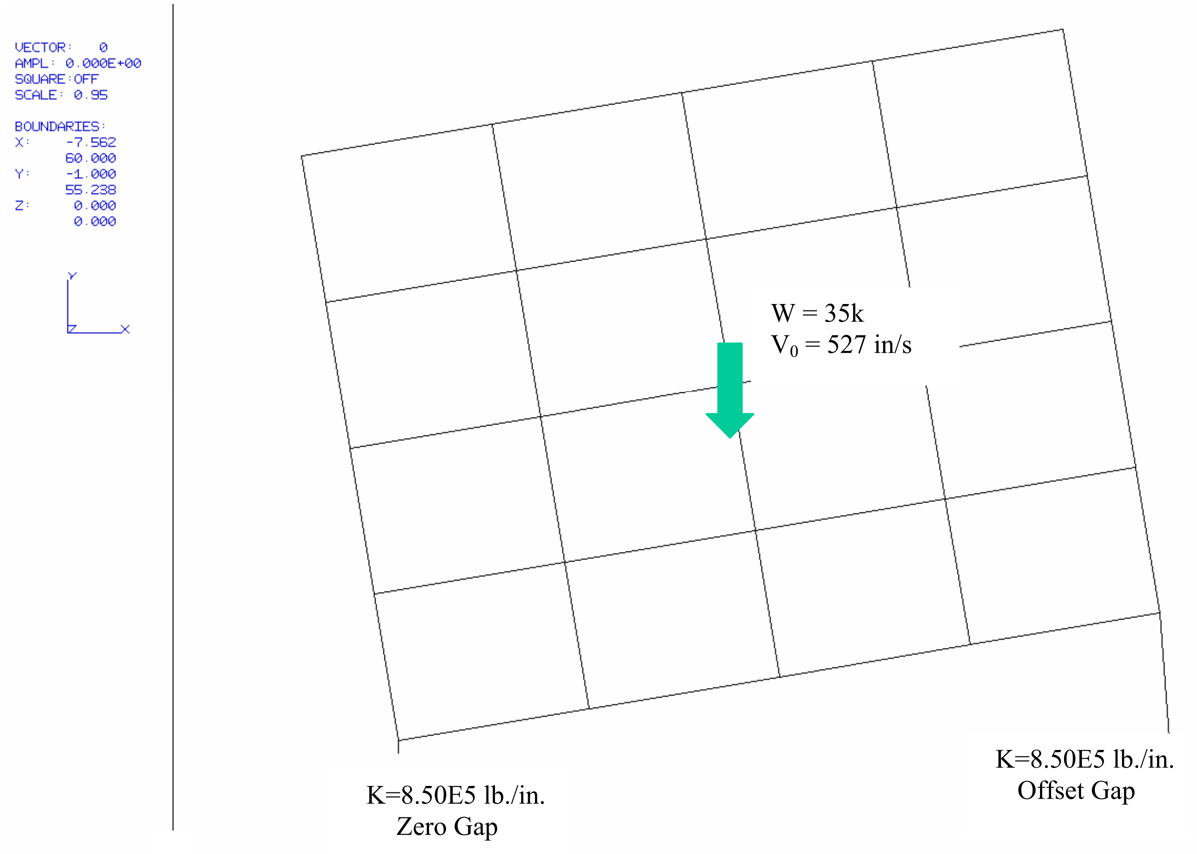


Figure 2-48. Slap Finite Element Model – AOS-165A Prototype

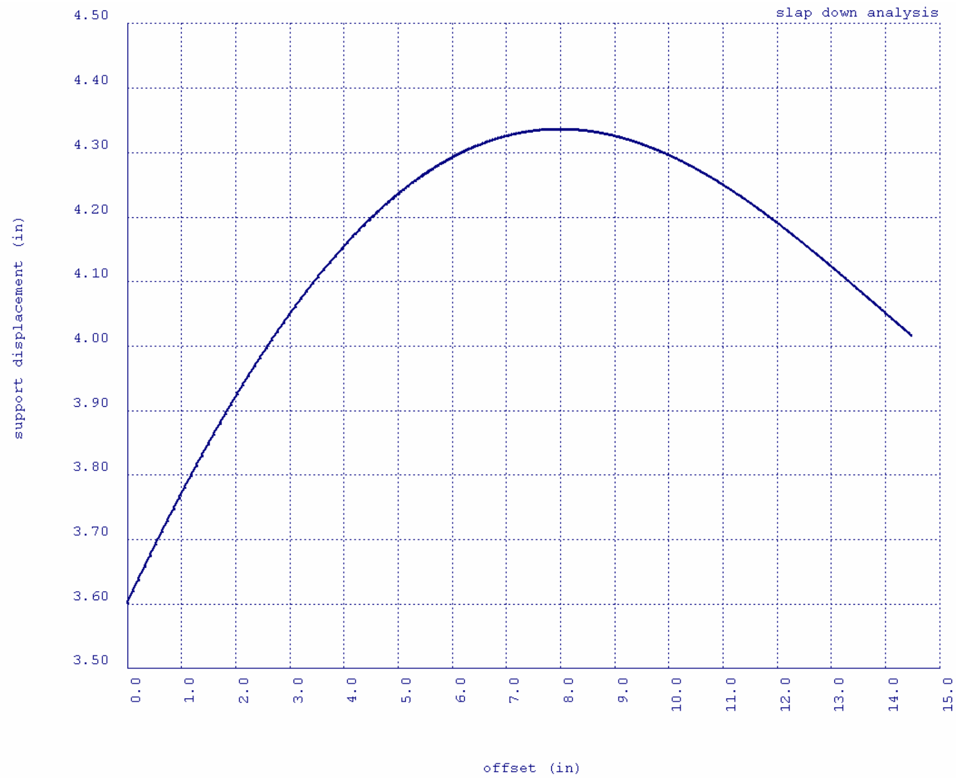


Figure 2-49. Maximum Support Displacement versus Offset – AOS-165A Prototype

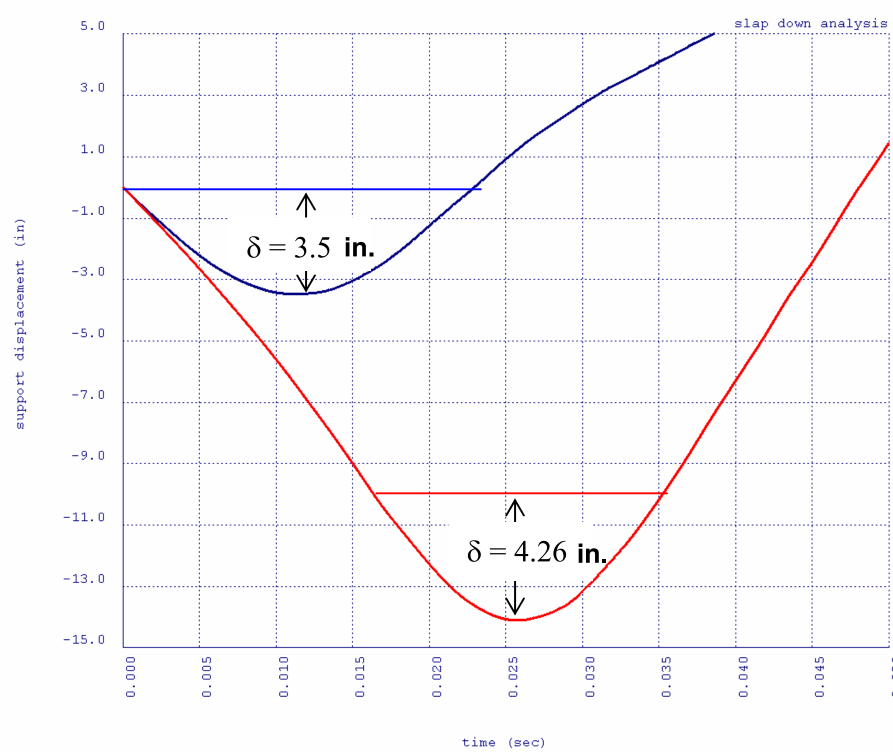


Figure 2-50. Slap-Down Analysis Support Displacements versus Time – AOS-165A Prototype

2.7.1.2.5 Correlation of Slap-Down Drop Analysis and Test

The dimensional analysis results are used to correlate Slap-Down test and analysis results. In the analysis, a single radial displacement is assumed for each impact limiter structure. In the Side-Drop test, the impact limiter experienced small rotation, producing differences in radial displacement along the impact limiter. Consequently, the net average test radial displacement in each impact limiter is compared to the single analysis displacement. For the AOS-165A prototype, the net average test radial displacements at the two (2) impact limiters are provided in Table 2-44, from the Dimensional Inspection report, presented in Appendix 2.12.7.

The average of displacements is determined at three (3) locations along the impact limiter:

- **Point 1** – At the impact limiter base
- **Point 2** – Approximately halfway between the impact limiter base and crown
- **Point 3** – At the impact limiter crown

The net displacement – the sum of all displacements, at the inside and outside of the impact limiter – is used at each point.

The average radial displacement at Impact Limiter 1 is 7.14756 cm (2.814 in.). The average radial displacement at Impact Limiter 2 is 9.53516 cm (3.754 in.). From Figure 2-50, the corresponding analytical radial displacements are 8.89 cm (3.50 in.) and 10.8204 cm (4.26 in.). The analysis and test results differ by a maximum of 19.6%. The test and analysis ratio of displacements at the impact limiters are 3.302 cm (1.30 in.) for the test and 3.0734 cm (1.21 in.) for the analysis.

Table 2-44. Slap-Down Drop Analysis and Test,
Radial Displacement at Impact Limiters 1 and 2 – AOS-165A Prototype

Impact Limiter 1 (in.)				Impact Limiter 2 (in.)			
Area	**Base**	**Mid**	**Crown**	**Area**	**Base**	**Mid**	**Crown**
Outside	3.093	2.090	2.494	Outside	4.080	2.406	2.494
Inside	0.490	0.490	0.274	Inside	0.000	1.581	0.702
Total	3.583	2.580	2.768	Total	4.080	3.987	3.196

2.7.1.2.6 Slap-Down Drop Cask Analysis

Figure 2-51 illustrates this force distributed over the entire cask surface. For impact forces P_x and P_y, the load intensity distribution, as a function of the circumferential angle θ, is assumed to be:

$$q_y = 2/\pi * P_y / (R_2^2 - R_3^2)$$

$$q_x = -q * \cos^2\theta$$

$$q_z = q * \sin\theta * \cos\theta$$

$$P_x = 2L \int_{-\pi/2}^{\pi/2} -q * \cos^2\theta * r * d\theta$$

$$q_x = 2 * P / (\pi * R_1 * L)$$

In addition to the impact load, an opposing inertia body force is applied to the cask. Radial displacements are fixed along the cask meridian 180° from center of loading, to account for non-equilibrium of impact and inertia forces.

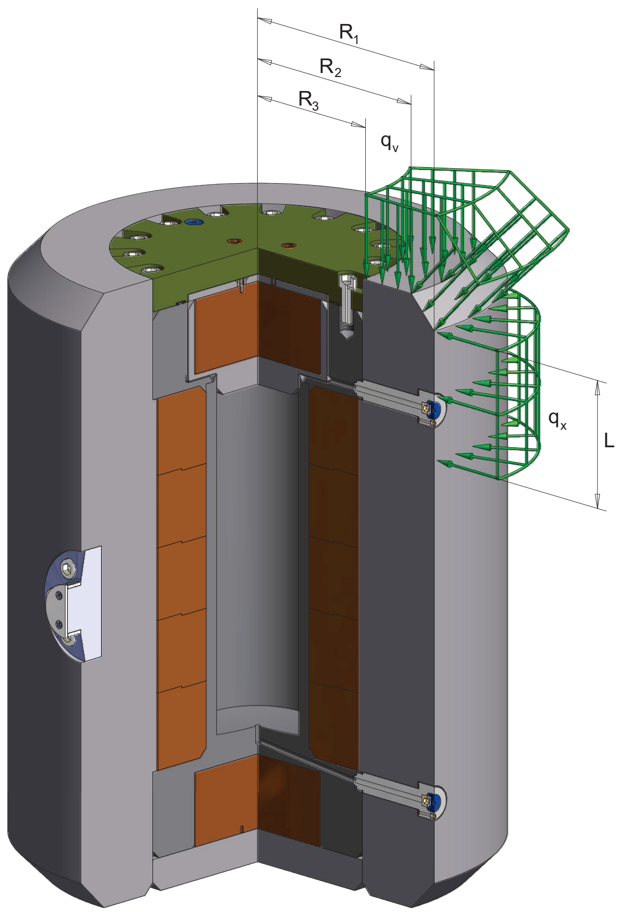


Figure 2-51. Cg/Corner Drop Analysis Load Distribution – All Models

2.7.1.3 Corner Drop

As with Head-On and Side Drops, evaluation of the Corner orientation (Cg/Corner) 30-Ft. Drop involves two separate analyses – a foam analysis to determine maximum impact force, and a cask analysis to evaluate cask stress due to impact loading. The impact limiter FEA model illustrated in Figure 2-32 is used to determine the maximum impact loading for a Cg/Corner Drop configuration. As in both the Head-On and Side Drop analyses, a series of 0.25-mm (0.01-in.) displacements of a rigid plane simulating foam impact onto a rigid surface is applied to the model in Figure 2-32. The model geometry and element constitutive properties are updated after each displacement step. The impact force and strain energy developed in the foam are determined in the analysis, and are plotted as functions of the rigid plane displacement. The maximum impact force is determined from the plots, and corresponds to the strain energy equal to the drop potential energy of 9,510 lbs * 30 ft., or 3.42×10^6 in-lb. This maximum force is then applied to the FEA model illustrated in Figure 2-7, with the load distribution illustrated in Figure 2-51.

2.7.1.4 Oblique Drops

The preceding analytical evaluations, together with the results of the full-scale Drop test presented in Appendix 2.12.6 and Appendix 2.12.7, demonstrate that the AOS Transport Packaging System models can survive the effects of the 9-m (30-ft.) free drop, without breaching containment nor suffering significant deformation on their cask components. In the Free-Drop test (Appendix 2.12.6), the prototype cask was dropped three (3) times, in different orientations, without any significant deformation nor failure of the containment system.

2.7.1.5 Summary of Results

All analyses associated with the 9-m (30-ft.) cask drops conducted for Models AOS-025, AOS-050, and AOS-100 are summarized within this paragraph.

2.7.1.5.1 9-m (30-ft.) Drop Analyses

Table 2-45 lists the six (6) analyses conducted on each of the three (3) cask models, for a total of 18 drop analyses.

Each drop analysis involves two (2) separate analyses. In the first analysis, the impact limiter is analyzed to determine impact loading upon the cask structure. The force-displacement curves generated in the impact limiter drop analyses are presented in Figure 2-54 through Figure 2-63. In the second analysis, the impact loading is applied in a cask stress analysis. Two (2) model types are used in cask stress analyses. Head-On drops are assumed to be axisymmetric, and the 2D cask model illustrated in Figure 2-52 is used. The 3D cask model illustrated in Figure 2-53 is used for Side and Cg/Corner Drop cask stress analyses.

Table 2-45. 9-m (30-ft.) Drop Analyses Conducted upon Each Cask Model

Load Case	Description
301	30-ft. Head-On Drop at 75°F
302	30-ft. Side Drop + Slap-Down at 75°F
303	30-ft. Cg/Corner Drop at 75°F
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

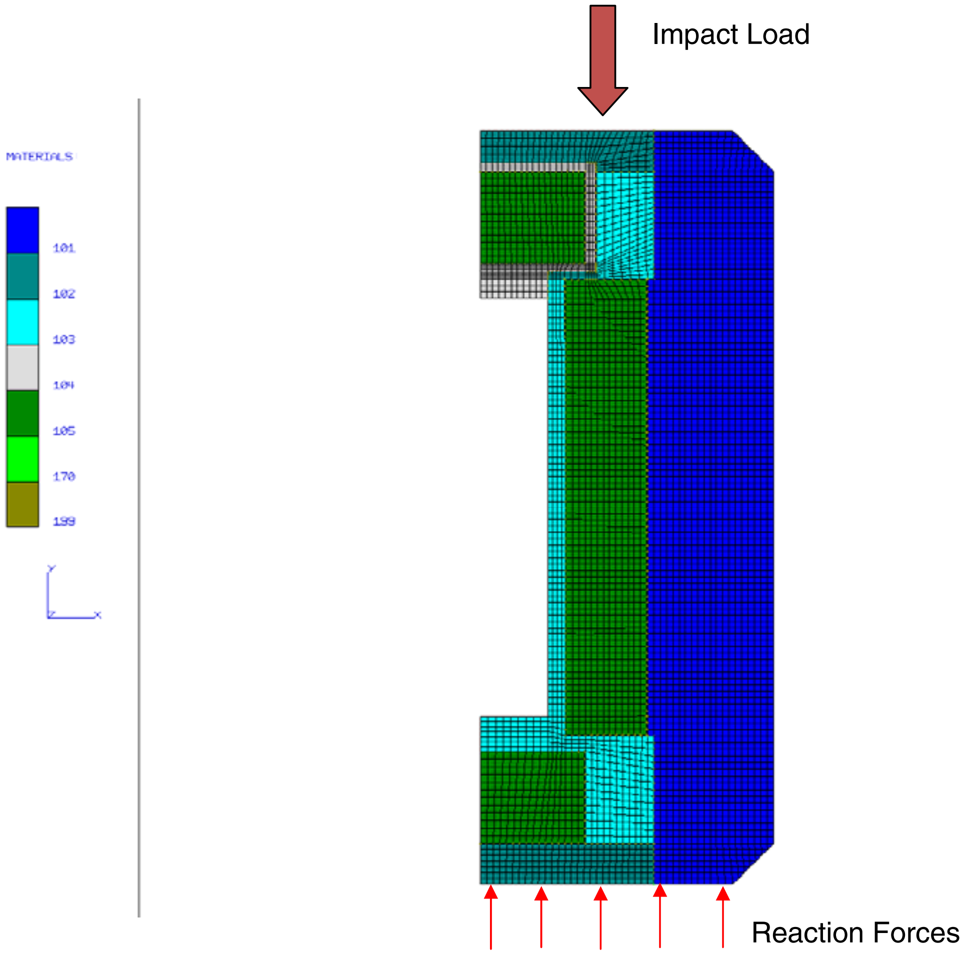


Figure 2-52. Head-On Drop Cask Model

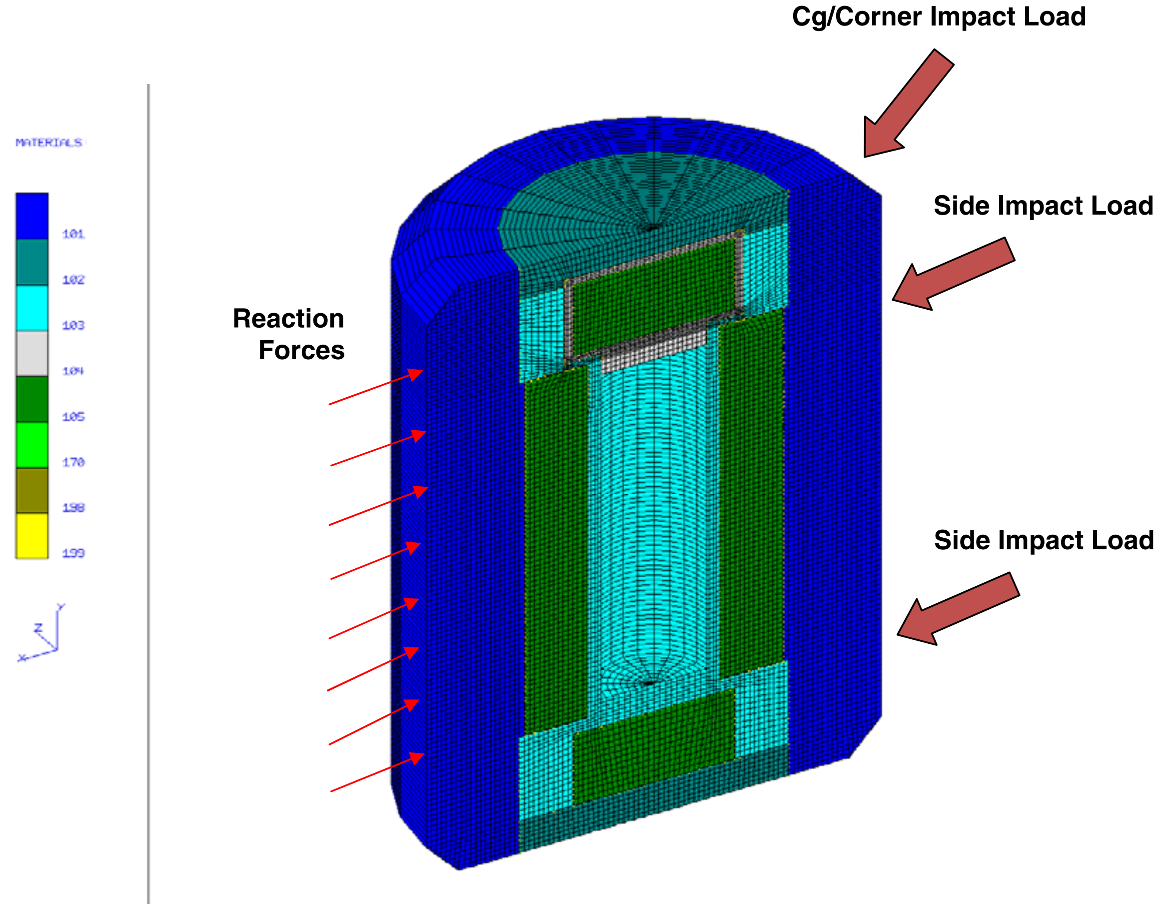


Figure 2-53. Side+Slap-Down and Cg/Corner Drop Cask Model

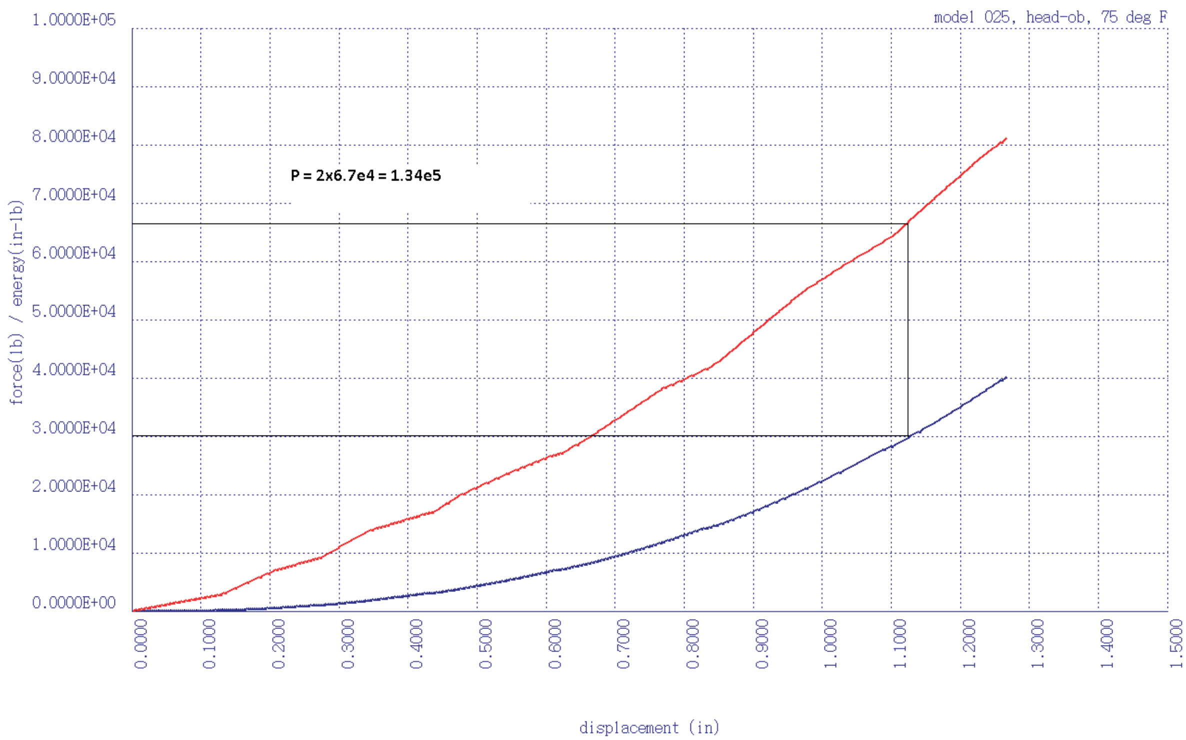
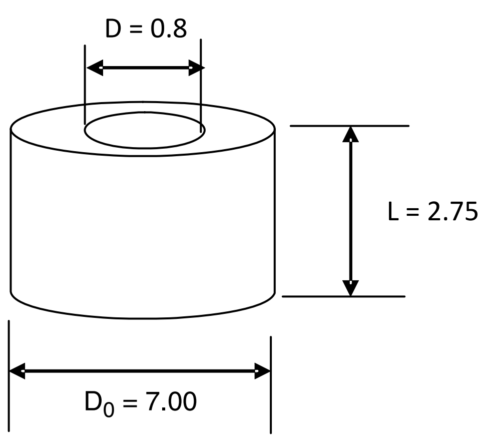


Figure 2-54. Force-Displacement for Head-On Drop at 75°F – Model AOS-025

Note: *The foam manufacturer, General Plastics, recommends a 50% strain limit to FR-3700 series foam that has 20-pcf density (FR-3720). This limit applies to nominal strain, and not to strain at every point. The recessed region at the top of the impact limiter has high localized strains under a head-on impact. The FEA model used in the drop analyses requires foam data for strains over 50% to accurately model these local regions. Nominal foam strain in the Model AOS-025 cask for a head-on impact is approximately 35%, as shown below. The dimensions provided are in inches.*



$V = 220 * 360 = 7.92 \times 10^4$ in-lb

$A = \pi (3.50^2 - 0.4^2) = 38.0$ in^2

$f = 2.168$ ksi (40% strain)

$P = A * f = 38.0 * 2.168 = 82.3$ k

$\delta = V / P = 79.2 \times 10^3 / 82.3 \times 10^3 = 0.96$ in.

$\varepsilon = \delta / L = 0.96 / 2.75 = 0.35$ in/in

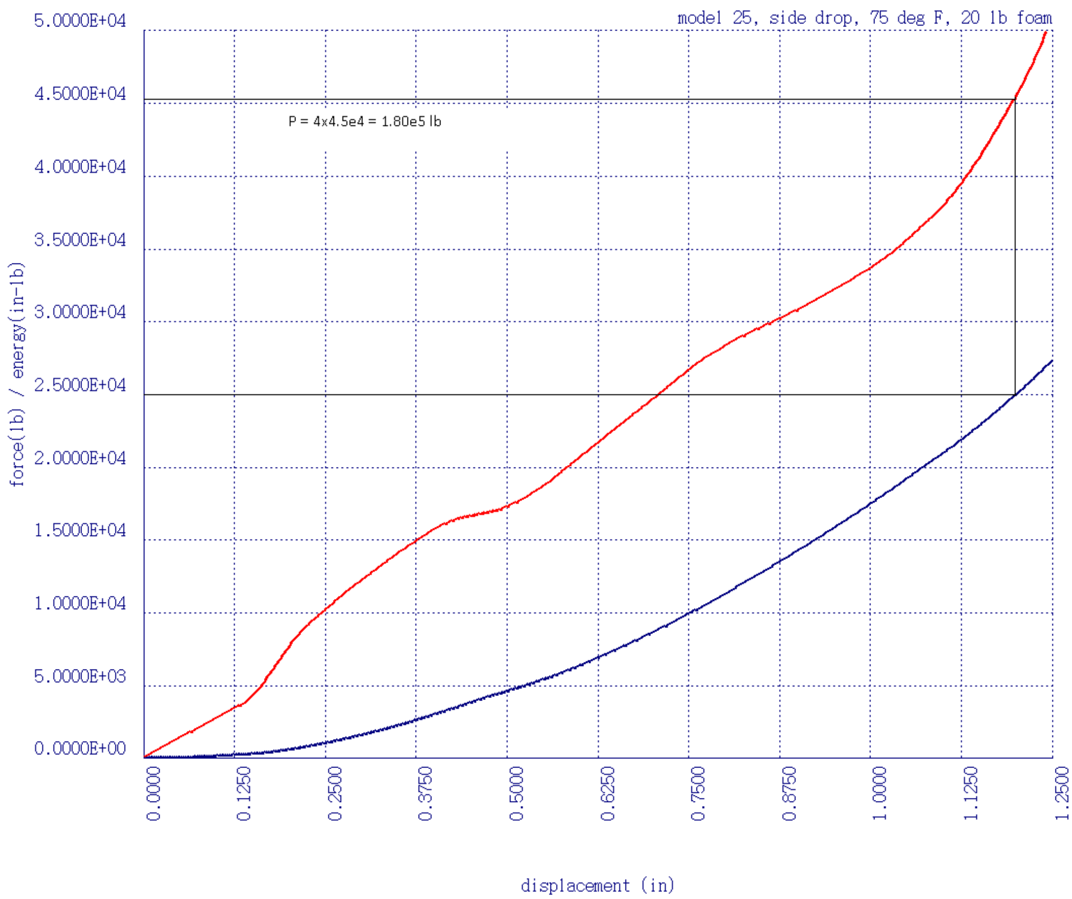


Figure 2-55. Force-Displacement for Side Drop at 75°F – Model AOS-025

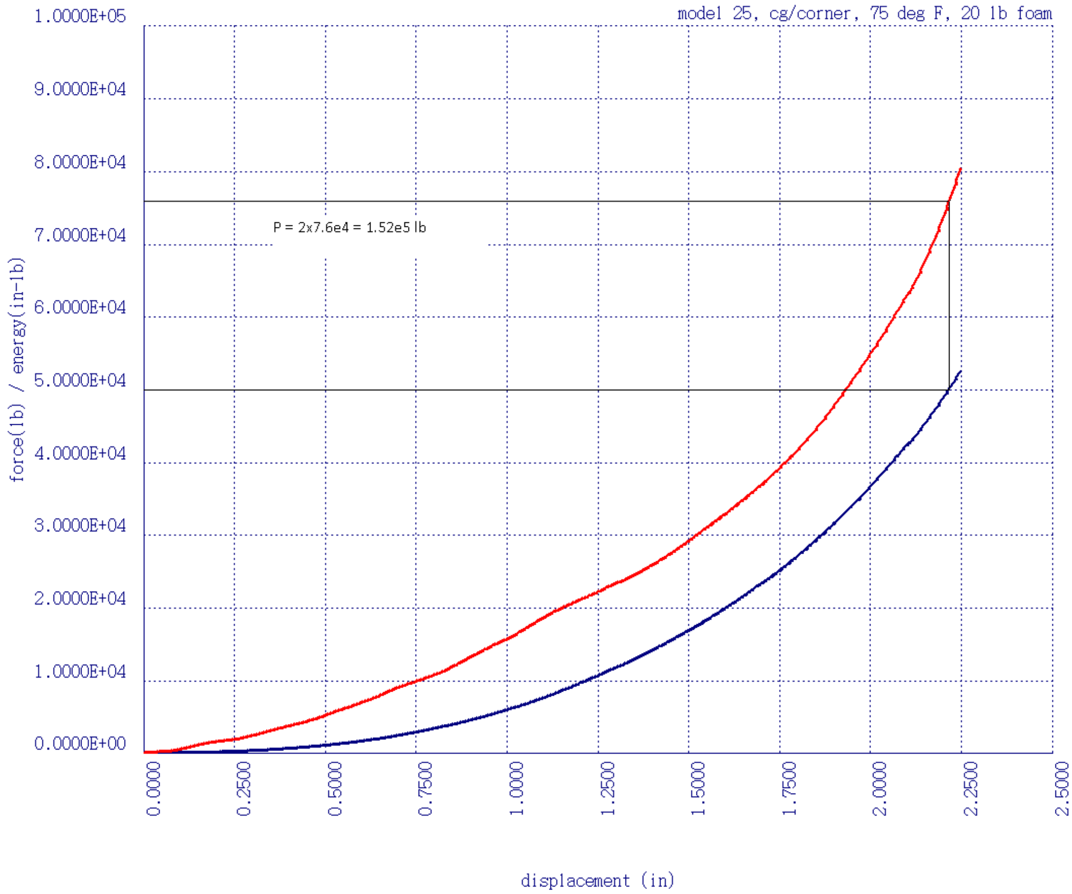


Figure 2-56. Force-Displacement for Cg/Corner Drop at 75°F – Model AOS-025

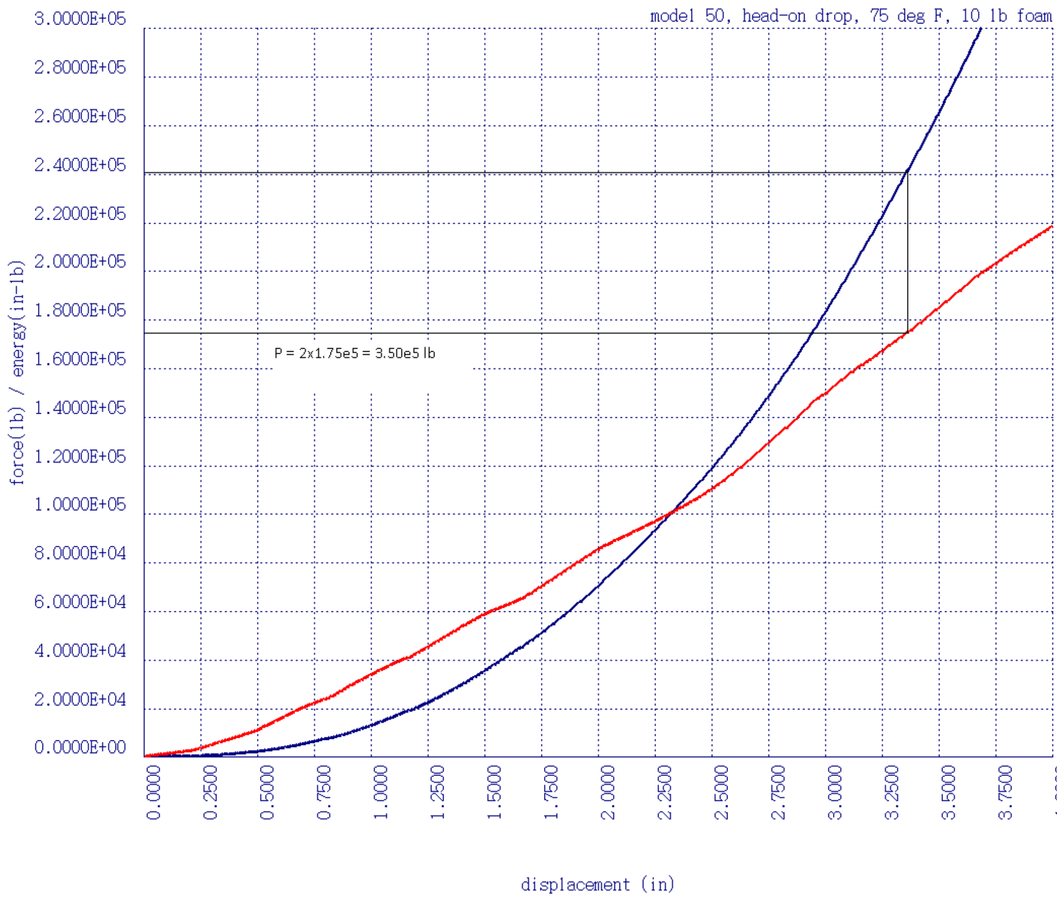


Figure 2-57. Force-Displacement for Head-On Drop at 75°F – Model AOS-050

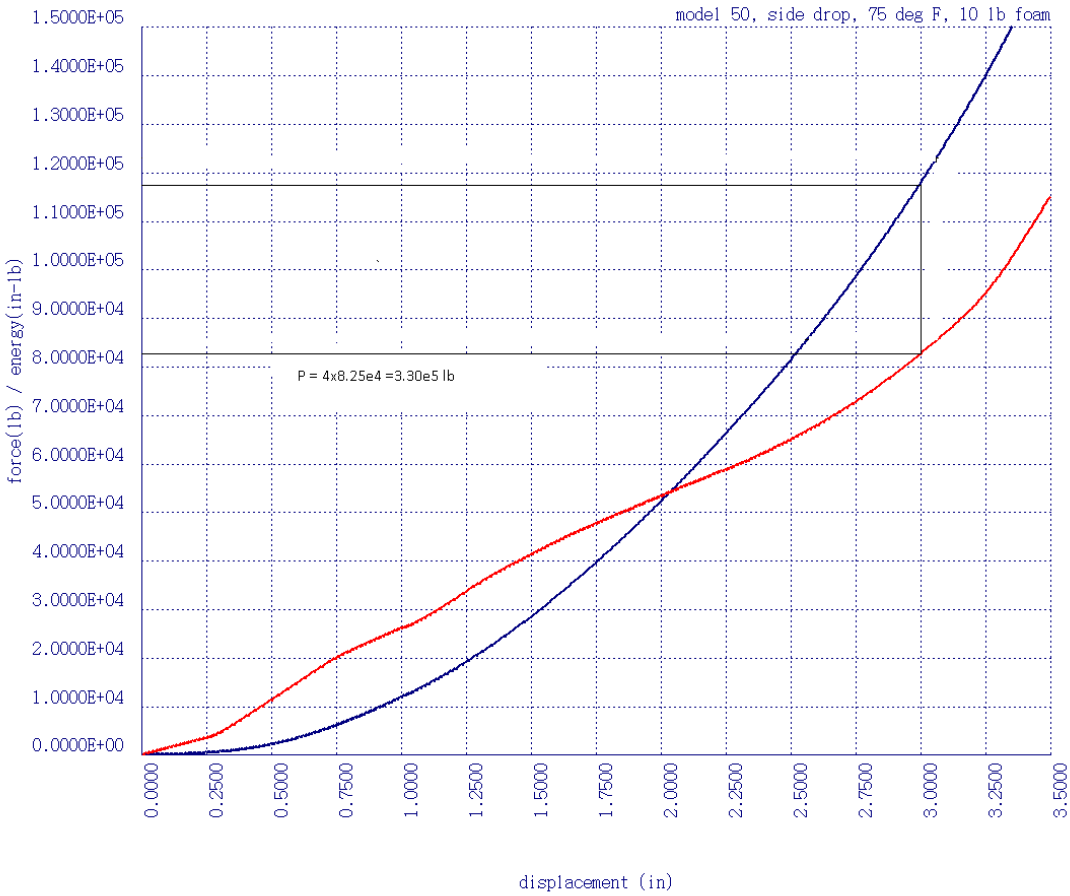


Figure 2-58. Force-Displacement for Side Drop at 75°F – Model AOS-050

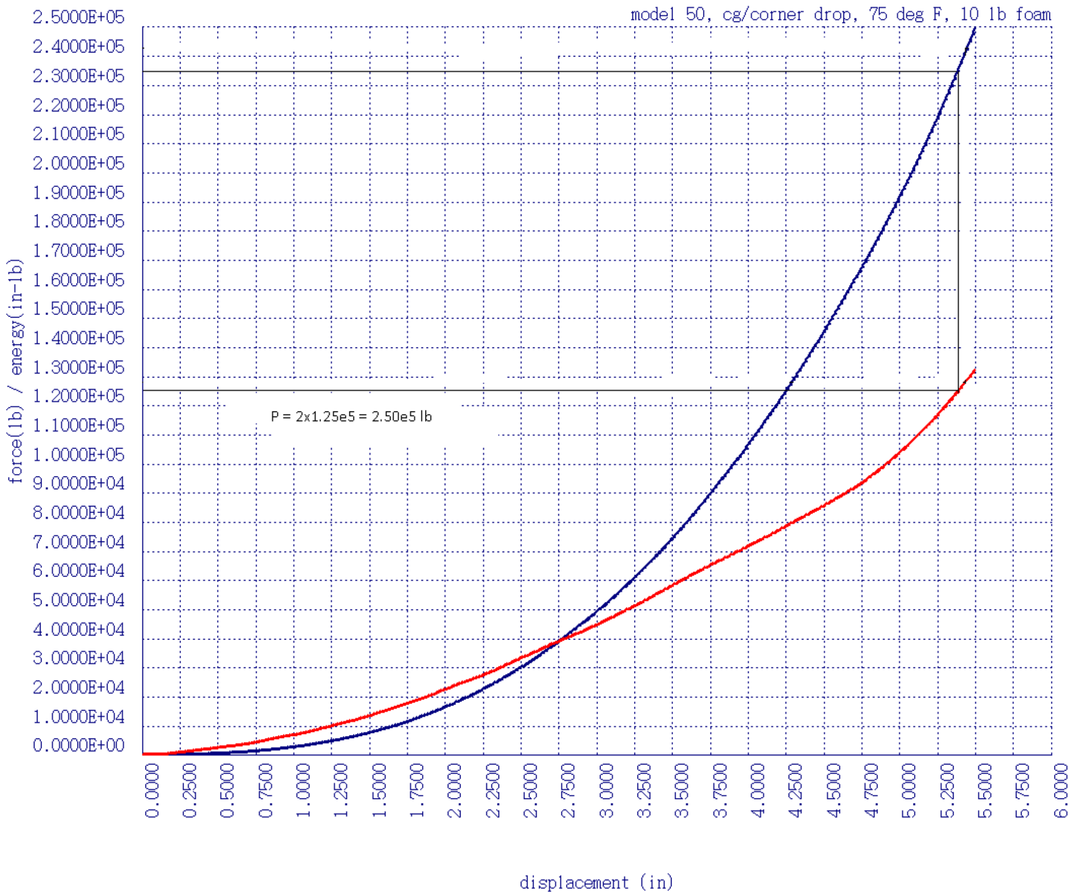


Figure 2-59. Force-Displacement for Cg/Corner Drop at 75°F – Model AOS-050

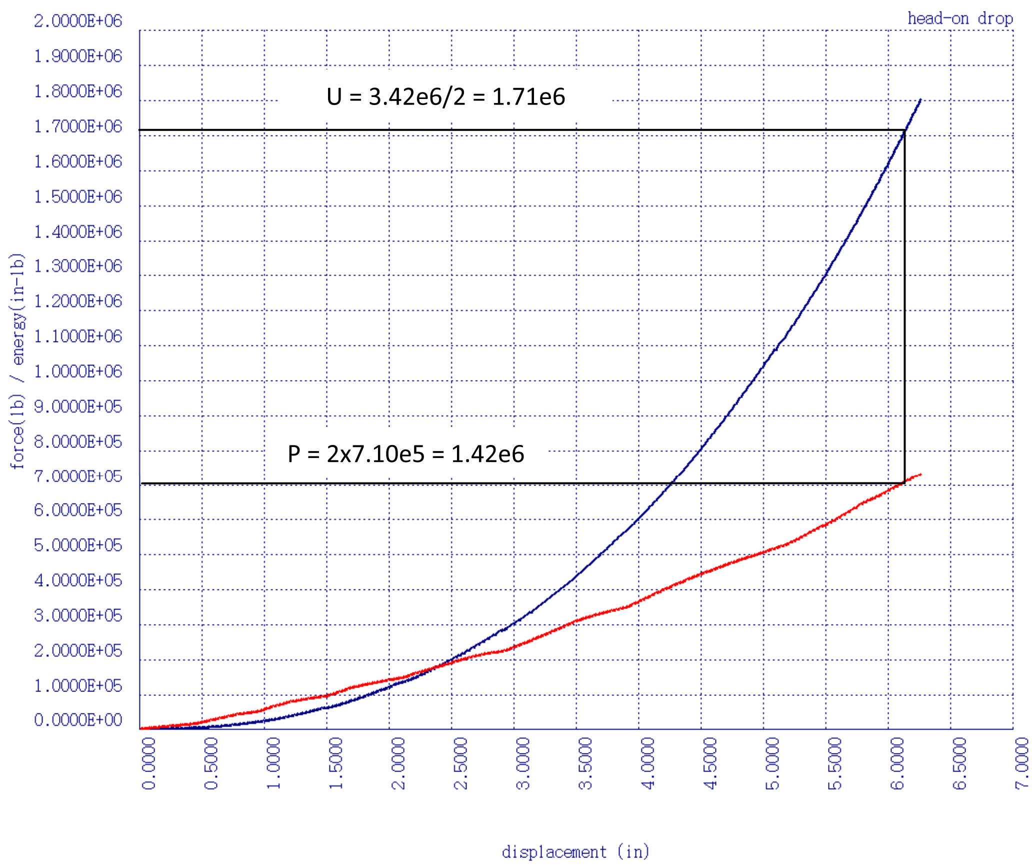


Figure 2-60. Force-Displacement for Head-On Drop at 75°F – Model AOS-100

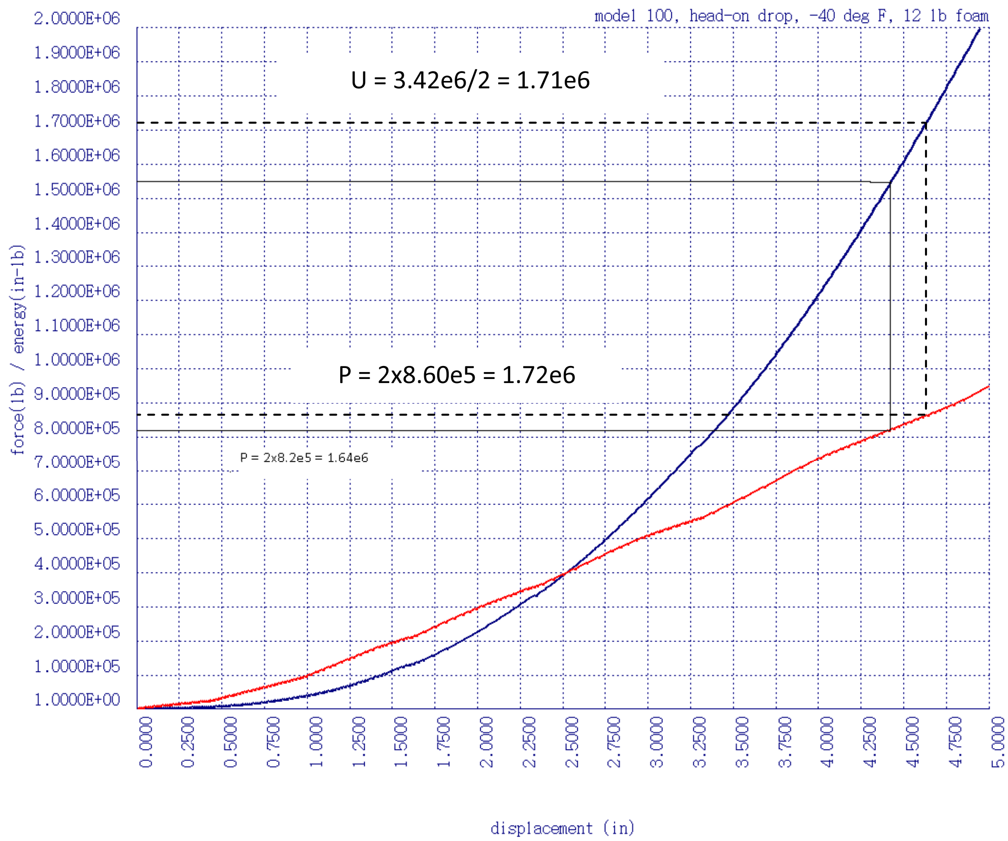


Figure 2-61. Force-Displacement for Head-On Drop at -40°F – Model AOS-100

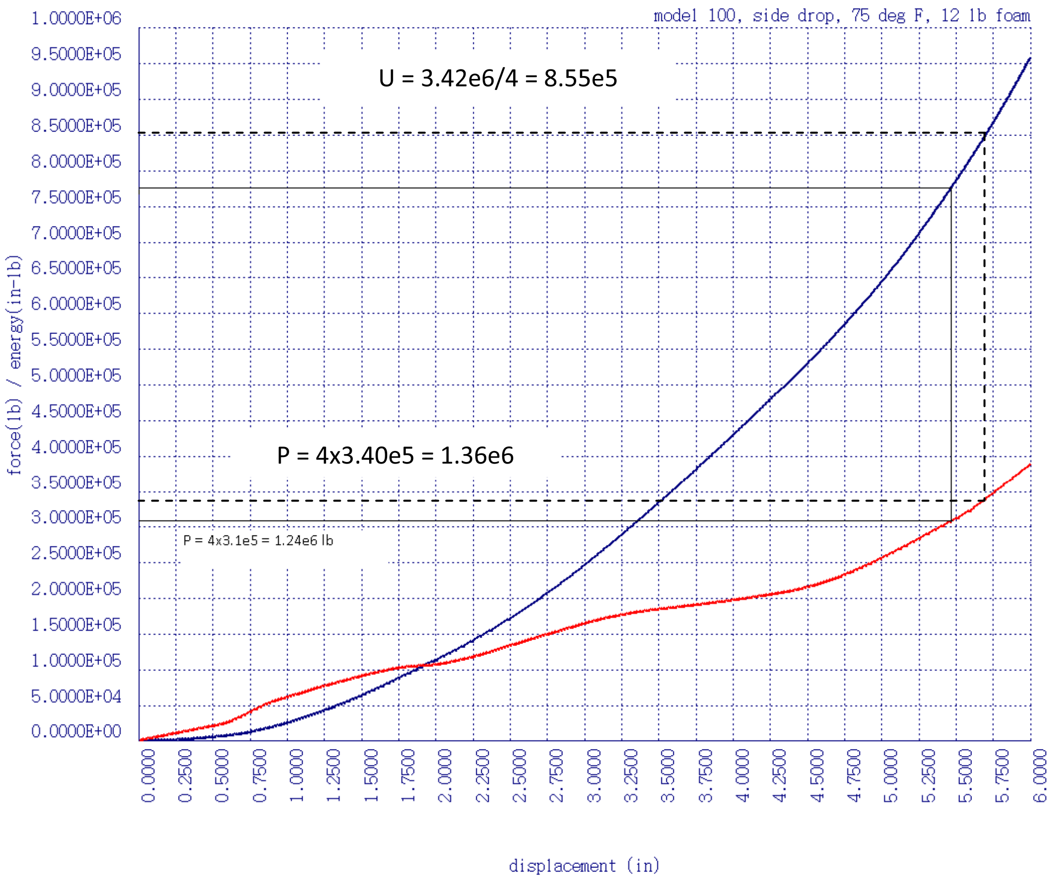


Figure 2-62. Force-Displacement for Side Drop at 75°F – Model AOS-100

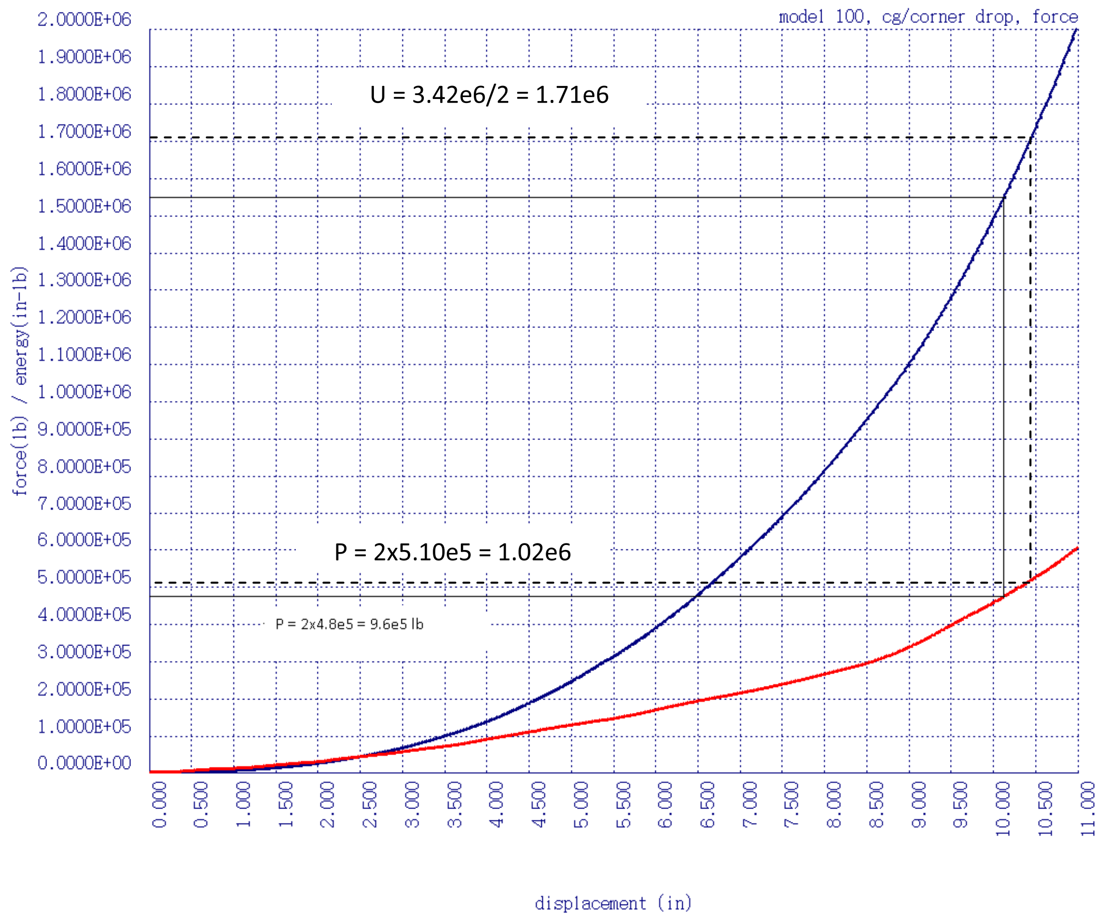


Figure 2-63. Force-Displacement for Cg/Corner Drop at 75°F – Model AOS-100

2.7.1.5.2 Cask Impact Loadings

Figure 2-64 and Figure 2-65 illustrate the impact load distributions applied in the cask stress analyses.

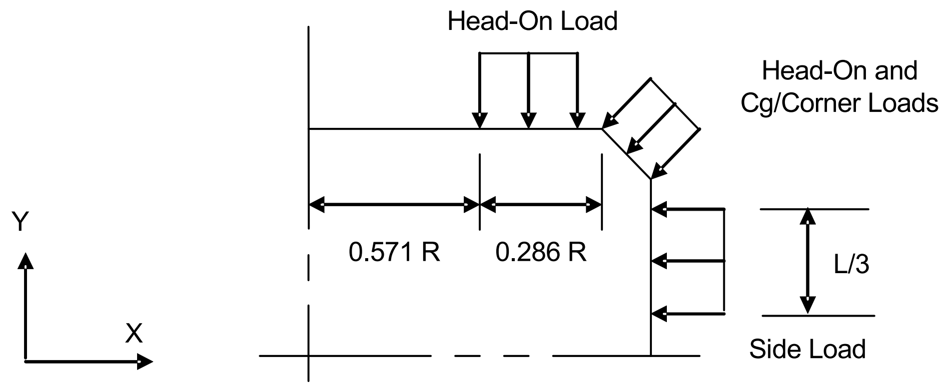


Figure 2-64. Impact Load Distributions

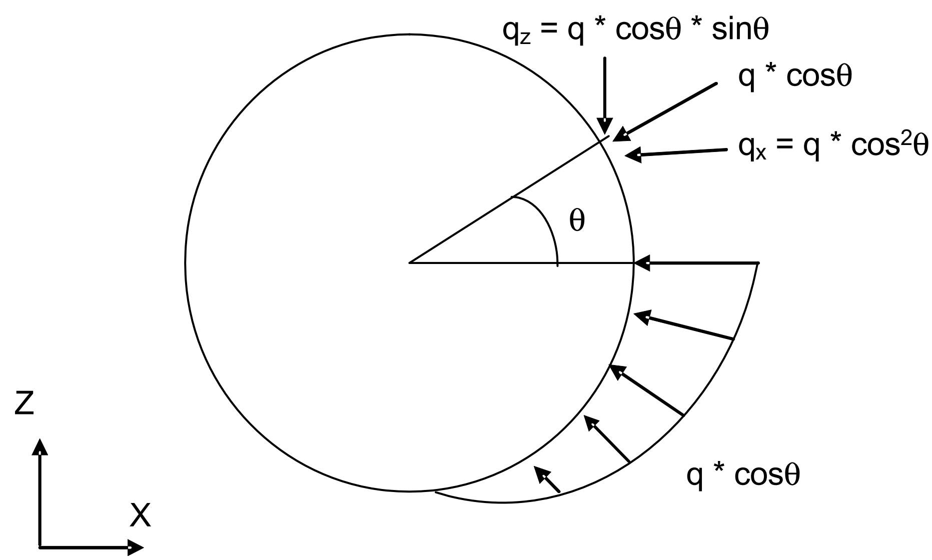


Figure 2-65. Circumferential Impact Load Distribution for Side and Cg/Corner Drops

These distributions are applied over the impact areas observed in the drop tests. The head-on impact load distribution is axisymmetric, and the applied traction, q, is provided by the force, P, divided by the surface area, A:

$$q = P/A$$

In the LIBRA program, q is entered with an LE -4[a] command.

The Side and Cg/Corner loadings vary circumferentially, as a cosine function. With reference to Figure 2-64 and Figure 2-65, Side and Cg/Corner surface tractions are provided by the following development:

$$P = 2\int_0^{\pi/2} q_x * r * d\theta$$

$$q_x = q * \cos^2\theta$$

$$P = 2q\int_0^{\pi/2} \cos^2\theta * r * d\theta = \pi L * r * q / 2$$

$$q = 2P / \pi L * r$$

where:

P	=	Impact load
q	=	Prescribed surface traction
r	=	Cask outside radius
L	=	Cask length

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

The traction, q, is applied by its x and z components:

$$q_x = q * \cos^2\theta$$
$$q_z = q * \cos\theta * \sin\theta$$

Impact loading is applied with LIBRA LE -4 and LE -5[a] commands. To apply q_x and q_z with LE -5, it is necessary to express $\cos^2\theta$ and $\cos\theta * \sin\theta$ as functions of 2θ. Using the trigonometric identities:

$$\cos^2\theta = (1 + \cos 2\theta) / 2$$
$$\cos\theta * \sin\theta = (\sin 2\theta) / 2$$

The traction x and Z components become:

$$q_x = q\ (1 + \cos 2\theta) / 2$$
$$q_z = q\ (\sin 2\theta) / 2$$

These surface traction components are entered into LIBRA with LE -4 and LE -5 commands. The constant part of q_x is entered with an LE -4 command, and the parts of q_x and q_z that vary as a function of 2θ are entered with an LE -5 command.

2.7.1.5.2.1 Impact Load Tables

Impact loads applied in cask stress analyses are summarized in two (2) tables for each AOS model. The first table presents impact loads found in the impact limiter drop analyses, and the corresponding loads upon the cask stress models. The second table presents actual loads applied in the cask stress analyses.

In addition to the impact load, P', an inertial acceleration, A', is applied in the cask stress analyses. The inertia forces prevent large, pseudo-stress at supports, and have only a marginal effect upon maximum stress values. The accelerations are listed in the second table, and are based upon the actual applied impact load and weight of the stress model. The reaction force found in the stress analysis is:

$$R = P' - (A' * M)$$

This reaction force, R, is listed in the second table. In all cases R/P' is less than 0.01, indicating that the inertia and impact loads differ by less than 1%. Locations of reaction forces are illustrated in Figure 2-52 and Figure 2-53, for head-on and side drops, respectively.

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a. *Ibid (refer to previous LIBRA LE -4 and LE -5 footnote a).*

In the first table for each of the three (3) cask models, impact loads determined in impact limiter impact analyses are modified by four (4) factors:

- Temperature load (f_T)
- Slap-down load (f_S)
- Geometric load factor (f_G)
- Shipping cage impact factor (f_P)

Each factor is described in the paragraphs that follow. The impact load applied in the cask analysis is then the product of these four (4) factors and the impact load determined in the impact limiter analysis.

Foam force-displacement properties are approximately 40% higher at -40°F than at 75°F. Results of Head-On Drop analyses for the Model AOS-100 with foam properties at 75°F and -40°F are illustrated in Figure 2-60 and Figure 2-61, respectively. A comparison of these two figures shows that the impact load at -40°F is approximately 28% higher than the load at 75°F. Although this increase in impact force is less than the increase in force-displacement properties, in the -40°F load cases, a foam temperature load factor of 1.4 is applied to the impact loads at 75°F.

Results of a slap-down study conducted for the AOS-165A prototype illustrated in Figure 2-66 shows that the slap-down load factor is approximately 1.2 (3.035/2.544). Because cask geometries are scaled, this factor is applicable to all AOS models. In Side Drops, Load Cases 302 and 305, impact loads are modified by this slap-down load factor.

A geometric load factor is used to account for model geometry. The Head-On drop uses a 2D model that reflects the full cask, whereas Side and Cg/Corner Drops use only a half model. As a result, impact loads for the full cask are reduced by a 0.5 factor in the Side and Cg/Corner Drop analyses.

Shipping cages add to the cask impact forces, for both Head-On and Cg/Corner 30-ft. Drops. Side Drops, however, are not affected by shipping cage impacts, because only barrier wire mesh, not pallets, impact the cask with negligible impact force. Ground impact forces react to both the shipping cage and cask impact forces; however, the shipping cage and ground forces affect opposite impact limiters and are not in phase. In addition, the foam impacted by the shipping cage is less compressed than the foam impacted by the cask, and is thereby softer. The LIBRA-AGS dynamic response analysis program is used to determine the shipping cage impact forces, and the AGS analyses take into account both the force phases and foam stiffness properties. The increases in ground impact forces, due to the shipping cage impacts, are determined as fractions of cask impact forces and applied as force factors, f_P. Table 2-46 lists the shipping cage used in the impact analyses. Analyses results that include the shipping cage in the 30-ft. drops are provided in Appendix 2.12.11.

Table 2-46. Shipping Cage Weights Used in LIBRA-AGS Dynamic Response Analyses

Model	Shipping Cage Weight (lbs.)
AOS-025	55.0
AOS-050	240.0
AOS-100	1,500.0

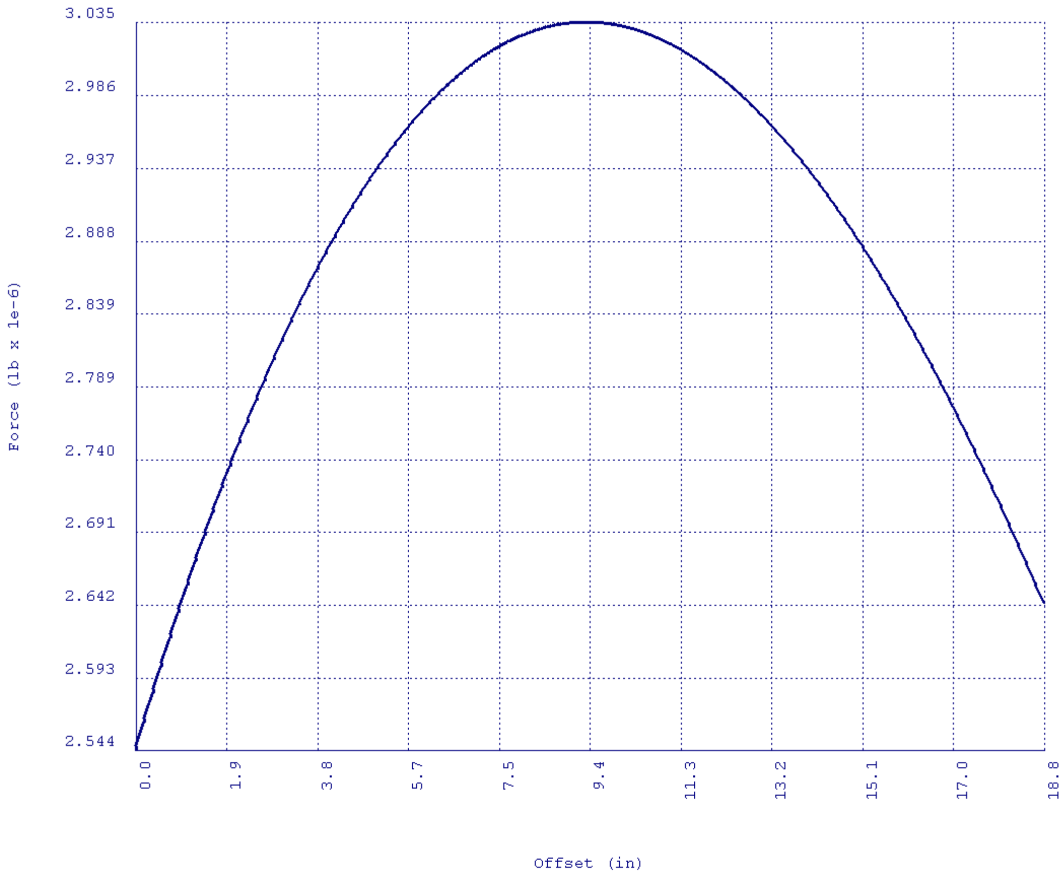

Figure 2-66. Side Impact Slap-Down Analysis

2.7.1.5.2.1.1 Cask Impact Loads – Model AOS-025

Table 2-47 presents the Model AOS-025 impact loads determined in the impact limiter analyses, and the corresponding cask stress analysis loads. The actual loads and accelerations applied in Model AOS-025 cask stress analyses are presented in Table 2-48. Table 2-48 also presents equilibrium checks.

Table 2-47. Loads and Accelerations Determined in Drop Analysis Impact – Model AOS-025

Load Case[a]	f_T	f_S	f_G	f_P	f	I (lbs.)	P (lbs.)
301	1.0	1.0	1.0	1.05	1.05	1.34×10^5	1.40×10^5
302	1.0	1.2	0.5	1.00	0.60	1.80×10^5	1.08×10^5
303_x	1.0	1.0	0.5	1.11	0.56	9.33×10^4	5.22×10^4
303_y	1.0	1.0	0.5	1.11	0.56	1.21×10^5	6.78×10^4
304	1.4	1.0	1.0	1.05	1.47	1.34×10^5	1.97×10^5
305	1.4	1.2	0.5	1.00	0.84	1.80×10^5	1.51×10^5
306_x	1.4	1.0	0.5	1.11	0.78	9.33×10^4	7.28×10^4
306_y	1.4	1.0	0.5	1.11	0.78	1.21×10^5	9.44×10^4

a. Subscripts x and y designate components of the loading.

where:

f_T = Temperature load factor

f_S = Slap-down load factor

f_G = Geometric load factor

f_P = Shipping cage load factor

f = Total load factor, $f = f_T * f_S * f_G * f_P$

I = Impact force from drop analysis load-displacement curve

P = Drop analysis impact load, P = f * I

Table 2-48. Loads and Accelerations Applied in Cask Stress Analyses – Model AOS-025

Load Case[a]	P' (lbs.)	A' (g)	M (lbs.)	R (lbs.)	R/P'
301	2.08×10^5	1,779.5	117.17	24.2	0.00
302	1.08×10^5	1,865	57.91	20.3	0.00
303_x	5.36×10^4	925.4	57.91	3.2	0.00
303_y	6.96×10^4	1,201.4	57.91	2.7	0.00
304	2.90×10^5	2,470.9	117.17	9.2	0.00
305	1.51×10^5	2,611	57.91	28.4	0.00
306_x	7.50×10^4	1,295.6	57.91	6.8	0.00
306_y	9.74×10^4	1,682	57.91	6.3	0.00

a. Subscripts x and y designate components of the loading.

where:

P' = Applied impact force

A' = Applied body acceleration

M = FEA cask model weight

R = Total reaction force from FEM cask analysis, R = P' - A' * M

2.7.1.5.2.1.2 Cask Impact Loads – Model AOS-050

Table 2-49 presents the Model AOS-050 impact loads determined in the impact limiter analyses, and the corresponding cask stress analysis loads. The actual loads and accelerations applied in Model AOS-050 cask stress analyses are presented in Table 2-50. Table 2-50 also presents equilibrium checks.

Table 2-49. Loads Determined in Drop Impact Analyses – Model AOS-050

Load Case[a]	f_T	f_S	f_G	f_P	f	I (lbs.)	P (lbs.)
301	1.0	1.0	1.0	1.06	1.06	3.50×10^5	3.71×10^5
302	1.0	1.2	0.5	1.00	0.60	3.30×10^5	1.98×10^5
303_x	1.0	1.0	0.5	1.06	0.53	1.54×10^5	0.82×10^5
303_y	1.0	1.0	0.5	1.06	0.53	1.97×10^5	1.04×10^5
304	1.4	1.0	1.0	1.06	1.48	3.50×10^5	5.18×10^5
305	1.4	1.2	0.5	1.00	0.84	3.30×10^5	2.77×10^5
306_x	1.4	1.0	0.5	1.06	0.74	1.54×10^5	1.14×10^5
306_y	1.4	1.0	0.5	1.06	0.74	1.97×10^5	1.46×10^5

a. Subscripts x and y designate components of the loading.

where:

f_T = Temperature load factor

f_S = Slap-down load factor

f_G = Geometric load factor

f_P = Shipping cage load factor

f = Total load factor, $f = f_T * f_S * f_G * f_P$

I = Impact force from drop analysis load-displacement curve

P = Drop analysis impact load, $P = f * I$

Table 2-50. Loads and Accelerations Applied in Cask Stress Analyses – Model AOS-050

Load Case[a]	P' (lbs.)	A' (g)	M (lbs.)	R (lbs.)	R/P'
301	3.85×10^5	410.9	932	109.6	0.00
302	1.98×10^5	427.4	463.3	19.0	0.00
303_x	0.85×10^5	182.8	463.3	13.6	0.00
303_y	1.08×10^5	231.2	463.3	286.9	0.00
304	5.31×10^5	566.2	932	60.4	0.00
305	2.77×10^5	598.4	463.3	9.4	0.00
306_x	1.19×10^5	256.0	463.3	42.9	0.00
306_y	1.51×10^5	325.8	463.3	412.1	0.00

a. Subscripts x and y designate components of the loading.

where:

P' = Applied impact force

A' = Applied body acceleration

M = FEA cask model weight

R = Total reaction force from FEM cask analysis, R = P' - A' * M

2.7.1.5.2.1.3 Cask Impact Loads – Model AOS-100

Table 2-51 presents the Model AOS-100 impact loads determined in the impact limiter analyses, and the corresponding cask stress analysis loads. The actual loads and accelerations applied in Model AOS-100 cask stress analyses are presented in Table 2-52. Table 2-52 also presents equilibrium checks.

Table 2-51. Loads Determined in Drop Analysis – Model AOS-100

Load Case[a]	f_T	f_S	f_G	f_P	f	I (lbs.)	P (lbs.)
301	1.0	1.0	1.0	1.04	1.040	1.42×10^6	1.48×10^6
302	1.0	1.2	0.5	1.00	0.600	1.36×10^6	8.16×10^5
303_x	1.0	1.0	0.5	1.05	0.525	6.25×10^5	3.28×10^5
303_y	1.0	1.0	0.5	1.05	0.525	8.05×10^5	4.23×10^5
304	1.4	1.0	1.0	1.04	1.456	1.42×10^6	2.07×10^6
305	1.4	1.2	0.5	1.00	0.840	1.36×10^6	1.14×10^6
306_x	1.4	1.0	0.5	1.05	0.735	6.25×10^5	4.59×10^5
306_y	1.4	1.0	0.5	1.05	0.735	8.05×10^5	5.92×10^5

a. Subscripts x and y designate components of the loading.

where:

f_T = Temperature load factor

f_S = Slap-down load factor

f_G = Geometric load factor

f_P = Shipping cage load factor

f = Total load factor, $f = f_T * f_S * f_G * f_P$

I = Impact force from drop analysis load-displacement curve

P = Drop analysis impact load, $P = f * I$

Table 2-52. Loads and Accelerations Applied in Cask Stress Analyses – Model AOS-100

Load Case[a]	P' (lbs.)	A' (g)	M (lbs.)	R (lbs.)	R / P'
301	1.48×10^6	197.0	7,498	2.14×10^3	0.00
302	8.16×10^5	220.2	3,706	0.29×10^3	0.00
303_x	3.54×10^5	95.5	3,706	263.9	0.00
303_y	4.54×10^5	122.4	3,706	315.9	0.00
304	2.07×10^6	276.1	7,498	863.9	0.00
305	1.14×10^6	307.6	3,706	4.61×10^3	0.00
306_x	4.96×10^5	117.1	3,706	214.0	0.00
306_y	6.35×10^5	154.1	3,706	384.8	0.00

a. Subscripts x and y designate components of the loading.

where:

P' = Applied impact force

A' = Applied body acceleration

M = FEA cask model weight

R = Total reaction force from FEM cask analysis, R = P' - A' * M

2.7.2 Crush

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

2.7.3 Puncture

The cask component of the AOS Transport Packaging System is evaluated for accidental drops in Load Case 311. The Model AOS-025, AOS-050, and AOS-100 transport packages are analyzed for 121.92-cm (4-ft.) drops onto a rod with a 15 cm (6 in.) diameter. The orientation selected for the drop is Head-On, impacting the package concentric with its vertical center line. This orientation is selected because at this point, the impact limiter has the least thickness. Because the cask/cask lid seal joint is recessed into the cask body and also covered by the impact limiter structure, there is no damage resulting from Free drop of Crush events.

Figure 2-67 illustrates the cask FEA model for a puncture drop. The impacted bar is modeled as fixed points, and the cask is given an initial velocity corresponding to the free-drop height. Figure 2-67 also illustrates the stress state at the time of maximum displacement, at the monitored node used for stress evaluation. Maximum cask weights are used in the Puncture analyses.

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

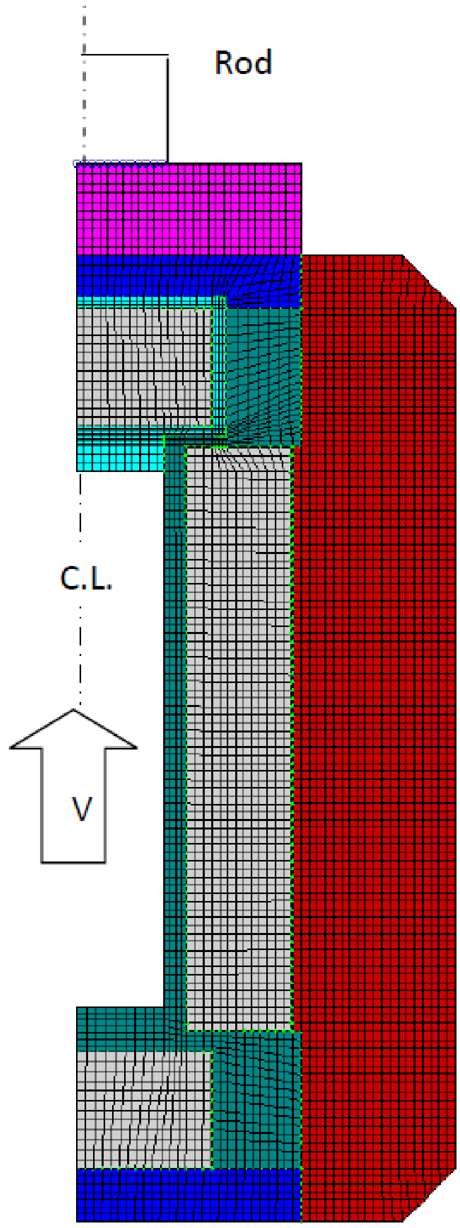

Figure 2-67. FEA Model of Puncture Drop

2.7.4 Thermal

The Fire condition is analyzed in Section 3.4, "Thermal Evaluation under Hypothetical Accident Conditions." In the following paragraphs, maximum values of temperature and pressure are provided for all AOS Transport Packaging System models. In addition, Load Cases representing the Fire condition, at 0.5-hr. intervals throughout the Fire event, are identified. The resulting stresses are provided in Paragraph 2.7.4.4.

2.7.4.1 Summary of Pressures and Temperatures

Table 2-53 presents the maximum temperatures, throughout the transport package, resulting from the Fire condition. The structural analyses are applied the temperature field generated by the thermal analysis, to determine the thermal stresses. Table 2-54 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 2-54. Therefore, the transport package can withstand pressures and temperatures in excess of those encountered in the Fire condition.

Pressure-related Load Cases 201 through 204 are analyzed by the 2D cask model. Design pressure, specific for each transport package model, 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 2-53. Temperature Summary of Fire Condition – All Models

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	136	277	259	499	246	476	241	467
Shielding Material	135	276	262	504	246	475	242	467
Cask Lid Seal Area	134	274	223	434	207	404	204	399
Cask Vent Port	134	274	225	437	208	407	206	403
Cask Drain Port	135	276	227	440	210	410	207	405
Test Port	134	274	223	433	206	402	203	397
Cask Vent Port Pipe Plug	134	274	225	437	209	407	206	402
Cask Drain Port Pipe Plug	135	276	227	441	211	411	208	406
Cask Vent Port Conical Seal	134	274	224	435	207	405	205	400
Cask Drain Port Conical Seal	135	276	224	436	208	407	206	402
Cask Outside Surface	145	294	414	777	463	866	463	866

Table 2-54. Maximum Cask Cavity Pressure Due to Fire Condition – All Models

Model	Temperature[a]		Pressure[b]			Design Pressure[c]	
	°C	°F	kPa	psia		kPa	psia
AOS-025A	136	277	139	20	<	207	30
AOS-050A	259	499	181	26	<	414	60
AOS-100A AOS-100A-S	246	476	177	26	<	1,930	280
AOS-100B	241	467	175	25	<	1,930	280

a. *Temperature listed is the maximum value obtained throughout the Fire event.*

b. *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.*

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

2.7.4.2 Differential Thermal Expansion

Thermal stresses and deformations due to thermal load cases and load combination specified in Reference **[2.4]** are determined from LIBRA Finite Element analyses, applying the 2D model shown in Figure 2-6. Stresses are calculated, combined and evaluated, as described in Paragraph 2.7.4.3.

2.7.4.3 Stress Calculations

Stress calculations are calculated using the LIBRA Finite Element analysis program. The models used in the finite element stress analyses are shown in Figure 2-6 and Figure 2-7. Membrane and bending stresses are calculated at the 22 model cross-sections shown in Figure 2-9. Stresses are calculated for the individual Hypothetical Accident Load Combinations specified in Reference **[2.4]**. The Load Cases specified in Reference **[2.3]**, and the corresponding analysis Load Case numbers, are listed in Table 2-4.

Each of the 22 cross-sections at which stresses are evaluated involve a number of elements. The elements comprising the cross-sections are listed in Table 2-4. For each cross-section and Load Case, axial, shear, and bending stress resultants are determined by integrating element stresses over the cross-section. Membrane and bending stresses are then determined from the stress resultants and cross-section area properties.

The individual Load Case stresses at the 22 cross-sections shown are combined, according to the Load Combinations specified in Reference **[2.4]**. The applicable Load Combinations specified in Reference **[2.4]** are listed in Table 2-5, along with analysis Load Combination numbers. The membrane and bending stresses combined according to Reference **[2.4]** are listed in Paragraph 2.7.4.4 for Hypothetical Accident conditions of transport.

The combined membrane and bending stresses are evaluated for Margins of Safety (MS), according to the Design Criteria specified in Reference **[2.3]**. Paragraph 2.7.8.1 provides the minimum Margin of Safety (MS) obtained for each Load Combination and System model, under Hypothetical Accident conditions of transport.

2.7.4.4 Comparison with Allowable Stresses

Table 2-55 and Table 2-56 identify the particular table in which the resulting stresses are reported for each AOS Transport Packaging System model, for all Hypothetical Accident conditions of transport Load Cases and Load Combinations, respectively. 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 2-55. Load Cases Associated with Thermal Stresses under Hypothetical Accident Conditions of Transport – All Models

Load Case	Description	Data, by Model			
		AOS-025A	AOS-050A	AOS-100A AOS-100A-S	AOS-100B
111	Fire at 30 Minutes, 1,475°F Ambient, Maximum Decay Heat	Table 2-105	Table 2-174	Table 2-242	Table 2-310
112	Post Fire at 60 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation	Table 2-106	Table 2-175	Table 2-243	Table 2-311
	Post Fire at 90 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation	Table 2-107	Table 2-176	Table 2-244	Table 2-312
	Post Fire at 120 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation	Table 2-108	Table 2-177	Table 2-245	Table 2-313
	Post Fire at 150 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation	Table 2-109	Table 2-178	Table 2-246	Table 2-314
	Post Fire at 180 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation	Table 2-110	Table 2-179	Table 2-247	Table 2-315

Table 2-56. Load Combinations Associated with Thermal Stresses under Hypothetical Accident Conditions of Transport – All Models

Load Combinations	Load Cases	Description	Data, by Model			
			AOS-025A	AOS-050A	AOS-100A AOS-100A-S	AOS-100B
350	111, 201, 211	Fire at 30 Minutes	Table 2-127	Table 2-196	Table 2-264	Table 2-332
351	112, 201, 211	Post Fire at 60 Minutes	Table 2-128	Table 2-197	Table 2-265	Table 2-333
352		Post Fire at 90 Minutes	Table 2-129	Table 2-198	Table 2-266	Table 2-334
353		Post Fire at 120 Minutes	Table 2-130	Table 2-199	Table 2-267	Table 2-335
354		Post Fire at 150 Minutes	Table 2-131	Table 2-200	Table 2-268	Table 2-336
355		Post Fire at 180 Minutes	Table 2-132	Table 2-201	Table 2-269	Table 2-337

2.7.5 Immersion – Fissile Material

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

2.7.6 Immersion – All Packages

This condition is less demanding to the transport packages than the Deep Water Immersion condition, and is therefore covered by the Deep Water condition. All AOS Transport Packaging System models are analyzed to the Deep Water condition and meet the performance requirements.

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

A pressure load of 2 MPa (290 psia) is applied to the cask component of the AOS Transport Packaging System. This condition, represented by Load Case 204, is analyzed by the use of a 2D cask model. Pressure is applied to the model outside the cask 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. Terminal nodes define the nodal lines.

Load Case 204 information is presented in Table 2-57. 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 2-57. Stresses Resulting from Additional Increased External Pressure under Hypothetical Accident Conditions of Transport – All Models

Load Case	Description	Data, by Model			
		AOS-025A	AOS-050A	AOS-100A AOS-100A-S	AOS-100B
204	Additional Increased External Pressure, 2 MPa (290 psia)	Table 2-75	Table 2-144	Table 2-213	Table 2-281

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

2.7.8 Summary of Damages

The evaluation presented in this subsection (Section 2.7, "Hypothetical Accident Conditions") demonstrates the ability of the AOS Transport Packaging System to meet the Hypothetical Accident conditions of transport specified in References **[2.1]** and **[2.2]**. All damage is confined to the impact limiter component, as designed. The integrity of the containment system is not affected by these events.

The cask drain port, cask vent port, and test port also do not suffer any damage, as a consequence of Hypothetical Accident conditions of transport. These cask component features are well-protected by the impact limiter's inside shell. The results of the Free-Drop test verify that the shell does not suffer damage that could negatively impact these features, protecting them from direct impact. Also, the analytical evaluation shows that these ports are located within areas of low-stress intensity, for all Hypothetical Accident conditions of transport.

Table 2-58 and Table 2-59 identify the particular table in which the resulting stresses are reported for each AOS Transport Packaging System model, for all Hypothetical Accident conditions of transport Load Cases and Load Combinations, respectively. Paragraph 2.7.8.1 provides the minimum Margin of Safety (MS) obtained for each Load Combination and System model, under Hypothetical Accident conditions of transport.

This data shows that the AOS Transport Packaging System has the capacity to endure all Hypothetical Accident conditions of transport without affecting its ability to contain and to shield the radioactive material payload from undue risk to the public.

Table 2-58. Load Cases Associated with Allowable Stresses under Hypothetical Accident Conditions of Transport – All Models

Load Case	Description	Data, by Model			
		AOS-025A	AOS-050A	AOS-100A AOS-100A-S	AOS-100B
111	Fire at 30 Minutes, 1,475°F Ambient, Maximum Decay Heat	Table 2-105	Table 2-174	Table 2-242	Table 2-310
112	Post Fire at 60 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation	Table 2-106	Table 2-175	Table 2-243	Table 2-311
	Post Fire at 90 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation	Table 2-107	Table 2-176	Table 2-244	Table 2-312
	Post Fire at 120 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation	Table 2-108	Table 2-177	Table 2-245	Table 2-313
	Post Fire at 150 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation	Table 2-109	Table 2-178	Table 2-246	Table 2-314
	Post Fire at 180 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation	Table 2-110	Table 2-179	Table 2-247	Table 2-315
301	30-ft. Head-On Drop	Table 2-111	Table 2-180	Table 2-248	Table 2-316
302	30-ft. Side Drop + Slap-Down	Table 2-112	Table 2-181	Table 2-249	Table 2-317
303	30-ft. Cg/Corner Drop	Table 2-113	Table 2-182	Table 2-250	Table 2-318
304	30-ft. Head-On Drop at -40°F, Low Temperature	Table 2-114	Table 2-183	Table 2-251	Table 2-319
305	30-ft. Side Drop + Slap-Down at -40°F, Low Temperature	Table 2-115	Table 2-184	Table 2-252	Table 2-320
306	30-ft. Cg/Corner Drop at -40°F, Low Temperature	Table 2-116	Table 2-185	Table 2-253	Table 2-321
311	4-ft. Drop onto Rod	Table 2-117	Table 2-186	Table 2-254	Table 2-322

Table 2-59. Load Combinations Associated with Allowable Stresses under Hypothetical Accident Conditions of Transport – All Models

Load Combinations	Load Cases	Description	Data, by Model			
			AOS-025A	AOS-050A	AOS-100A AOS-100A-S	AOS-100B
301	301, 102, 201, 211	Head-On Drop Orientation	Table 2-118	Table 2-187	Table 2-255	Table 2-323
302	302, 102, 201, 211	Side Drop Orientation	Table 2-119	Table 2-188	Table 2-256	Table 2-324
303	303, 102, 201, 211	Cg/Corner Drop Orientation	Table 2-120	Table 2-189	Table 2-257	Table 2-325
304	304, 105, 202, 211	Head-On Drop Orientation at -40°F, Cold Environment	Table 2-121	Table 2-190	Table 2-258	Table 2-326
305	305, 105, 202, 211	Side Drop Orientation at -40°F, Cold Environment	Table 2-122	Table 2-191	Table 2-259	Table 2-327
306	306, 105, 202, 211	Cg/Corner Drop Orientation at -40°F, Cold Environment	Table 2-123	Table 2-192	Table 2-260	Table 2-328
310	204, 101, 211	Additional Increased External Pressure (290 psi)	Table 2-124	Table 2-193	Table 2-261	Table 2-329
311	311, 101, 201, 211	4-ft. Drop onto Rod	Table 2-125	Table 2-194	Table 2-262	Table 2-330
312	311, 104, 201, 211	4-ft. Drop onto Rod at -40°F, Cold Environment	Table 2-126	Table 2-195	Table 2-263	Table 2-331
350	111, 201, 211	Fire at 30 Minutes	Table 2-127	Table 2-196	Table 2-264	Table 2-332
351	112, 201, 211	Post Fire at 60 Minutes	Table 2-128	Table 2-197	Table 2-265	Table 2-333
352		Post Fire at 90 Minutes	Table 2-129	Table 2-198	Table 2-266	Table 2-334
353		Post Fire at 120 Minutes	Table 2-130	Table 2-199	Table 2-267	Table 2-335
354		Post Fire at 150 Minutes	Table 2-131	Table 2-200	Table 2-268	Table 2-336
355		Post Fire at 180 Minutes	Table 2-132	Table 2-201	Table 2-269	Table 2-337

2.7.8.1 Minimum Margins of Safety

Table 2-60 through Table 2-63 provide the Minimum Margin of Safety (MS) obtained for each Load Combination and System model, under Hypothetical Accident conditions of transport.

Table 2-60. Min MS for Hypothetical Accident Conditions of Transport – Model AOS-025A

Ld_Cmb	Load_Cases					Min_MS	Loc	Str_Cmb
301	301	102	201	211	0	2.457E+00	4	Pm+Pb
302	302	102	201	211	0	7.184E+00	19	Pm
303	303	102	201	211	0	4.434E+00	4	Pm
304	304	105	202	211	0	1.833E+00	4	Pm+Pb
305	305	105	202	211	0	5.825E+00	19	Pm
306	306	105	202	211	0	3.265E+00	4	Pm
310	204	101	211	0	0	1.138E+00	4	Pm+Pb
311	311	101	201	211	0	2.782E+00	15	Pm
312	311	104	201	211	0	2.782E+00	15	Pm
350	111	201	211	0	0	1.365E+01	20	Pm+Pb
351	112	201	211	0	0	1.365E+01	20	Pm+Pb
352	113	201	211	0	0	1.365E+01	20	Pm+Pb
353	114	201	211	0	0	1.365E+01	20	Pm+Pb
354	115	201	211	0	0	1.365E+01	20	Pm+Pb
355	116	201	211	0	0	1.365E+01	20	Pm+Pb

Table 2-61. Min MS for Hypothetical Accident Conditions of Transport – Model AOS-050A

Ld_Cmb	Load_Cases					Min_MS	Loc	Str_Cmb
301	301	102	201	211	0	3.771E+00	4	Pm+Pb
302	302	102	201	211	0	7.094E+00	1	Pm+Pb
303	303	102	201	211	0	7.457E+00	4	Pm+Pb
304	304	105	202	211	0	3.103E+00	4	Pm+Pb
305	305	105	202	211	0	5.793E+00	1	Pm+Pb
306	306	105	202	211	0	7.087E+00	4	Pm+Pb
310	204	101	211	0	0	2.815E+00	4	Pm+Pb
311	311	101	201	211	0	3.697E-01	15	Pm
312	311	104	201	211	0	4.167E-01	15	Pm
350	111	201	211	0	0	1.407E+01	4	Pm+Pb
351	112	201	211	0	0	1.257E+01	4	Pm+Pb
352	113	201	211	0	0	1.257E+01	4	Pm+Pb
353	114	201	211	0	0	1.257E+01	4	Pm+Pb
354	115	201	211	0	0	1.257E+01	4	Pm+Pb
355	116	201	211	0	0	1.257E+01	4	Pm+Pb

Table 2-62. Min MS for Hypothetical Accident Conditions of Transport – Models AOS-100A and AOS-100A-S

Ld_Cmb	Load_Cases					Min_MS	Loc	Str_Cmb
301	301	102	201	211	0	1.525E+00	4	Pm+Pb
302	302	102	201	211	0	2.843E+00	4	Pm+Pb
303	303	102	201	211	0	2.665E+00	4	Pm+Pb
304	304	105	202	211	0	2.463E+00	4	Pm+Pb
305	305	105	202	211	0	7.547E+00	1	Pm
306	306	105	202	211	0	7.608E+00	4	Pm
310	204	101	211	0	0	2.724E+00	4	Pm+Pb
311	311	101	201	211	0	2.703E-01	15	Pm
312	311	104	201	211	0	3.138E-01	15	Pm
350	111	201	211	0	0	3.854E+00	4	Pm+Pb
351	112	201	211	0	0	3.524E+00	4	Pm+Pb
352	113	201	211	0	0	3.524E+00	4	Pm+Pb
353	114	201	211	0	0	3.524E+00	4	Pm+Pb
354	115	201	211	0	0	3.524E+00	4	Pm+Pb

Table 2-63. Min MS for Hypothetical Accident Conditions of Transport – Model AOS-100B

Ld_Cmb	Load_Cases					Min_MS	Loc	Str_Cmb
301	301	102	201	211	0	1.525E+00	4	Pm+Pb
302	302	102	201	211	0	2.843E+00	4	Pm+Pb
303	303	102	201	211	0	2.665E+00	4	Pm+Pb
304	304	105	202	211	0	2.463E+00	4	Pm+Pb
305	305	105	202	211	0	7.547E+00	1	Pm
306	306	105	202	211	0	7.608E+00	4	Pm
310	204	101	211	0	0	2.724E+00	4	Pm+Pb
311	311	101	201	211	0	2.703E-01	15	Pm
312	311	104	201	211	0	3.138E-01	15	Pm
350	111	201	211	0	0	3.854E+00	4	Pm+Pb
351	112	201	211	0	0	3.524E+00	4	Pm+Pb
352	113	201	211	0	0	3.524E+00	4	Pm+Pb
353	114	201	211	0	0	3.524E+00	4	Pm+Pb
354	115	201	211	0	0	3.524E+00	4	Pm+Pb

2.8 ACCIDENT CONDITIONS FOR AIR TRANSPORT OF PLUTONIUM

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

2.9 ACCIDENT CONDITIONS FOR FISSILE MATERIAL PACKAGE FOR AIR TRANSPORT

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

2.10 *SPECIAL FORM*

The AOS Transport Packaging system is authorized to ship both *Normal* and *Special form* material, as described in Subsection 1.2.2, "Contents."

2.11 FUEL RODS

Not applicable. This section does not apply to the AOS Transport Packaging System.