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(Docket No. 71-9316)

Radioactive Material Transport Packaging System

Safety Analysis Report

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

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Revision	Date	Description of Changes
J	January 31, 2021	• Consolidation of Revisions H – H7 (Revision I intentionally skipped) • Subsection 1.2.2 and Section 7.1 – Clarified that the shoring materials are structural • Paragraphs 2.5.3.1.2 through 2.5.3.1.4 – Calculations revised to correct minor errors and typos • Subsection 2.6.7 – Removed stale note created in Revision H-5 • Figures 3-18 through 3-20 – Replaced thermal transient plots for AOS Model-025 fire condition • Figure 4-3 – Changed port cover torque requirement • Chapter 9 – Updated with current requirements, approval letter, and certificate • Updated *ANSI N14.5* references to 2014 edition • Applied miscellaneous corrections (table of changes included with cover page of the submittal)
J-1	April 20, 2021	• Revised Subsection 1.2.2 (added discussion related to cask loading temperature and backfilling pressure) • Revised Subsection 2.2.3 (expanded discussion related effects of radiation), Paragraph 2.6.1.1 (revised initial conditions for NCT pressure calculations), Table 2-31 and Table 2-54 (omitted footnotes b and c, respectively; updated calculated pressures); added new Reference **[2.35]** • Revised Subsection 3.2.2 (update calculated NCT pressures and elaborate on initial conditions and mechanisms that can increase internal cask pressure) • Revised Table 4-6 and Table 4-7 (omitted footnotes b and c, respectively; revised pressure calculations based on updated initial conditions) • Revised Paragraph 7.1.3.1 (revised instructions for wet-loading cask), Figure 7-4 (updated to reflect current equipment), and Paragraph 7.1.3.3 (revised leak testing procedure) • Revised Table 8-1 footnote (clarified test procedure sensitivity), Subsection 8.1.4 (revised fabrication leak testing requirements), Section 8.2 (removed statement regarding pre-shipment leak testing because this belongs in Chapter 7), Subsection 8.2.2 (updated leak testing requirements)
J-2	June 22, 2021	• In Paragraph 7.1.3.3, changed title of “Test B – Tracer Gas: …” to “Test B – Helium Mass Spectrometer Leak Test: …” • In Paragraph 7.1.3.3, Test B, step a, changed “The cask lid seal, and vent and drain threaded pipe plugs must be leak-tested in accordance with *ANSI N14.5-2014* **[7.8]**.” to “The cask lid seal, and vent and drain threaded pipe plugs must be leak-tested in accordance with test method A.5.3 or A.5.4 from *ANSI N14.5-2014* **[7.8]**.”
J-3	July 19, 2023	• Changed Cask Lid Attachment Bolt – All Models preload torque requirements with a minimum / maximum value • Clarified that cask lid attachment bolts must be lubricated prior to use • Replaced Appendices 4.5.2 and 4.5.3 with new Appendix 4.5.2, “Cask Lid Attachment Bolt Evaluation” • Clarified Chapter 4 and 8 Reference lists

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1 GENERAL INFORMATION

1.1 INTRODUCTION

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

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

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

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

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

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

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

1.3 APPENDIX

1.3.1 AOS Transport Packaging System, Certification Drawings

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

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

Component	Drawing Part Number and Revision, by Model									
	AOS-025A	Rev.	AOS-050A	Rev.	AOS-100A	Rev.	AOS-100B	Rev.	AOS-100A-S	Rev.
Assembly	166D8142	K	105E9718	K	105E9711	L	105E9711	L	105E9711	L
Impact Limiter	105E9722	J	166D8138	I	105E9713	J	105E9713	J	105E9713	J
Cask[a]	166D8143	K	166D8137	K	105E9712G001	N	105E9712G002	N	105E9719	N
Liner	183C8485	H	–	–	–	–	–	–	–	–
Axial Shielding Plates	–	–	183C8519	A	183C8491	I	–	–	183C8491	I
Cavity Spacer Plates	–	–	–	–	183C8518	B	–	–	183C8518	B

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

AOS Drawing No. 166D8143

Model AOS-025A Cask

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

AOS Drawing No. 166D8137

Model AOS-050A Cask

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

AOS Drawing No. 105E9712G001

Model AOS-100A Cask

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

AOS Drawing No. 105E9712G002

Model AOS-100B Cask

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

AOS Drawing No. 105E9719

Model AOS-100A-S Cask

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

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	500	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.*

Table 2-20. Lifting Load Analysis – All Models

Item	Units		Model					
			AOS-025A		AOS-050A		AOS-100A[a]	
			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
$I_{x\text{-}x\ per\ unit\ area}$[b]	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
l	cm	in.	9.40E-01	3.70E-01	1.27E+00	5.00E-01	2.84E+00	1.12E+00
k_b	N/m	lbf/in.	6.78E+08	3.87E+06	1.13E+09	6.45E+06	2.02E+09	1.15E+07
k_m	N/m	lbf/in.	5.26E+09	3.00E+07	8.76E+09	5.00E+07	1.56E+10	8.93E+07
$k_b / (k_b + k_m)$			1.14E-01	1.14E-01	1.14E-01	1.14E-01	1.14E-01	1.14E-01

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

Item	Units		Model					
			AOS-025A		AOS-050A		AOS-100A[a]	
			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. *Model AOS-100A is the heaviest of the AOS-100 models and is therefore the bounding case.*

b. *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]**.

2.6.5 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 fatigue analysis is presented in Paragraph 4.5.2.6, "Cask Lid Attachment Bolt Fatigue Analysis." This analysis considers operating cycles and vibration loads and is based on the ASME Code provided in Reference **[2.14]**.

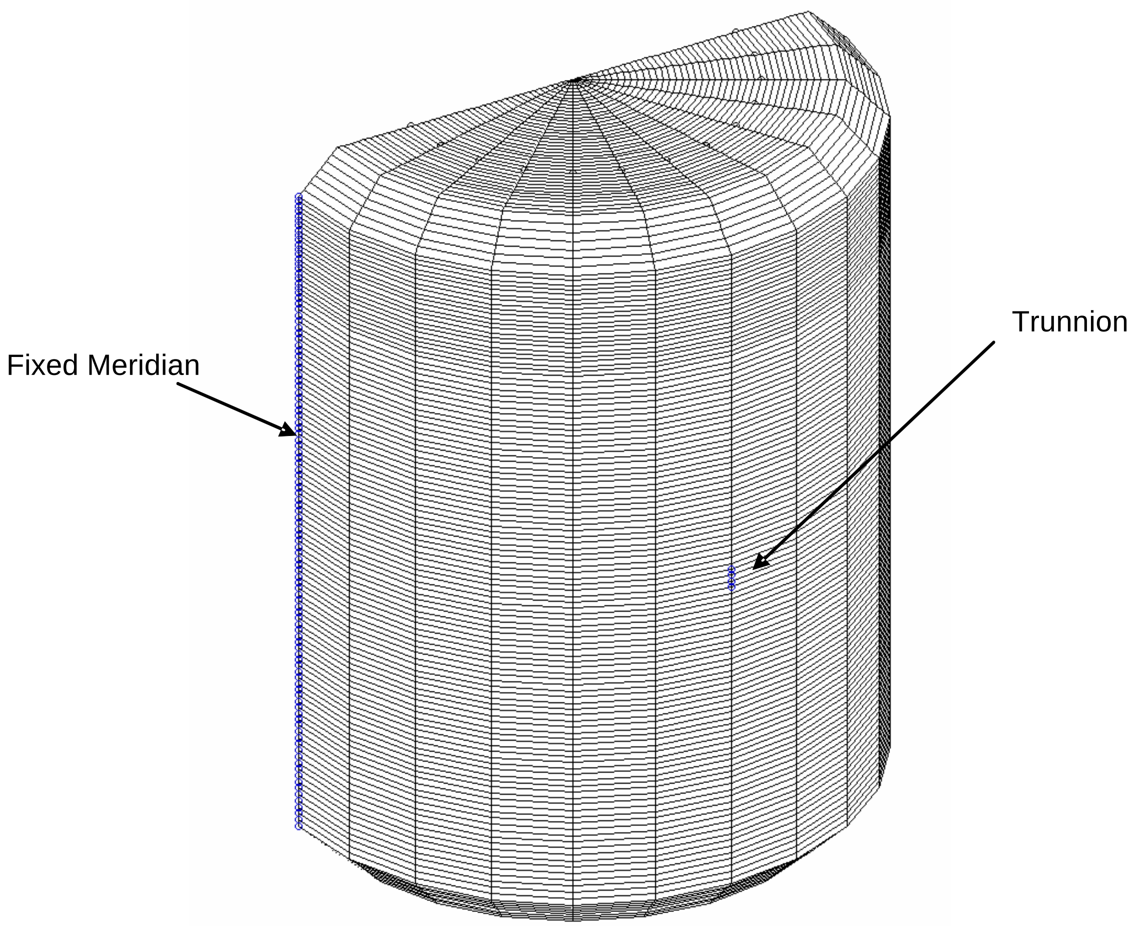

Figure 2-26. Fixed Points for Shock and Vibration Analyses

4.1.4 Closure

A set of cask lid attachment bolts, ASME SB-637, UNS N07718, attaches the cask lid to the cask. The cask lid bolted joint is recessed within the cask body, to protect the joint from transportation loads. The cask lid attachment bolt stress evaluation is presented in Appendix 4.5.2 and follows the methodology and acceptance criteria specified in *NUREG/CR-6007* (Reference **[4.6]**). The cask and bolt features and properties required for the analysis are listed in Table 4-1.

A bolting analysis is performed for Normal and Hypothetical Accident conditions of transport. Ambient conditions of 38°C (100°F) and -40°C (-40°F) are considered. The cask lid and cask lid attachment bolt head are protected in the cask lid design. Cask loadings for pressure, temperature, impact, and vibration are considered in this evaluation. Design conditions for minimum gasket loads and bolt preload are also considered. The Hypothetical Accident conditions of transport ambient temperature of 800°C (1,475°F) is a combination of fire and cool-down transient conditions, following a 30-ft. drop accident event. There are no impact accelerations associated with cool-down, and the evaluation results show that bolting loads are not significant.

Temperatures within the cask lid, cask lid attachment bolts, and cask are used to perform the evaluation, at the locations indicated in Figure 4-6.

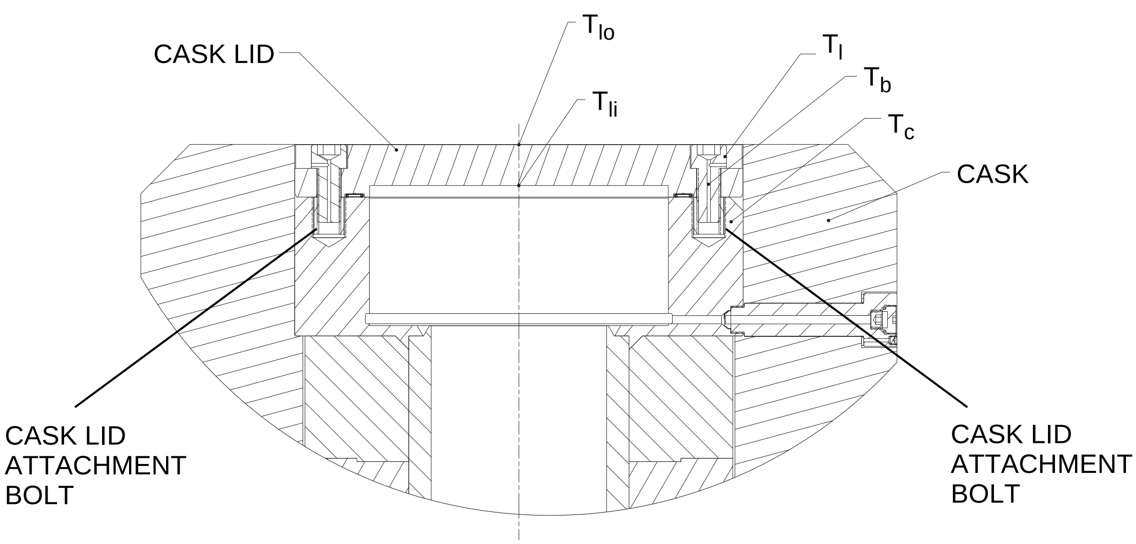

Figure 4-6. Cask Lid, Cask Lid Attachment Bolt, and Cask Temperature Evaluation Nodes

Note: *In Figure 4-6, the cask lid plug is removed for clarity.*

where:

T_b	=	Temperature of cask lid attachment bolt, node 4995
T_c	=	Temperature of cask wall, node 4995
T_l	=	Temperature of cask lid, node 3557
T_{lo}	=	Temperature of outside surface of cask lid, node 3309
T_{li}	=	Temperature of inside surface of cask lid, node 3233

Note: *All temperature changes are measured from the stress-free temperature (70°F).*

Normal Conditions of Transport, Maximum Stress Analysis

The following stress limits must be met, per *NUREG/CR-6007* (Reference **[4.6]**):

- Tension
  - Average stress < S_m (Allowable stress)
- Shear
  - Average stress < 0.6 S_m (Allowable stress)
- Tension plus shear
  - Stress ratio = Computed average stress/allowable average stress
  - Rt = Stress ratio for average tensile stress
  - Rs = Stress ratio for average shear stress
  - $Rt^2 + Rs^2 \leq 1.0$
- Tension plus shear plus bending plus residual torsion
  - For bolts having minimum tensile strength (S_u) greater than 100 ksi
  - Maximum stress intensity < 1.35 S_m

where:

S_m = Basic allowable stress limit for the bolt material, equal to 2/3 of S_y at the room temperature –or– 2/3 of S_y at the operating temperature, whichever is less

S_y = Minimum yield stress or strength of the bolt material

Normal Conditions of Transport, Fatigue Stress Analysis

The following stress limits must be met, per *NUREG/CR-6007* (Reference **[4.6]**):

- Maximum cumulative usage factor (U) due to alternating stress intensity < 1.0
- For bolts with minimum yield strength greater than 100 ksi
  - Use ASME Code, Section III Division 1 (Reference **[4.13]**), Appendix I, fatigue curves I-9-4

Table 4-1. Cask Lid Attachment Bolt Features and Properties – All Models

Item	Model and Ambient Temperatures, by Condition[a, b]					
	AOS-025		AOS-050		AOS-100	
	38°C (100°F)	-40°C (-40°F)	38°C (100°F)	-40°C (-40°F)	38°C (100°F)	-40°C (-40°F)
Geometry Definitions						
Seal Type (Cask Lid)[c]	Metallic	Metallic	Metallic	Metallic	Metallic	Metallic
Quantity of Bolts	8	8	10	10	14	14
Cask Lid Diameter at Bolt Line (in.)	3.9	3.9	7.414	7.414	14.064	14.064
Arc Length per Bolt (in.)	1.53	1.53	2.33	2.33	3.16	3.16
Cask Lid Diameter at Gasket (in.)	3.07	3.07	6.09	6.09	12.172	12.172
Bolt Diameter (in.)	0.375	0.375	0.5	0.5	0.875	0.875
Cask Lid Diameter – Inside (in.)	2.61	2.61	5.51	5.51	11.02	11.02
Cask Lid Diameter – Outside (in.)	4.65	4.65	8.90	8.90	16.59	16.59
Cask Lid Thickness (in.)	0.37	0.37	0.75	0.75	1.49	1.49
Cask Lid Flange Thickness (in.)	0.48	0.48	0.97	0.97	1.92	1.92
Cask Wall Thickness (in.)	1.02	1.02	1.695	1.695	2.785	2.785
Bolt Length (in.)	0.15	0.15	0.41	0.41	1.04	1.04

Table 4-1. Cask Lid Attachment Bolt Features and Properties – All Models (Continued)

Item	Model and Ambient Temperatures, by Condition[a, b]					
	AOS-025		AOS-050		AOS-100	
	38°C (100°F)	-40°C (-40°F)	38°C (100°F)	-40°C (-40°F)	38°C (100°F)	-40°C (-40°F)
Material Properties (Provided at the component temperature resulting from the specified Thermal Condition)						
Young Modulus – Cask Lid (psi)[d]	27.3E+06	28.3E+06	27.0E+06	28.3E+06	27.0E+06	28.3E+06
Young Modulus – Flange (psi)[d]	27.3E+06	28.3E+06	27.0E+06	28.3E+06	27.0E+06	28.3E+06
Young Modulus – Cask (psi)[d]	27.3E+06	28.3E+06	27.0E+06	28.3E+06	27.0E+06	28.3E+06
Young Modulus – Bolt (psi)[d]	28.0E+06	29.2E+06	27.8E+06	28.9E+06	27.8E+06	28.9E+06
Poisson's Ratio – Cask Lid	0.3	0.3	0.3	0.3	0.3	0.3
Poisson's Ratio – Cask	0.3	0.3	0.3	0.3	0.3	0.3
Cask Lid – CTE, in/in/°F	9.1E-06	8.6E-06	9.2E-06	8.6E-06	9.2E-06	8.6E-06
Bolt – CTE, in/in/°F	7.3E-06	7.0E-06	7.3E-06	7.0E-06	7.3E-06	7.0E-06
Cask Wall – CTE, in/in/°F	9.1E-06	8.6E-06	9.2E-06	8.6E-06	9.2E-06	8.6E-06
Basic Allowable Stress Unit – Bolt, S_m, ksi	95	100	94	100	94	100
Yield Strength – Bolt, S_y, ksi[e]	142	150	141	150	141	150
Ultimate Tensile Strength – Bolt, S_u, ksi[e]	176	185	174	185	174	185

Table 4-1. Cask Lid Attachment Bolt Features and Properties – All Models (Continued)

Item	Model and Ambient Temperatures, by Condition[a, b]					
	AOS-025		AOS-050		AOS-100	
	38°C (100°F)	-40°C (-40°F)	38°C (100°F)	-40°C (-40°F)	38°C (100°F)	-40°C (-40°F)
Mechanical Loads						
Inside Pressure at Cask Lid (psia)	30	30	60	60	280	280
Outside Pressure at Cask Lid (psia)	15	15	15	15	15	15
Inside Pressure at Cask Wall (psia)	30	30	60	60	280	280
Outside Pressure at Cask Wall (psia)	15	15	15	15	15	15
Temperature Change across Cask Lid	103°C (185°F)	-19°C (-34°F)	120°C (216°F)	8°C (15°F)	124°C (223°F)	9°C (16°F)
Temperature Change across Bolt	103°C (185°F)	-19°C (-34°F)	120°C (216°F)	8°C (15°F)	124°C (223°F)	9°C (16°F)
Temperature Change across Cask Wall	103°C (185°F)	-19°C (-34°F)	120°C (216°F)	8°C (15°F)	124°C (223°F)	9°C (16°F)
Temperature Change at outside of Cask Lid	103°C (185°F)	-19°C (-34°F)	120°C (216°F)	8°C (15°F)	124°C (224°F)	9°C (16°F)
Temperature Change at inside of Cask Lid	103°C (185°F)	-19°C (-34°F)	120°C (216°F)	9°C (16°F)	124°C (224°F)	9°C (16°F)
Weight of Cask Contents + (Plug Weight) (lbs.)	10 + 4 = 14	10 + 4 = 14	60 + 35 = 95	60 + 35 = 95	500 + 278 = 778	500 + 278 = 778
Weight of Cask Lid (lbs.)	2	2	14	14	105	105

Table 4-1. Cask Lid Attachment Bolt Features and Properties – All Models (Continued)

Item	Model and Ambient Temperatures, by Condition[a, b]					
	AOS-025		AOS-050		AOS-100	
	38°C (100°F)	-40°C (-40°F)	38°C (100°F)	-40°C (-40°F)	38°C (100°F)	-40°C (-40°F)
Mechanical Loads (Continued)						
Head-On Drop						
Drop Angle of Impact (Degrees)	90	90	90	90	90	90
Impact Acceleration (g)[f]	883	1,173	314	439	156	218
Side Drop						
Drop Angle of Impact (Degrees)	0	0	0	0	0	0
Impact Acceleration (g)[f]	1,286	1,798	335	469	172	240
Cg/Corner Drop						
Drop Angle of Impact (Degrees)	52	52	52	52	52	52
Impact Acceleration (g)[f]	1,019	1,419	224	314	113	158
Dynamic Load Factor	1.15	1.15	1.15	1.15	1.15	1.15
Puncture Load	0	0	0	0	0	0
Puncture Angle of Impact (Degrees)	0	0	0	0	0	0
Axial Vibration Acceleration (g)[g]	10	10	10	10	10	10
Transverse Vibration Acceleration (g)	5	5	5	5	5	5
Vibration Transmissibility	1.0	1.0	1.0	1.0	1.0	1.0
Preload Torque, minimum (ft-lb)	29	29	62.5	62.5	400	400
Preload Torque, maximum (ft-lb)	35	35	68	68	500	500
Nut Factor for Preload Torque	0.15	0.15	0.15	0.15	0.15	0.15
Gasket Seating Width (in.)	1.0	1.0	1.0	1.0	1.0	1.0
Gasket Seating Stress (psi)	3,000	3,000	3,000	3,000	3,000	3,000
Gasket Factor[h]	9.53	9.53	3.18	3.18	0.54	0.54

Table 4-1. Cask Lid Attachment Bolt Features and Properties – All Models (Continued)

Item	Model and Ambient Temperatures, by Condition[a, b]					
	AOS-025		AOS-050		AOS-100	
	38°C (100°F)	-40°C (-40°F)	38°C (100°F)	-40°C (-40°F)	38°C (100°F)	-40°C (-40°F)
Geometry Loads						
Number of Threads per Inch	16	16	13	13	9	9

a. *The conditions are defined in Table 3-1, "Transport Package Thermal Environment Conditions – All Models."*

b. *Temperature changes are measured from the stress-free temperature of 70°F.*

c. *Garlock Helicoflex drawing numbers H-309854 (Model AOS-025), H-309852 (Model AOS-050), and H309850 (Model AOS-100). Only the cask lid metallic seal was considered in this analysis, because it requires a higher gasket factor than the cask lid elastomeric seal.*

d. *Material properties for Models AOS-050A and AOS-100A are documented at temperatures of 86°F and 300°F for hot and cold properties, respectively. Material properties for Model AOS-025A are documented at temperatures of 255°F and 36°F for hot and cold properties, respectively. Basis: The cask's seal areas have NCT hot temperatures of 255°F , 286°F, and 293°F for Models AOS-025A, AOS-050A, and AOS-100A, respectively, and cold temperatures of 36°F, 85°F, and 86°F for Models AOS-025A, AOS-050A, and AOS-100A, respectively, as documented in Chapter 3, "Thermal Evaluation."*

e. *Room temperature properties are used for the temperature range of -20°F to 100°F. Because yield and tensile strength properties are inversely proportional with temperature, room temperature properties are conservatively used for lower temperatures. Additionally, the room temperature properties of ASME high strength bolts do not change significantly up to 100°F.*

f. *Accelerations are obtained from the impact forces defined in the drop analysis results provided in Paragraph 2.7.1.5.2.1, "Impact Load Tables."*

g. *Normal conditions of transport accelerations, g, are:*

Axial 10

Lateral 5

h. *Helicoflex spring seal (cask lid metallic seal), per Helicoflex calculations, for gasket factor, m:*

Model AOS-025 cask $m = Y1 / (2 * \Delta P) = 286 / (2 * (30 - 15)) = 9.53$

Model AOS-050 cask $m = Y1 / (2 * \Delta P) = 286 / (2 * (60 - 15)) = 3.18$

Model AOS-100 cask $m = Y1 / (2 * \Delta P) = 286 / (2 * (280 - 15)) = 0.54$

where:

Y1 = Linear load on the seal, to maintain sealing in service at low pressure

ΔP = Pressure inside the cask cavity

Table 4-2. Cask Lid Attachment Bolt Results Summary – All Models

Item	Model and Ambient Temperatures, by Condition[a]					
	AOS-025		AOS-050		AOS-100	
	38°C (100°F)	-40°C (-40°F)	38°C (100°F)	-40°C (-40°F)	38°C (100°F)	-40°C (-40°F)
Bolt size (in.)	3/8		1/2		7/8	
Number of threads per in.	16		13		9	
Number of Bolts	8		10		14	
Torque, ft-lb	35		68		500	
Normal Conditions of Transport						
Axial Stress / S_m	0.09	0.08	0.19	0.16	0.41	1.35
Shear Stress / 0.6 S_m	0.01	0.01	0.03	0.03	0.17	0.16
$Rt^2 + Rs^2$	0.01	0.01	0.04	0.03	0.20	0.15
Se / 1.35 S_m	0.55	0.52	0.49	0.45	0.81	0.75
Accumulated Fatigue Usage	0.20	–	0.19	–	0.72	–
Hypothetical Accident Conditions of Transport						
Head-On Drop						
Axial Stress / 0.7 S_u	0.64	0.83	0.72	0.87	0.81	0.92
Shear Stress / 0.42 S_u	0.00	0.00	0.02	0.02	0.13	0.13
$Rt^2 + Rs^2$	0.41	0.68	0.52	0.76	0.67	0.86
Side Drop						
Axial Stress / 0.7 S_u	0.07	0.06	0.15	0.12	0.31	0.27
Shear Stress / 0.42 S_u	0.06	0.08	0.07	0.08	0.17	0.18
$Rt^2 + Rs^2$	0.01	0.01	0.03	0.02	0.13	0.10
Cg/Corner Drop						
Axial Stress / 0.7 S_u	0.62	0.79	0.47	0.54	0.60	0.64
Shear Stress / 0.42 S_u	0.03	0.04	0.04	0.05	0.15	0.15
$Rt^2 + Rs^2$	0.39	0.63	0.22	0.30	0.38	0.43

a. *The conditions are defined in Table 3-1, "Transport Package Thermal Environment Conditions – All Models."*

4.5 APPENDIX

This appendix includes a lists of references, applicable pages from referenced documents, supporting information and analysis, test results, and other supplemental information:

- Garlock Helicoflex Cask Lid Metallic Seal and AOS Cask Lid Elastomeric Seal Drawings
- Cask Lid Attachment Bolt Evaluation

4.5.2 Cask Lid Attachment Bolt Evaluation

The following analyses document the bolting evaluation **[4.14]** of the AOS transport packaging system's cask lid attachment bolts per *NUREG/CR-6007* **[4.6]**. The required thread engagement length is also evaluated.

Note: *All references to "bolt" within this appendix are to the cask lid attachment bolt.*

4.5.2.1 Package Accelerations

The cask accelerations are required as input for the bolt stress calculations under Hypothetical Accident Conditions (HAC). The cask accelerations are calculated using the total impact load, P, and total cask weight. The weights and impact loads of the packages are documented in Subsection 2.1.3. The total cask weight includes the cask itself, its contents, and the impact limiters, as documented in Table 4-8. The accelerations are calculated by dividing the impact load by the cask's overall mass. The Model AOS-025A, AOS-050A, and AOS-100A accelerations are documented in Table 4-9.

Table 4-8. Weights of AOS Transport Packages

Item	Units	Model		
		AOS-025A	AOS-050A	AOS-100A
Cask + Contents	lbs.	140	1,058	8,481
Impact limiters (x2)	lbs.	28	123	1,029
Total Cask Weight	lbs.	168	1,181	9,510

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Table 4-9. AOS Transport Package Accelerations

Model	Load Case	Impact Load, P (lbs.)	Weight (lbs.)[a]	Acceleration (g)[b]
AOS-025A	Head-on drop hot (100°F)/Case 301	1.40E+05	168	833
	Head-on drop cold (-40°F)/Case 304	1.97E+05	168	1,173
	Side drop hot (100°F)/Case 302	1.08E+05	84	1,286
	Side drop cold (-40°F)/Case 305	1.51E+05	84	1,798
	Cg/Corner drop hot (100°F)/Case 303[c]	8.56E+04	84	1,019
	Cg/Corner drop cold (-40°F)/Case 306[c]	1.19E+05	84	1,419
AOS-050A	Head-on drop hot (100°F)/Case 301	3.71E+05	1181	314
	Head-on drop cold (-40°F)/Case 304	5.18E+05	1181	439
	Side drop hot (100°F)/Case 302	1.98E+05	591	335
	Side drop cold (-40°F)/Case 305	2.77E+05	591	469
	Cg/Corner drop hot (100°F)/Case 303[c]	1.32E+05	591	224
	Cg/Corner drop cold (-40°F)/Case 306[c]	1.85E+05	591	314
AOS-100A	Head-on drop hot (100°F)/Case 301	1.48E+06	9,510	156
	Head-on drop cold (-40°F)/Case 304	2.07E+06	9,510	218
	Side drop hot (100°F)/Case 302	8.16E+05	4,755	172
	Side drop cold (-40°F)/Case 305	1.14E+06	4,755	240
	Cg/Corner drop hot (100°F)/Case 303[c]	5.35E+05	4,755	113
	Cg/Corner drop cold (-40°F)/Case 306[c]	7.49E+05	4,755	158

a. *The full model is used for head-on drop impact load calculations, whereas a half model is used for the side and Cg/Corner drops as documented in Paragraph 2.7.1.5.2.1.1, Paragraph 2.7.1.5.2.1.2, and Paragraph 2.7.1.5.2.1.3 for Models AOS-025A, AOS-050A, and AOS-100A, respectively. Therefore, the weight of the full and half models are used in calculating the accelerations of the Head-on drops, and the Side and Cg/Corner drops, respectively.*

b. *Acceleration = Impact load / weight.*

c. *The resultant impact load is calculated using the square root of the sum of the squares of the x and y components.*

4.5.2.2 Dynamic Load Factors

The equivalent-static acceleration loads for the free drops are equal to the peak rigid body accelerations of the packaging multiplied by a Dynamic Load Factor (DLF) that accounts for possible dynamic amplification within the packaging. The Dynamic Load Factors for the transport packages are determined in the paragraphs that follow.

The DLF is a function of the general shape of the rigid-body acceleration time-history pulse and the ratio of the duration of the rigid body acceleration to the component's natural period (t / T). The general shape of the rigid-body acceleration time-history curve is characterized as a half-sine wave. The DLF (or Dynamic Amplification Factor, DAF) for a half-sine wave pulse from *NUREG/CR-3966* **[4.9]**, *Figure 2.15*, is shown in Figure 4-7.

The DAF graph shown in Figure 4-7 is truncated at the ratio of pulse duration (t) to natural period (T) of six (6). However, for ratios greater than one (1), DAF is generally inversely proportional with frequency as shown in Figure 4-7. Therefore, for t / T ratios greater than six (6), the DAF value at ratio of t / T = 6 is conservatively considered.

4.5.2.2.1 Model AOS-025A Transport Package Lid Dynamic Load Factor

4.5.2.2.1.1 Natural Frequency

The cask lid's natural frequency is calculated by considering the cask lid as a simply supported circular plate using Reference **[4.10]**, *Table 11.1*, *Case 2*, as follows:

f $= \frac{\lambda_{ij}}{2\pi a^2}\left[\frac{Eh^3}{12\Upsilon(1-\nu^2)}\right]^{\frac{1}{2}}$ = 3,131 Hz, Natural frequency

where:

λ_{ij} = 4.98, dimensionless parameter (for i = j = 0), Reference **[4.10]**, *Table 11.1*, *Case 2*

a = 2.325 in., cask lid radius

h = 0.37 in., cask lid thickness

E_b = 27.3 × 10^6 psi, modulus of elasticity

ν = 0.3, Poisson's ratio

μ $= \frac{0.29\frac{lb}{in^3}}{386.4\frac{in}{s^2}}$ = 7.50518E^{-4} $\frac{lb \times s^2}{in^4}$ = mass density

ρ = 0.29 $\frac{lb}{in^3}$, density

Υ = h × μ = 2.78E^{-4} $\frac{lb \times s^2}{in^3}$ = mass per unit area

The corresponding natural period of vibration (T) is 1 / f = 0.00032 seconds.

4.5.2.2.1.2 Impact Duration

The impact duration (t) is approximated using the mass, impact initial velocity and impact loads, per methods presented in Reference **[4.9]**, as follows:

t $= \frac{MV_o}{F_{max}}$ = 0.0012 sec.

where:

M = 168 lbs./386.4 in/sec^2 = 0.43 lb-sec^2/in, mass

F_{max} = 1.97 × 10^5 lbs., Impact load maximum

V_o = $\sqrt{2gh}$ = 527 in/sec, initial velocity at impact

g = 386.4, in/sec^2, gravitational acceleration

h = 360 in., drop height (30 ft.)

Accordingly, the ratio of impact duration to the natural period (t / T) = 3.75. Therefore, the corresponding DLF from Figure 4-7 is approximately 1.15.

4.5.2.2.2 Model AOS-050A Transport Package Cask Lid Dynamic Load Factor

4.5.2.2.2.1 Natural Frequency

The cask lid's natural frequency is calculated by considering the cask lid as a simply supported circular plate using Reference **[4.10]**, *Table 11.1*, *Case 2*, as follows:

f $= \frac{\lambda_{ij}}{2\pi a^2}\left[\frac{Eh^3}{12\Upsilon(1-\nu^2)}\right]^{\frac{1}{2}}$ = 1,723 Hz, Natural frequency

where:

λ_{ij} = 4.98, dimensionless parameter (for i = j = 0), Reference **[4.10]**, *Table 11.1*, *Case 2*

a = 4.45 in., cask lid radius

h = 0.75 in., cask lid thickness

E_b = 27.0 × 10^6 psi, modulus of elasticity

ν = 0.3, Poisson's ratio

μ $= \frac{0.29\frac{lb}{in^3}}{386.4\frac{in}{s^2}}$ = 7.50518E-4 $\frac{lb \times s^2}{in^4}$ = mass density

ρ = 0.29 $\frac{lb}{in^3}$, density

Υ = h × μ = 5.63E-4 $\frac{lb \times s^2}{in^3}$ = mass per unit area

The corresponding natural period of vibration (T) is 1 / f = 0.00058 seconds.

4.5.2.2.2.2 Impact Duration

The impact duration (t) is approximated using the mass, impact initial velocity and impact loads, per methods presented in Reference [4.9], as follows:

t $= \frac{MV_o}{F_{max}}$ = 0.0031 sec.

where:

M = 1,181 lbs./386.4 in/sec^2 = 3.06 lb-sec^2/in, mass

F_{max} = 5.18 × 10^5 lbs., Impact load maximum

V_o = $\sqrt{2gh}$ = 527 in/sec, initial velocity at impact

g = 386.4, in/sec^2, gravitational acceleration

h = 360 in., drop height (30 ft.)

Accordingly, the ratio of impact duration to the natural period (t / T) = 5.34. Therefore, the corresponding DLF from Figure 4-7 is approximately 1.1. However, a DLF value of 1.15 is conservatively used in the analysis for the Model AOS-050A.

4.5.2.2.3 Model AOS-100A Transport Package Cask Lid Dynamic Load Factor

4.5.2.2.3.1 Natural Frequency

The cask lid's natural frequency is calculated by considering the cask lid as a simply supported circular plate using Reference **[4.10]**, *Table 11.1*, *Case 2*, as follows:

$$f = \frac{\lambda_{ij}}{2\pi a^2}\left[\frac{Eh^3}{12\Upsilon(1-\nu^2)}\right]^{\frac{1}{2}} = 984.4 \text{ Hz, Natural frequency}$$

where:

λ_{ij} = 4.98, dimensionless parameter (for i = j = 0), Reference **[4.10]**, *Table 11.1*, *Case 2*

a = 8.295 in., cask lid radius

h = 1.49 in., cask lid thickness

E_b = 27.0 × 10^6 psi, modulus of elasticity

ν = 0.3, Poisson's ratio

$$\mu = \frac{0.29\frac{lb}{in^3}}{386.4\frac{in}{s^2}} = 7.50518E^{-4}\ \frac{lb \times s^2}{in^4} = \text{mass density}$$

ρ = 0.29 $\frac{lb}{in^3}$, density

$$\Upsilon = h \times \mu = 1.12E^{-3}\ \frac{lb \times s^2}{in^3} = \text{mass per unit area}$$

The corresponding natural period of vibration (T) is 1 / f = 0.001 seconds

4.5.2.2.3.2 Impact Duration

The impact duration (t) is approximated using the mass, impact initial velocity and impact loads, per methods presented in Ref. [2]

$$t = \frac{MV_o}{F_{max}} = 0.0063 \text{ sec.}$$

where:

M = 9,510 lbs./386.4 in/sec^2 = 24.61 lb-sec^2/in, mass

F_{max} = 2.07 × 10^6 lbs., Impact load maximum

V_o = $\sqrt{2gh}$ = 527 in/sec, initial velocity at impact

g = 386.4, in/sec^2, gravitational acceleration

h = 360 in., drop height (30 ft.)

Accordingly, the ratio of impact duration to the natural period (t / T) = 6.18. The DAF graph shown in Figure 4-7 is truncated at the ratio of pulse duration to the natural period of 6. However, for ratios greater than 1, DAF is generally inversely proportional with frequency as shown in Figure 4-7. Therefore, for the ratio (t / T) values greater than 6, the DAF value at t / T = 6 is conservatively considered. The corresponding DLF from Figure 4-7 is approximately 1.1. However, a DLF value of 1.15 is conservatively used in the analysis for the Model AOS-100A.

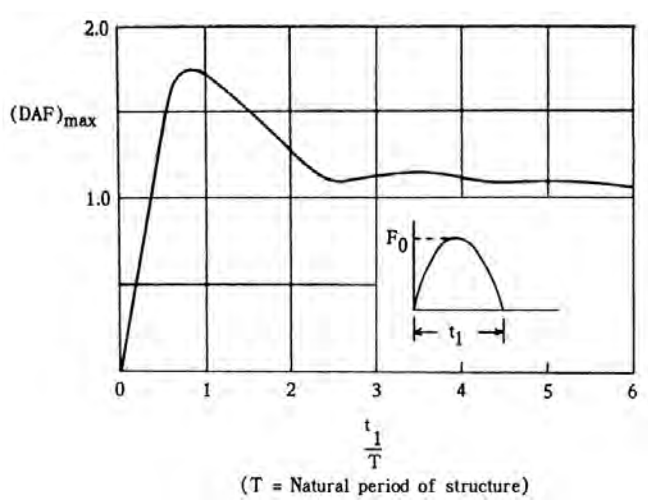

Figure 4-7. Impact Response Spectrum for SDOF System – Half-Sine Pulse Shape, No Damping, All Models

4.5.2.3 Cask Lid Attachment Bolt Stress Analysis

4.5.2.3.1 Acceptance Criteria

The cask lid attachment bolts are subjected to operational loads such as gasket seating and operating loads, bolt tightening preload, vibration, internal pressure, differential thermal expansion, and the loads associated with free drops.

NCT Acceptance criteria is as documented in *NUREG/CR-6007* **[4.6]**, *Table 6.1* and *Table 6.2*, which are based on *ASME B&PVC, Section III, Subsection NB* **[4.12]**. HAC acceptance criteria are as documented in Reference **[4.6]**, *Table 6.3*.

NCT acceptance criteria are that the average tensile stress must be less than the basic allowable stress in tension, and the average shear stress must be less than 60% of the basic allowable stress per Reference **[4.6]**, *Table 6.1*. In addition, stress ratio is calculated for all bolts per that table. The sum of the squares of the stress ratios for average tensile stress and the average shear stress must be less than 1. Further, the maximum stress intensity must be less than 1.35 times the allowable stress for bolts having a minimum tensile strength greater than 100 ksi, and 1.5 times for bolts that have a minimum tensile strength of less than 100 ksi.

HAC acceptance criteria is based on Reference **[4.6]**, *Table 6.3*. In accordance with that table, the average stress in tension must be less than the smaller of 0.7 S_u or of S_y at temperature T. The average stress in shear must be less than the smaller of 0.42 S_u or 0.6 S_y at temperature T. Additionally, the sum of the squares of the HAC stress ratio for average tensile stress and average shear stress must be less than 1.

4.5.2.3.2 Equations for Bolt Loads and Stresses per NUREG/CR-6007 [4.6]

4.5.2.3.2.1 Forces and Moments Generated by Preload

Preload for the bolts is calculated using the equation presented in *NUREG/CR-6007* **[4.6]**, *Table 4.1*, which is the non-prying axial bolt force per bolt, F_a, that is generated when the bolt is torqued:

$$F_a = \frac{Q}{KD_b}$$

where:

Q = Applied torque (in-lb) for the preload

K = Nut factor for empirical relation between the applied torque and achieved preload

D_b = Nominal diameter (in.) of the cask lid attachment bolt

The torsional bolt moment per bolt, M_t, is defined by the following formula:

$$M_t = 0.5\ Q$$

4.5.2.3.2.2 Forces and Moments Generated by Gasket Loads

NUREG/CR-6007 **[4.6]**, *Table 4.2*, lists the formulas for calculating the forces and moments generated by gasket loads. The axial force produced by the gasket seating is evaluated by use of the following equation:

$$F_a = \frac{\pi\, D_{lg}\, b\, y}{N_b}$$

where the minimum design seating stress (y) and the effective gasket seating width (b) are defined in accordance with *ASME B&PV Code* **[4.13]**, *Appendix E*:

D_{lg} = Face seal diameter (in.)

N_b = Number of cask lid attachment bolts

The torsional bolt moment (M_t) due to the gasket seating is as follows:

$$M_t = \frac{0.5\pi K D_b\, D_{lg}\, b\, y}{N_b}$$

where:

D_b = Nominal diameter of the cask lid attachment bolt (in.)

Additionally, the non-prying tensile bolt force per bolt produced by the operating gasket load is determined by the following equation:

$$F_a = \frac{2\,\pi\, D_{lg}\, b\, m\,(P_{li} - P_{lo})}{N_b}$$

where the gasket factor (m) and the effective gasket seating width (b) are defined in accordance with *ASME B&PV Code* **[4.13]**, *Appendix E*, and:

D_{lg} = Face seal diameter (in.)

N_b = Number of cask lid attachment bolts

P_{li} = Pressure inside the cask lid (psi)

P_{lo} = Pressure outside the cask lid (psi)

The effective gasket seating width, b, is calculated using the method in *ASME B&PV Code* **[4.13]**, *Appendix E*. As documented in *ASME B&PV Code* **[4.13]**, *Table E-1210*:

$b = b_o$ for $b_o \leq 1/4$

$b = C_b\sqrt{b_o}$ for $b_o > 1/4$

where:

C_b = 0.5

The basic gasket seating width, b_o, is calculated using the design contact width, N, of the gasket. As documented in *ASME B&PV Code* **[4.13]**, *Table E-1210*:

$$b_o = \frac{N}{2}$$

The gasket factor (m) and minimum design seating stress (y) for various gasket types are provided in *ASME B&PV Code* **[4.13]**, *Table E-1210-1*. Values for self-energizing types (O-rings, metallic, elastomeric, other gasket types considered as self-sealing) are used in the calculation.

4.5.2.3.2.3 Forces and Moments Generated by Pressure Loads

NUREG/CR-6007 **[4.6]**, *Table 4.3*, is applied to determine the moments and forces that are generated due to the pressure difference between the inside and outside of the cask. The associated equation for the axial force due to pressure loads is as follows:

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

where:

D_{lg} = Face seal diameter (in.)

N_b = Number of cask lid attachment bolts

P_{li} = Pressure inside the cask lid

P_{lo} = Pressure outside the cask lid

The shear bolt force per bolt is as follows:

$$F_s = \frac{\pi E_l t_l (P_{ci} - P_{co}) D_{lb}^2}{2 N_b E_c t_c (1 - N_{ul})}$$

where:

E_l = Young's modulus of the cask lid material

E_c = Young's modulus of the cask wall material

t_l = Thickness of the cask lid

t_c = Thickness of the cask wall

N_b = Number of cask lid attachment bolts

D_{lb} = Cask lid diameter at the bolt circle

P_{ci} = Pressure inside the cask wall

P_{co} = Pressure outside the cask wall

N_{ul} = Poisson's ratio of the cask lid material

The fixed-edge cask lid force generated by internal pressure is as follows:

$$F_f = \frac{D_{lb}(P_{li} - P_{lo})}{4}$$

where:

D_{lb} = Cask lid diameter at the bolt circle

P_{li} = Pressure inside the cask lid

P_{lo} = Pressure outside the cask lid

The fixed-edge moment is as follows:

$$M_f = \frac{(P_{li} - P_{lo})\, D_{lb}^2}{32}$$

where:

D_{lb} = Cask lid diameter at the bolt circle

P_{li} = Pressure inside the cask lid

P_{lo} = Pressure outside the cask lid

4.5.2.3.2.4 Forces and Moments Generated by Temperature Loads

NUREG/CR-6007 **[4.6]**, *Table 4.4*, provides the formulas for bolt forces/moments that are generated by thermal expansion difference between the cask lid, cask lid attachment bolt, and cask wall. The axial force due to a temperature difference between the cask lid attachment bolt and cask lid is as follows:

$$F_{at} = 0.25\, \pi\, D_b^2 E_b (a_l T_l - a_b T_b)$$

where:

D_b = Nominal diameter of the cask lid attachment bolt (in.)

E_b = Young's modulus of the cask lid attachment bolt material

a_l = Thermal expansion coefficient of the cask lid material

a_b = Thermal expansion coefficient of the cask lid attachment bolt material

T_l = Temperature change (ΔT) of the cask lid

T_b = Temperature change of the cask lid attachment bolt

The shear force acting on each bolt is as follows:

$$F_s = \frac{\pi E_l t_l D_{lb}(a_l T_l - a_c T_c)}{N_b(1 - N_{ul})}$$

where:

E_l = Young's modulus of the cask lid material

t_l = Thickness of the cask lid material

D_{lb} = Cask lid diameter at the bolt circle

a_l = Thermal expansion coefficient of the cask lid material

a_c = Thermal expansion coefficient of the cask wall material

T_l = Temperature change (ΔT) of the cask lid

T_c = ΔT of the cask wall

N_b = Number of cask lid attachment bolts

N_{ul} = Poisson's ratio of the cask lid material

Fixed-edge force and fixed-edge moment due to temperature difference between the inner and outer surface of the cask lid is determined by use of the following equations:

F_f = 0 lb/bolt

$$M_f = \frac{E_l a_l t_l^2 (T_{lo} - T_{li})}{12(1 - N_{ul})}$$

where:

E_l = Young's modulus of the cask lid material

a_l = Thermal expansion coefficient of the cask lid material

t_l = Thickness of the cask lid

T_{lo} = ΔT outer surface of the cask lid

T_{li} = ΔT inner surface of the cask lid

N_{ul} = Poisson's ratio of the cask lid material

4.5.2.3.2.5 Forces and Moments Generated by Impact Loads

The equations in *NUREG/CR-6007* **[4.6]**, *Table 4.5*, are used to calculate the bolt loads due to impact. The non-prying tensile bolt force per bolt due to impact is as follows:

$$F_a = \frac{1.34 \times \sin(x_i)\ \mathrm{DLF}\ a_i(W_l + W_c)}{N_b}$$

where:

a_i = Maximum rigid body acceleration (g) of the cask

DLF = Dynamic load factor

x_i = Impact angle between the cask axis and target surface

W_l = Weight of the cask lid

W_c = Weight of the contents

N_b = Number of cask lid attachment bolts

The shear bolt force per bolt is as follows:

$$F_s = \frac{\cos(x_i)a_i W_l}{N_b}$$

where:

a_i = Maximum rigid body acceleration (g) of the cask

x_i = Impact angle between the cask axis and target surface

W_l = Weight of cask lid

N_b = Number of cask lid attachment bolts

Further, the fixed-edge force and fixed-edge moment are defined as follows:

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

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

where:

a_i = Maximum rigid body acceleration (g) of the cask

DLF = Dynamic load factor

x_i = Impact angle between the cask axis and target surface

W_l = Weight of the cask lid

W_c = Weight of the contents

N_b = Number of cask lid attachment bolts

D_{lb} = Cask lid diameter at the bolt circle

4.5.2.3.2.6 Forces and Moments Generated by Vibration Loads

Although vibration loads are not significant, they are considered during normal conditions of transport. The loads that are generated due to vibration are outlined in *NUREG/CR-6007* **[4.6]**, *Table 4.8*. The accelerations recommended for tie-down in the regulations, *10 CFR 71.45(b)(1)* **[4.1]**, are considered in calculating the maximum loads due to vibration acceleration. Accordingly, 10-g axial and 5-g transverse vibration accelerations are considered for calculating the tensile and shear bolt forces, respectively.

The tensile bolt force per bolt is as follows:

$$F_a = \frac{VTR\ ava\ W_l}{N_b}$$

where:

VTR = 1, Vibration transmissibility of acceleration between the cask support and cask lid

ava = 10g, Maximum axial vibration acceleration at the cask support

W_l = Weight of the cask lid

N_b = Number of cask lid attachment bolts

The shear bolt force per bolt is as follows:

$$F_s = \frac{VTR\ avt\ W_l}{N_b}$$

where:

VTR = 1, Vibration transmissibility of acceleration between the cask support and the cask lid

avt = 5g, Maximum transverse vibration acceleration at the cask support

W_l = Weight of the cask lid

N_b = Number of cask lid attachment bolts

The fixed-edge force and fixed-edge moment are defined as follows:

$$F_f = \frac{\sin(xi)\ VTR\ ava\ W_l}{\pi D_{lb}}$$

$$M_f = \frac{VTR\ ava\ W_l}{8\ \pi}$$

where:

VTR = 1, Vibration transmissibility of acceleration between the cask support and the cask lid

ava = 10g, Maximum axial vibration acceleration at the cask support

x_i Impact angle between the cask axis and the target surface

W_l = Weight of the cask lid

D_{lb} = Cask lid diameter at the bolt circle

4.5.2.3.2.7 Prying Action Forces Generated by Applied Loads

From *NUREG/CR-6007* **[4.6]**, *Table 2.1*. the axial bolt force per bolt that is caused by the prying action of the cask lid is as follows:

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

where:

C1 = 1

$$C2 = \left(\frac{8}{3(D_{lo} - D_{lb})^2}\right)\left[\frac{E_l\ t_l^3}{1-N_{ul}} + \frac{(D_{lo} - D_{li})\ E_{lf}\ t_{lf}^3}{D_{lb}}\right]\left(\frac{L_b}{N_b\ D_b^2\ E_b}\right)$$

L_b = Bolt length between the top and bottom surfaces of the cask lid at the bolt circle

B = F_f if $F_f > P$; otherwise, B = P

In calculating C2, E_l and E_{lf} are the Young's modulus of the cask lid and cask lid flange, respectively. Because the cask lid and its flange are the same material, E_l is the same as E_{lf}.

E_b = Young's modulus of the cask lid attachment bolt material

D_b = Nominal diameter of the cask lid attachment bolt

D_{lb} = Cask lid diameter at the bolt circle

D_{lo} = Cask lid diameter at the outer edge

D_{li} = Cask lid diameter at the inner edge

M_f = Fixed-edge moment of the cask lid at the bolt circle that is caused by the applied loads (per unit length of the bolt circle)

F_f = Fixed-edge force of the cask lid at the bolt circle that is caused by the applied loads (per unit length of the bolt circle)

N_b = Number of cask lid attachment bolts

N_{ul} = Poisson's ratio of the cask lid material

P = Bolt preload per unit length of the bolt circle (the combined preload and temperature load (F_{a-pt}) is used to calculate P, per *NUREG/CR-6007* **[4.6]**, *Table 4.9*, *II.3*

t_l = Thickness of the cask lid

t_{lf} = Thickness of the cask lid flange

The prying action load is calculated for the combined load using the combined fixed-edge force (F_{f-c}) and the combined fixed-edge moment (M_{f-c}).

4.5.2.3.2.8 Bending Bolt Moment Generated by Applied Loads

NUREG/CR-6007 **[4.6]**, *Table 2.2*, includes the formula for calculating the bending bolt moment per bolt that is caused by the rotation or bending of the cask lid and is expressed as follows:

$$M_{bb} = \left(\frac{\pi D_{lb}}{N_b}\right)\left(\frac{K_b}{K_b + K_l}\right)M_f$$

where:

$$K_b = \left(\frac{N_b}{L_b}\right)\left(\frac{E_b}{D_{lb}}\right)\left(\frac{D_b^4}{64}\right)$$

$$K_l = \frac{E_l\ t_l^3}{3\left[\left(1 - N_{ul}^2\right) + \left(1 - N_{ul}\right)^2\left(\frac{D_{lb}}{D_{lo}}\right)^2\right]D_{lb}}$$

D_b = Nominal diameter of the cask lid attachment bolt

D_{lb} = Cask lid diameter at the bolt circle

D_{lo} = Cask lid diameter at the outer edge

D_{li} = Cask lid diameter at the inner edge

E_b = Young's modulus of the cask lid attachment bolt material

E_l = Young's modulus of the cask lid material

F_f = Fixed-edge force of the cask lid at the bolt circle that is caused by the applied load (per unit length of the bolt circle)

L_b = Bolt length between the top and bottom surfaces of the cask lid at the bolt circle

M_f = Fixed-edge moment of the cask lid at the bolt circle that is caused by the applied load (per unit length of the bolt circle)

N_b = Number of cask lid attachment bolts

N_{ul} = Poisson's ratio of the cask lid material

t_l = Thickness of the cask lid

4.5.2.3.2.9 Total Bolt Loads and Stresses

To accurately combine total bolt forces, the method of *NUREG/CR-6007* **[4.6]**, *Table 4.9*, is applied. The total tensile bolt force is obtained by adding the total non-prying tensile bolt forces and the total prying tensile bolt forces, as documented in *NUREG/CR-6007*, *Table 4.9*, *III.I*.

The total shear force, as documented in *NUREG/CR-6007*, *Table 4.9*, is evaluated as the absolute sum of the shear forces generated by all applied loads.

The combined bending moment is obtained using the combined fixed edge moment and the formula in *NUREG/CR-6007*, *Table 2.2*.

As stated in *NUREG/CR-6007*, *Table 4.9*, the torsional bolt moment is calculated using the torsional bolt moments from preload.

Bolt stresses are calculated from *NUREG/CR-6007*, *Table 5.1*. From the nominal bolt diameter, D_b, a new bolt diameter, D, is calculated for stress calculation.

For the tensile stress calculation:

$$D = D_{ba}$$

where:

D_{ba} = Alternate Bolt Diameter for Stress Calculation = $D_b - 0.9743p$

D_b = Nominal bolt diameter

p = Bolt thread pitch, equals 1 / n

n = Number of bolt threads per unit length

For the shear stress calculation:

$D = D_{ba}$ (if maximum shear occurs in the thread)

$D = D_b$ (if maximum shear occurs in the shank)

For the bending stress calculation:

$D = D_{ba}$ (if maximum bending occurs in the thread)

$D = D_b$ (if maximum bending occurs in the shank)

The average bolt direct stress (S_{ba}) that is caused by the tensile bolt force is calculated as follows:

$$S_{ba} = 1.2732\ F_a / D^2$$

The average bolt shear stress (S_{bs}) that is caused by shear bolt stress is as follows:

$$S_{bs} = 1.2732\ F_s / D^2$$

The maximum bending stress (S_{bb}) that is caused by the bending bolt moment is as follows:

$$S_{bb} = 10.186\ M_{bb} / D^3$$

And, the maximum shear stress (S_{bt}) that is caused by the torsional bolt moment is as follows:

$$S_{bt} = 5.093\ M_t / D^3$$

Where F_a, F_s, M_{bb}, and M_t all represent total values of the tensile bolt force, shear bolt force, bending bolt moment, and torsional bolt moment, respectively.

The resulting stress intensity (S_{bi}) that is caused by tension + shear + bending + torsion is as follows:

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

4.5.2.3.3 Model AOS-025A Cask Lid Attachment Bolt Load and Stress Analysis

4.5.2.3.3.1 Cask Lid Attachment Bolt Input Parameters

Table 4-10 lists the Model AOS-025A cask lid attachment bolt input parameters. The Model AOS-025A minimum and maximum preload torque limits are 29 ft-lb and 35 ft-lb, respectively. The preload torque value used in the stress calculations is 35 ft-lb because the calculated bolt stresses are highest using the maximum preload torque.

Table 4-10. Model AOS-025A Cask Lid Attachment Bolt Input Parameters

Parameter	Variable	Input Value		Units
Temperature	T	(38) 100	(-40) -40	(°C) °F
Number of Bolts	N_b	8	8	–
Lid Diameter at Bolt Circle	D_{lb}	3.9	3.9	in.
Lid Diameter at Gasket	D_{lg}	3.07	3.07	in.
Nominal Bolt Diameter	D_b	0.375	0.375	in.
Threads per Inch	n	16	16	–
Lid Diameter at Inner Edge	D_{li}	2.61	2.61	in.
Lid Diameter at Outer Edge	D_{lo}	4.65	4.65	in.
Thickness of Cask Lid	t_l	0.37	0.37	in.
Thickness of Cask Lid Flange	t_{lf}	0.48	0.48	in.
Thickness of Cask Wall	t_c	1.02	1.02	in.
Bolt Length between the Top and Bottom Surface of Cask Lid	L_b	0.15	0.15	in.
Young's Modulus for Cask Lid	E_l	27,300,000	28,300,000	psi
Young's Modulus for Cask	E_c	27,300,000	28,300,000	psi
Young's Modulus for Bolt	E_b	28,000,000	29,200,000	psi
Poisson's Ratio for Cask Lid	N_{ul}	0.3	0.3	–
Poisson's Ratio for Cask	N_{uc}	0.3	0.3	–
Lid Thermal Expansion Coefficient	a_l	0.0000091	0.0000086	1/°F
Bolt Thermal Expansion Coefficient	a_b	0.0000073	0.0000070	1/°F
Cask Wall Thermal Expansion Coefficient	a_c	0.0000091	0.0000086	1/°F
Weight of Cask Contents	W_c	14	14	lbs.
Weight of Cask Lid	W_l	2	2	lbs.
Bolt Torque (in-lb)	Q	420	420	in-lb
Bolt Torque (ft-lb)		35	35	ft-lb
Nut Factor for Preload Torque	K	0.15	0.15	–

Table 4-10. Model AOS-025A Cask Lid Attachment Bolt Input Parameters (Continued)

Parameter	Variable	Input Value		Units
Gasket Seating Width	b	1	1	in.
Gasket Seating Stress	y	3,000	3,000	psi
Gasket Factor	m	9.53	9.53	–
Minimum Yield Strength	S_y	142,000	150,000	psi
Minimum Ultimate Strength	S_u	176,000	185,000	psi
Basic Allowable Stress Limit	S_m	95,000	100,000	psi
Initial Temperature	T_i	70	70	°F
Temperature of Cask Lid at Bolts	T_l	255	36	°F
Temperature of Bolts	T_b	255	36	°F
Temperature of Cask Wall	T_c	255	36	°F
Temperature of Cask Lid Inner Surface	T_{li}	255	36	°F
Temperature of Cask Lid Outer Surface	T_{lo}	255	36	°F
Transport Package Internal Pressure	P_i	30	30	psia
Atmospheric Pressure	P_a	15	15	psia

4.5.2.3.3.2 Model AOS-025A Cask Lid Attachment Bolt NCT Results

Table 4-11 summarizes the forces and moments from individual loads. Table 4-12 documents the NCT load combinations.

Table 4-11. Model AOS-025A Cask Lid Attachment Bolt NCT Loads

Summary Bolt Loads from Individual Loads	Variable	Units	Temperature	
			(38°C) 100°F	(-40°C) -40°F
Preload				
Non-Prying Tensile Bolt Force Due to Preload	F_a	lbs.	7,467	7,467
Torsional Bolt Moment	M_t	lb-in	210	210
Gasket				
Non-Prying Tensile Bolt Force for Gasket Seating	F_a	lbs.	3,617	3,617
Non-Prying Tensile Bolt Force for Gasket Operation	F_a	lbs.	345	345
Torsional Bolt Moment	M_t	lb-in	102	102
Pressure				
Pressure inside the Cask Lid	P_{li}	psi	30.0	30.0
Pressure outside the Cask Lid	P_{lo}	psi	15.0	15.0
Pressure inside the Cask Wall	P_{ci}	psi	30.0	30.0
Pressure outside the Cask Wall	P_{co}	psi	15.0	15.0
Non-Prying Tensile Bolt Force	F_a	lbs.	13.9	13.9
Shear Bolt Force per Bolt	F_s	lbs.	23.2	23.2
Fixed-Edge Cask Lid Force	F_f	lb/in	14.6	14.6
Fixed-Edge Cask Lid Moment	M_f	(lb-in)/in	7.1	7.1
Temperature				
Temperature Change of Cask Lid at Bolts	T_l	°F	185.0	-34.0
Temperature Change of Bolts	T_b	°F	185.0	-34.0
Temperature Change of Cask Wall	T_c	°F	185.0	-34.0
Temperature Change of Inner Surface of Cask Lid	T_{li}	°F	185.0	-34.0
Temperature Change of Outer Surface of Cask Lid	T_{lo}	°F	185.0	-34.0
Non-Prying Tensile Bolt Force	F_a	lbs.	1,030	-175
Shear Bolt Force per Bolt	F_s	lbs.	0.00	0.00
Fixed-Edge Cask Lid Force	F_f	lb/in	0.00	0.00
Fixed-Edge Cask Lid Moment	M_f	(lb-in)/in	0.00	0.00

Table 4-11. Model AOS-025A Cask Lid Attachment Bolt NCT Loads (Continued)

Summary Bolt Loads from Individual Loads	Variable	Units	Temperature	
			(38°C) 100°F	(-40°C) -40°F
Impact				
Maximum Impact Acceleration	a_i	g	–	–
Impact Angle	x_i	°	–	–
Dynamic Load Factor	DLF	–	–	–
Non-Prying Axial Load Due to Impact	F_a	lbs.	–	–
Shear Load Due to Impact	F_s	lbs.	–	–
Fixed-Edge Load Due to Impact	F_f	lb/in	–	–
Fixed-Edge Moment Due to Impact	M_f	(lb-in)/in	–	–
Vibration				
Vibration Transmissibility of Acceleration (cask support to cask lid)	VTR	–	1.00	1.00
Maximum Axial Vibration Acceleration (g) at the Cask Support	ava	g	10.00	10.00
Maximum Transverse Vibration Acceleration (g) at the Cask Support	avt	g	5.00	5.00
Axial Load Due to Vibration	F_a	lbs.	2.50	2.50
Shear Load Due to Vibration	F_s	lbs.	1.25	1.25
Fixed-Edge Force	F_f	lb/in	1.63	1.63
Fixed-Edge Moment Due to Vibration	M_f	(lb-in)/in	0.80	0.80
Prying Action				
Bolt Length between Top and Bottom Surface of Cask Lid	L_b	in.	0.15	0.15
Constant1	C1	–	1.0	1.0
Constant2 (for outward loads)	C2	–	0.0802	0.0798
Bolt Preload per Unit Length of the Bolt Circle	P	lb/in	5,548	4,761
Non-Prying Tensile Bolt Force	B	lb/in	5,548	4,761
Combined Axial Load on Bolt Due to Prying	F_{ap-c}	lbs.	-7,813	-6,699

Table 4-12. Model AOS-025A Cask Lid Attachment Bolt NCT Load Combinations

Loads/Stresses	Variable	Units	Temperature	
			(38°C) 100°F	(-40°C) -40°F
Temperature and Preload Non-Prying Axial Load	F_{a-pt}	lbs.	8,496	7,291
Axial Load Less Temperature and Preload	F_{a-al}	lbs.	361	361
Combined Non-Prying Tensile Bolt Force (Greater of F_{a-pt} and F_{a-al})	F_{a-c}	lbs.	8,496	7,291
Prying Axial Load of Bolt	F_{ap-c}	lbs.	-7,813	-6,699
Total Tensile Bolt Load (F_{a-c} + F_{ap-c})	F_a	lbs.	684	592
Total Shear Bolt Force	F_s	lbs.	24.5	24.5
Total Bending Bolt Moment	M_{bb-c}	lb-in	6.8	6.8
Total Torsional Bolt Moment	M_t	lb-in	210.0	210.0
Diameter Used for Stress Calculations	D_{ba}	in.	0.314	0.314
Average Bolt Axial Stress	S_{ba}	psi	8,825	7,638
Average Bolt Shear Stress	S_{bs}	psi	316	316
Maximum Bending Stress	S_{bb}	psi	2,221	2,227
Maximum Shear Stress Due to Torsional Bolt Moment	S_{bt}	psi	34,511	34,511
Maximum Stress Intensity	S_{bi}	psi	70,525	70,349
Allowable Tensile Stress	S_m	psi	95,000	100,000
Allowable Shear Stress	$0.6\ S_m$	psi	57,000	60,000
Allowable Stress Intensity	$1.35\ S_m$	psi	128,250	135,000
Axial Stress Ratio	R_t	–	0.09	0.08
Shear Stress Ratio	R_s	–	0.01	0.01
Combined Stress Ratio	$R_t^2 + R_s^2$	–	0.01	0.01
Stress Intensity Ratio	R_i	–	0.55	0.52

4.5.2.3.3.3 Model AOS-025A Cask Lid Attachment Bolt HAC Results

Table 4-13 documents the HAC forces from individual loads. Table 4-14 summarizes the corresponding load combinations.

Table 4-13. Model AOS-025A Cask Lid Attachment Bolt HAC Loads

Summary Bolt Loads from Individual Loads	Variable	Units	Drop Type, by Temperature (T)					
			Head-On		Side		Cg/Corner	
			(38°C) 100°F	(-40°C) -40°F	(38°C) 100°F	(-40°C) -40°F	(38°C) 100°F	(-40°C) -40°F
Preload								
Non-Prying Tensile Bolt Force Due to Preload	F_a	lbs.	7,467	7,467	7,467	7,467	7,467	7,467
Torsional Bolt Moment	M_t	lb-in	210	210	210	210	210	210
Gasket								
Non-Prying Tensile Bolt Force for Gasket Seating	F_a	lbs.	3,617	3,617	3,617	3,617	3,617	3,617
Non-Prying Tensile Bolt Force for Gasket Operation	F_a	lbs.	345	345	345	345	345	345
Torsional Bolt Moment	M_t	lb-in	102	102	102	102	102	102
Pressure								
Pressure inside the Cask Lid	P_{li}	psi	30.0	30.0	30.0	30.0	30.0	30.0
Pressure outside the Cask Lid	P_{lo}	psi	15.0	15.0	15.0	15.0	15.0	15.0
Pressure inside the Cask Wall	P_{ci}	psi	30.0	30.0	30.0	30.0	30.0	30.0
Pressure outside the Cask Wall	P_{co}	psi	15.0	15.0	15.0	15.0	15.0	15.0
Non-Prying Tensile Bolt Force	F_a	lbs.	13.9	13.9	13.9	13.9	13.9	13.9
Shear Bolt Force per Bolt	F_s	lbs.	23.2	23.2	23.2	23.2	23.2	23.2
Fixed-Edge Cask Lid Force	F_f	lb/in	14.6	14.6	14.6	14.6	14.6	14.6
Fixed-Edge Cask Lid Moment	M_f	(lb-in)/in	7.1	7.1	7.1	7.1	7.1	7.1

Table 4-13. Model AOS-025A Cask Lid Attachment Bolt HAC Loads (Continued)

Summary Bolt Loads from Individual Loads	Variable	Units	Drop Type, by Temperature (T)					
			Head-On		Side		Cg/Corner	
			(38°C) 100°F	(-40°C) -40°F	(38°C) 100°F	(-40°C) -40°F	(38°C) 100°F	(-40°C) -40°F
Temperature								
Temperature Change of Cask Lid at Bolts	T_l	°F	185.0	-34.0	185.0	-34.0	185.0	-34.0
Temperature Change of Bolts	T_b	°F	185.0	-34.0	185.0	-34.0	185.0	-34.0
Temperature Change of Cask Wall	T_c	°F	185.0	-34.0	185.0	-34.0	185.0	-34.0
Temperature Change of Inner Surface of Cask Lid	T_{li}	°F	185.0	-34.0	185.0	-34.0	185.0	-34.0
Temperature Change of Outer Surface of Cask Lid	T_{lo}	°F	185.0	-34.0	185.0	-34.0	185.0	-34.0
Non-Prying Tensile Bolt Force	F_a	lbs.	1,030	-175	1,030	-175	1,030	-175
Shear Bolt Force per Bolt	F_s	lbs.	0.00	0.00	0.00	0.00	0.00	0.00
Fixed-Edge Cask Lid Force	F_f	lb/in	0.00	0.00	0.00	0.00	0.00	0.00
Fixed-Edge Cask Lid Moment	M_f	(lb-in)/in	0.00	0.00	0.00	0.00	0.00	0.00
Impact								
Maximum Impact Acceleration	a_i	g	833.0	1,173.0	1,286.0	1,798.0	1,019.0	1,419.0
Impact Angle	x_i	°	90.0	90.0	0.0	0.0	52.0	52.0
Dynamic Load Factor	DLF	–	1.15	1.15	1.15	1.15	1.15	1.15
Non-Prying Axial Load Due to Impact	F_a	lbs.	2,567.3	3,615.2	0.0	0.0	2,474.8	3,446.3
Shear Load Due to Impact	F_s	lbs.	0.0	0.0	321.5	449.5	156.8	218.4
Fixed-Edge Load Due to Impact	F_f	lb/in	1,676.3	2,360.5	0.0	0.0	1,615.9	2,250.2
Fixed-Edge Moment Due to Impact	M_f	(lb-in)/in	817.2	1,150.7	0.0	0.0	787.8	1,097.0

Table 4-13. Model AOS-025A Cask Lid Attachment Bolt HAC Loads (Continued)

Summary Bolt Loads from Individual Loads	Variable	Units	Drop Type, by Temperature (T)					
			Head-On		Side		Cg/Corner	
			(38°C) 100°F	(-40°C) -40°F	(38°C) 100°F	(-40°C) -40°F	(38°C) 100°F	(-40°C) -40°F
Vibration								
Vibration Transmissibility of Acceleration (cask support to cask lid)	VTR	–	–	–	–	–	–	–
Maximum Axial Vibration Acceleration (g) at the Cask Support	ava	g	–	–	–	–	–	–
Maximum Transverse Vibration Acceleration (g) at the Cask Support	avt	g	–	–	–	–	–	–
Axial Load Due to Vibration	F_a	lbs.	–	–	–	–	–	–
Shear Load Due to Vibration	F_s	lbs.	–	–	–	–	–	–
Fixed-Edge Force	F_f	lb/in	–	–	–	–	–	–
Fixed-Edge Moment Due to Vibration	M_f	(lb-in)/in	–	–	–	–	–	–
Prying Action								
Bolt Length	L_b	in	0.15	0.15	0.15	0.15	0.15	0.15
Constant1	C1	–	1.0	1.0	1.0	1.0	1.0	1.0
Constant2 (for outward loads)	C2	–	0.0802	0.0798	0.0802	0.0798	0.0802	0.0798
Bolt Preload per Unit Length of Bolt Circle	P	lb/in	5,548	4,761	5,548	4,761	5,548	4,761
Non-Prying Tensile Bolt Force	B	lb/in	5,548	4,761	5,548	4,761	5,548	4,761
Axial Load of Bolt Due to Prying	F_{ap-c}	lbs.	-2,352	996	-7818	-6,705	-2,549	636

Table 4-14. Model AOS-025A Cask Lid Attachment Bolt HAC Load Combinations

Loads/Stresses	Variable	Units	Drop Type, by Temperature (T)					
			Head-On		Side		Cg/Corner	
			(38°C) 100°F	(-40°C) -40°F	(38°C) 100°F	(-40°C) -40°F	(38°C) 100°F	(-40°C) -40°F
Temperature and Preload Non-Prying Axial Load	F_{a-pt}	lbs.	8,496	7,291	8,496	7,291	8,496	7,291
Axial Load Less Temperature and Preload	F_{a-al}	lbs.	2,926	3,974	359	359	2,833	3,805
Combined Non-Prying Tensile Bolt Force (Greater of F_{a-pt} and F_{a-al})	F_{a-c}	lbs.	8,496	7,291	8,496	7,291	8,496	7,291
Axial Load of Bolt Due to Prying Combined	F_{ap-c}	lbs.	-2,352	996	-7,818	-6,705	-2,549	636
Total Tensile Bolt Load (F_{a-c} + F_{ap-c})	F_a	lbs.	6,145	8,287	679	587	5,948	7,927
Total Shear Bolt Force	F_s	lbs.	23.2	23.2	344.7	472.7	180.1	241.6
Total Bending Bolt Moment	M_{bb-c}	lb-in	703	990	6.1	6.1	678	944
Total Torsional Bolt Moment	M_t	lb-in	210	210	210	210	210	210
Diameter Used for Stress Calculations	D_{ba}	in.	0.314	0.314	0.314	0.314	0.314	0.314
Average Bolt Direct Stress	S_{ba}	psi	79,297	106,940	8,756	7,569	76,756	102,296
Average Bolt Shear Stress	S_{bs}	psi	300	300	4,448	6,100	2,324	3,118
Maximum Bending Stress	S_{bb}	psi	231,020	325,359	1,998	2,003	222,767	310,249
Total Tensile Stress	S_{bt}	psi	34,511	34,511	34,511	34,511	34,511	34,511
Allowable Direct Stress	Minimum of 0.7 S_u and S_y	psi	123,200	129,500	123,200	129,500	123,200	129,500
Allowable Shear Stress	Minimum of 0.42 S_u and 0.6 S_y	psi	73,920	77,700	73,920	77,700	73,920	77,700
Average Direct Stress Ratio	R_t	–	0.64	0.83	0.07	0.06	0.62	0.79
Shear Stress Ratio	R_s	–	0.00	0.00	0.06	0.08	0.03	0.04
Combined Axial and Shear Stress Ratio	$R_t^2 + R_s^2$	–	0.41	0.68	0.01	0.01	0.39	0.63

4.5.2.3.4 Model AOS-050A Cask Lid Attachment Bolt Load and Stress Analysis

4.5.2.3.4.1 Cask Lid Attachment Bolt Input Parameters

Table 4-15 lists the Model AOS-050A cask lid attachment bolt input parameters. The Model AOS-050A minimum and maximum preload torque limits are 62.5 ft-lb and 68 ft-lb, respectively. The preload torque value used in the stress calculations is 68 ft-lb because the calculated bolt stresses are highest using the maximum preload torque.

Table 4-15. Model AOS-050A Cask Lid Attachment Bolt Input Parameters

Parameter	Variable	Input Value		Units
Temperature	T	(38) 100	(-40) -40	(°C) °F
Number of Bolts	N_b	10	10	–
Lid Diameter at Bolt Circle	D_{lb}	7.414	7.414	in.
Lid Diameter at Gasket	D_{lg}	6.09	6.09	in.
Nominal Bolt Diameter	D_b	0.5	0.5	in.
Threads per Inch	n	13	13	–
Lid Diameter at Inner Edge	D_{li}	5.51	5.51	in.
Lid Diameter at Outer Edge	D_{lo}	8.9	8.9	in.
Thickness of Cask Lid	t_l	0.75	0.75	in.
Thickness of Cask Lid Flange	t_{lf}	0.97	0.97	in.
Thickness of Cask Wall	t_c	1.695	1.695	in.
Bolt Length between the Top and Bottom Surface of Cask Lid	L_b	0.41	0.41	in.
Young's Modulus for Cask Lid	E_l	27,000,000	28,300,000	psi
Young's Modulus for Cask	E_c	27,000,000	28,300,000	psi
Young's Modulus for Bolt	E_b	27,800,000	28,900,000	psi
Poisson's Ratio for Cask Lid	N_{ul}	0.3	0.3	–
Poisson's Ratio for Cask	N_{uc}	0.3	0.3	–
Lid Thermal Expansion Coefficient	a_l	0.0000092	0.0000086	1/°F
Bolt Thermal Expansion Coefficient	a_b	0.0000073	0.0000070	1/°F
Cask Wall Thermal Expansion Coefficient	a_c	0.0000092	0.0000086	1/°F
Weight of Cask Contents	W_c	95	95	lbs.
Weight of Cask Lid	W_l	14	14	lbs,
Bolt Torque (in-lb)	Q	816	816	in-lb
Bolt Torque (ft-lb)		68	68	ft-lb
Nut Factor for Preload Torque	K	0.15	0.15	–

Table 4-15. Model AOS-050A Cask Lid Attachment Bolt Input Parameters (Continued)

Parameter	Variable	Input Value		Units
Gasket Seating Width	b	1	1	in.
Gasket Seating Stress	y	3,000	3,000	psi
Gasket Factor	m	3.18	3.18	–
Minimum Yield Strength	S_y	141,000	150,000	psi
Minimum Ultimate Strength	S_u	174,000	185,000	psi
Basic Allowable Stress Limit	S_m	94,000	100,000	psi
Initial Temperature	T_i	70	70	°F
Temperature of Cask Lid at Bolts	T_l	286	85	°F
Temperature of Bolts	T_b	286	85	°F
Temperature of Cask Wall	T_c	286	85	°F
Temperature of Cask Lid Inner Surface	T_{li}	286	85	°F
Temperature of Cask Lid Outer Surface	T_{lo}	286	85	°F
Transport Package Internal Pressure	P_i	60	60	psia
Atmospheric Pressure	P_a	15	15	psia

4.5.2.3.4.2 Model AOS-050A Cask Lid Attachment Bolt NCT Results

Table 4-16 summarizes the forces and moments from individual loads. Table 4-17 documents the NCT load combinations.

Table 4-16. Model AOS-050A Cask Lid Attachment Bolt NCT Loads

Summary Bolt Loads from Individual Loads	Variable	Units	Temperature	
			(38°C) 100°F	(-40°C) -40°F
Preload				
Non-Prying Tensile Bolt Force Due to Preload	F_a	lbs.	10,000	10,000
Torsional Bolt Moment	M_t	lb-in	375	375
Gasket				
Non-Prying Tensile Bolt Force for Gasket Seating	F_a	lbs.	5,740	5,740
Non-Prying Tensile Bolt Force for Gasket Operation	F_a	lbs.	548	548
Torsional Bolt Moment	M_t	lb-in	215	215
Pressure				
Pressure inside the Cask Lid	P_{li}	psi	60.0	60.0
Pressure outside the Cask Lid	P_{lo}	psi	15.0	15.0
Pressure inside the Cask Wall	P_{ci}	psi	60.0	60.0
Pressure outside the Cask Wall	P_{co}	psi	15.0	15.0
Non-Prying Tensile Bolt Force	F_a	lbs.	131.1	131.1
Shear Bolt Force per Bolt	F_s	lbs.	245.6	245.6
Fixed-Edge Cask Lid Force	F_f	lb/in	83.4	83.4
Fixed-Edge Cask Lid Moment	M_f	(lb-in)/in	77.3	77.3
Temperature				
Temperature Change of Cask Lid at Bolts	T_l	°F	216.0	15.0
Temperature Change of Bolts	T_b	°F	216.0	15.0
Temperature Change of Cask Wall	T_c	°F	216.0	15.0
Temperature Change of Inner Surface of Cask Lid	T_{li}	°F	216.0	15.0
Temperature Change of Outer Surface of Cask Lid	T_{lo}	°F	216.0	15.0
Non-Prying Tensile Bolt Force	F_a	lbs.	2240	136
Shear Bolt Force per Bolt	F_s	lbs.	0.00	0.00
Fixed-Edge Cask Lid Force	F_f	lb/in	0.00	0.00
Fixed-Edge Cask Lid Moment	M_f	(lb-in)/in	0.00	0.00

Table 4-16. Model AOS-050A Cask Lid Attachment Bolt NCT Loads (Continued)

Summary Bolt Loads from Individual Loads	Variable	Units	Temperature	
			(38°C) 100°F	(-40°C) -40°F
Impact				
Maximum Impact Acceleration	a_i	g	–	–
Impact Angle	x_i	°	–	–
Dynamic Load Factor	DLF	–	–	–
Non-Prying Axial Load Due to Impact	F_a	lbs.	–	–
Shear Load Due to Impact	F_s	lbs.	–	–
Fixed-Edge Load Due to Impact	F_f	lb/in	–	–
Fixed-Edge Moment Due to Impact	M_f	(lb-in)/in	–	–
Vibration				
Vibration Transmissibility of Acceleration (cask support to cask lid)	VTR	–	1.00	1.00
Maximum Axial Vibration Acceleration (g) at the Cask Support	ava	g	10.00	10.00
Maximum Transverse Vibration Acceleration (g) at the Cask Support	avt	g	5.00	5.00
Axial Load Due to Vibration	F_a	lbs.	14.00	14.00
Shear Load Due to Vibration	F_s	lbs.	7.00	7.00
Fixed-Edge Force	F_f	lb/in	6.01	6.01
Fixed-Edge Moment Due to Vibration	M_f	(lb-in)/in	5.57	5.57
Prying Action				
Bolt Length between Top and Bottom Surface of Cask Lid	L_b	in.	0.41	0.41
Constant1	C1	–	1.0	1.0
Constant2 (for outward loads)	C2	–	0.1962	0.1978
Bolt Preload per Unit Length of the Bolt Circle	P	lb/in	5,255	4,352
Non-Prying Tensile Bolt Force	B	lb/in	5,255	4,352
Combined Axial Load on Bolt Due to Prying	$F_{ap\text{-}c}$	lbs.	-9,841	-8,072

Table 4-17. Model AOS-050A Cask Lid Attachment Bolt NCT Load Combinations

Loads/Stresses	Variable	Units	Temperature	
			(38°C) 100°F	(-40°C) -40°F
Temperature and Preload Non-Prying Axial Load	F_{a-pt}	lbs.	13,160	11,056
Axial Load Less Temperature and Preload	F_{a-al}	lbs.	693	693
Combined Non-Prying Tensile Bolt Force (Greater of F_{a-pt} and F_{a-al})	F_{a-c}	lbs.	13,160	11,056
Prying Axial Load of Bolt	F_{ap-c}	lbs.	-10,610	-8,840
Total Tensile Bolt Load (F_{a-c} + F_{ap-c})	F_a	lbs.	2,550	2,217
Total Shear Bolt Force	F_s	lbs.	253	253
Total Bending Bolt Moment	M_{bb-c}	lb-in	35	34
Total Torsional Bolt Moment	M_t	lb-in	410	410
Diameter Used for Stress Calculations	D_{ba}	in.	0.425	0.425
Average Bolt Axial Stress	S_{ba}	psi	17,969	15,620
Average Bolt Shear Stress	S_{bs}	psi	1,780	1,780
Maximum Bending Stress	S_{bb}	psi	4,582	4,551
Maximum Shear Stress Due to Torsional Bolt Moment	S_{bt}	psi	27,158	27,158
Maximum Stress Intensity	S_{bi}	psi	62,114	61,290
Allowable Tensile Stress	S_m	psi	94,000	100,000
Allowable Shear Stress	$0.6\ S_m$	psi	56,400	60,000
Allowable Stress Intensity	$1.35\ S_m$	psi	126,900	135,000
Axial Stress Ratio	R_t	–	0.19	0.16
Shear Stress Ratio	R_s	–	0.03	0.03
Combined Stress Ratio	$R_t^2 + R_s^2$	–	0.04	0.03
Stress Intensity Ratio	R_i	–	0.49	0.45

4.5.2.3.4.3 Model AOS-050A Cask Lid Attachment Bolt HAC Results

Table 4-18 documents the HAC forces from individual loads. Table 4-19 summarizes the corresponding load combinations.

Table 4-18. Model AOS-050A Cask Lid Attachment Bolt HAC Loads

Summary Bolt Loads from Individual Loads	Variable	Units	Drop Type, by Temperature (T)					
			Head-On		Side		Cg/Corner	
			(38°C) 100°F	(-40°C) -40°F	(38°C) 100°F	(-40°C) -40°F	(38°C) 100°F	(-40°C) -40°F
Preload								
Non-Prying Tensile Bolt Force Due to Preload	F_a	lbs.	10,000	10,000	10,000	10,000	10,000	10,000
Torsional Bolt Moment	M_t	lb-in	375	375	375	375	375	375
Gasket								
Non-Prying Tensile Bolt Force for Gasket Seating	F_a	lbs.	5,740	5,740	5,740	5,740	5,740	5,740
Non-Prying Tensile Bolt Force for Gasket Operation	F_a	lbs.	548	548	548	548	548	548
Torsional Bolt Moment	M_t	lb-in	215	215	215	215	215	215
Pressure								
Pressure inside the Cask Lid	P_{li}	psi	60.0	60.0	60.0	60.0	60.0	60.0
Pressure outside the Cask Lid	P_{lo}	psi	15.0	15.0	15.0	15.0	15.0	15.0
Pressure inside the Cask Wall	P_{ci}	psi	60.0	60.0	60.0	60.0	60.0	60.0
Pressure outside the Cask Wall	P_{co}	psi	15.0	15.0	15.0	15.0	15.0	15.0
Non-Prying Tensile Bolt Force	F_a	lbs.	131.1	131.1	131.1	131.1	131.1	131.1
Shear Bolt Force per Bolt	F_s	lbs.	245.6	245.6	245.6	245.6	245.6	245.6
Fixed-Edge Cask Lid Force	F_f	lb/in	83.4	83.4	83.4	83.4	83.4	83.4
Fixed-Edge Cask Lid Moment	M_f	(lb-in)/in	77.3	77.3	77.3	77.3	77.3	77.3

Table 4-18. Model AOS-050A Cask Lid Attachment Bolt HAC Loads (Continued)

Summary Bolt Loads from Individual Loads	Variable	Units	Drop Type, by Temperature (T)					
			Head-On		Side		Cg/Corner	
			(38°C) 100°F	(-40°C) -40°F	(38°C) 100°F	(-40°C) -40°F	(38°C) 100°F	(-40°C) -40°F
Temperature								
Temperature Change of Cask Lid at Bolts	T_l	°F	216.0	15.0	216.0	15.0	216.0	15.0
Temperature Change of Bolts	T_b	°F	216.0	15.0	216.0	15.0	216.0	15.0
Temperature Change of Cask Wall	T_c	°F	216.0	15.0	216.0	15.0	216.0	15.0
Temperature Change of Inner Surface of Cask Lid	T_{li}	°F	216.0	15.0	216.0	15.0	216.0	15.0
Temperature Change of Outer Surface of Cask Lid	T_{lo}	°F	216.0	15.0	216.0	15.0	216.0	15.0
Non-Prying Tensile Bolt Force	F_a	lbs.	2,240	136	2,240	136	2,240	136
Shear Bolt Force per Bolt	F_s	lbs.	0.00	0.00	0.00	0.00	0.00	0.00
Fixed-Edge Cask Lid Force	F_f	lb/in	0.00	0.00	0.00	0.00	0.00	0.00
Fixed-Edge Cask Lid Moment	M_f	(lb-in)/in	0.00	0.00	0.00	0.00	0.00	0.00
Impact								
Maximum Impact Acceleration	a_i	g	314.0	439.0	335.0	469.0	224.0	314.0
Impact Angle	x_i	°	90.0	90.0	0.0	0.0	52.0	52.0
Dynamic Load Factor	DLF	–	1.15	1.15	1.15	1.15	1.15	1.15
Non-Prying Axial Load Due to Impact	F_a	lbs.	5,274	7,374	0	0	2,965	4,156
Shear Load Due to Impact	F_s	lbs.	0.0	0.0	469	657	193	271
Fixed-Edge Load Due to Impact	F_f	lb/in	2,264	3,166	0.0	0.0	1,273	1,784
Fixed-Edge Moment Due to Impact	M_f	(lb-in)/in	2,099	2,934	0.0	0.0	1,180	1,654

Table 4-18. Model AOS-050A Cask Lid Attachment Bolt HAC Loads (Continued)

Summary Bolt Loads from Individual Loads	Variable	Units	Drop Type, by Temperature (T)					
			Head-On		Side		Cg/Corner	
			(38°C) 100°F	(-40°C) -40°F	(38°C) 100°F	(-40°C) -40°F	(38°C) 100°F	(-40°C) -40°F
Vibration								
Vibration Transmissibility of Acceleration (cask support to cask lid)	VTR	–	–	–	–	–	–	–
Maximum Axial Vibration Acceleration (g) at the Cask Support	ava	g	–	–	–	–	–	–
Maximum Transverse Vibration Acceleration (g) at the Cask Support	avt	g	–	–	–	–	–	–
Axial Load Due to Vibration	F_a	lbs.	–	–	–	–	–	–
Shear Load Due to Vibration	F_s	lbs.	–	–	–	–	–	–
Fixed-Edge Force	F_f	lb/in	–	–	–	–	–	–
Fixed-Edge Moment Due to Vibration	M_f	(lb-in)/in	–	–	–	–	–	–
Prying Action								
Bolt Length	L_b	in	0.41	0.41	0.41	0.41	0.41	0.41
Constant1	C1	–	1.0	1.0	1.0	1.0	1.0	1.0
Constant2 (for outward loads)	C2	–	0.1962	0.1978	0.1962	0.1978	0.1962	0.1978
Bolt Preload per Unit Length of Bolt Circle	P	lb/in	5,255	4,352	5,255	4,352	5,255	4,352
Non-Prying Tensile Bolt Force	B	lb/in	5,255	4,352	5,255	4,352	5,255	4,352
Axial Load of Bolt Due to Prying	F_{ap-c}	lbs.	41	5,737	-9,868	-8,098	-4,297	-300

Table 4-19. Model AOS-050A Cask Lid Attachment Bolt HAC Load Combinations

Loads/Stresses	Variable	Units	Drop Type, by Temperature (T)					
			Head-On		Side		Cg/Corner	
			(38°C) 100°F	(-40°C) -40°F	(38°C) 100°F	(-40°C) -40°F	(38°C) 100°F	(-40°C) -40°F
Temperature and Preload Non-Prying Axial Load	$F_{a\text{–}pt}$	lbs.	13,160	11,056	13,160	11,056	13,160	11,056
Axial Load Less Temperature and Preload	$F_{a\text{–}al}$	lbs.	5,953	8,052	679	679	3,644	4,835
Combined Non-Prying Tensile Bolt Force (Greater of $F_{a\text{–}pt}$ and $F_{a\text{–}al}$)	$F_{a\text{–}c}$	lbs.	13,160	11,056	13,160	11,056	13,160	11,056
Axial Load of Bolt Due to Prying Combined	$F_{ap\text{–}c}$	lbs.	-728	4,969	-10,637	-8,866	-5,067	-1,068
Total Tensile Bolt Load ($F_{a\text{–}c}$ + $F_{ap\text{–}c}$)	F_a	lbs.	12,432	16,025	2,524	2,190	8,094	9,988
Total Shear Bolt Force	F_s	lbs.	246	246	715	902	439	516
Total Bending Bolt Moment	$M_{bb\text{–}c}$	lb-in	907	1,247	32	32	524	717
Total Torsional Bolt Moment	M_t	lb-in	410	410	410	410	410	410
Diameter Used for Stress Calculations	D_{ba}	in.	0.425	0.425	0.425	0.425	0.425	0.425
Average Bolt Direct Stress	S_{ba}	psi	87,611	112,930	17,783	15,435	57,037	70,386
Average Bolt Shear Stress	S_{bs}	psi	1,731	1,731	5,036	6,358	3,091	3,638
Maximum Bending Stress	S_{bb}	psi	120,313	165,386	4,274	4,245	69,505	95,070
Total Tensile Stress	S_{bt}	psi	27,158	27,158	27,158	27,158	27,158	27,158
Allowable Direct Stress	Minimum of 0.7 S_u and S_y	psi	121,800	129,500	121,800	129,500	121,800	129,500
Allowable Shear Stress	Minimum of 0.42 S_u and 0.6 S_y	psi	73,080	77,700	73,080	77,700	73,080	77,700
Average Direct Stress Ratio	R_t	–	0.72	0.87	0.15	0.12	0.47	0.54
Shear Stress Ratio	R_s	–	0.02	0.02	0.07	0.08	0.04	0.05
Combined Axial and Shear Stress Ratio	$R_t^2 + R_s^2$	–	0.52	0.76	0.03	0.02	0.22	0.30

4.5.2.3.5 Model AOS-100A Cask Lid Attachment Bolt Load and Stress Analysis

4.5.2.3.5.1 Cask Lid Attachment Bolt Input Parameters

Table 4-20 lists the Model AOS-100A cask lid attachment bolt input parameters. The Model AOS-100A minimum and maximum preload torque limits are 400 ft-lb and 500 ft-lb, respectively. The preload torque value used in the stress calculations is 500 ft-lb because the calculated bolt stresses are highest using the maximum preload torque.

Table 4-20. Model AOS-100A Cask Lid Attachment Bolt Input Parameters

Parameter	Variable	Input Value		Units
Temperature	T	(38) 100	(-40) -40	(°C) °F
Number of Bolts	N_b	14	14	–
Lid Diameter at Bolt Circle	D_{lb}	14.064	14.064	in.
Lid Diameter at Gasket	D_{lg}	12.172	12.172	in.
Nominal Bolt Diameter	D_b	0.875	0.875	in.
Threads per Inch	n	9	9	–
Lid Diameter at Inner Edge	D_{li}	11.02	11.02	in.
Lid Diameter at Outer Edge	D_{lo}	16.59	16.59	in.
Thickness of Cask Lid	t_l	1.49	1.49	in.
Thickness of Cask Lid Flange	t_{lf}	1.92	1.92	in.
Thickness of Cask Wall	t_c	2.785	2.785	in.
Bolt Length between the Top and Bottom Surface of Cask Lid	L_b	1.04	1.04	in.
Young's Modulus for Cask Lid	E_l	27,000,000	28,300,000	psi
Young's Modulus for Cask	E_c	27,000,000	28,300,000	psi
Young's Modulus for Bolt	E_b	27,800,000	28,900,000	psi
Poisson's Ratio for Cask Lid	N_{ul}	0.3	0.3	–
Poisson's Ratio for Cask	N_{uc}	0.3	0.3	–
Lid Thermal Expansion Coefficient	a_l	0.0000092	0.0000086	1/°F
Bolt Thermal Expansion Coefficient	a_b	0.0000073	0.0000070	1/°F
Cask Wall Thermal Expansion Coefficient	a_c	0.0000092	0.0000086	1/°F
Weight of Cask Contents	W_c	778	778	lbs.
Weight of Cask Lid	W_l	105	105	lbs.
Bolt Torque (in-lb)	Q	6,000	6,000	in-lb
Bolt Torque (ft-lb)		500	500	ft-lb
Nut Factor for Preload Torque	K	0.15	0.15	–

Table 4-20. Model AOS-100A Cask Lid Attachment Bolt Input Parameters (Continued)

Parameter	Variable	Input Value		Units
Gasket Seating Width	b	1	1	in.
Gasket Seating Stress	y	3,000	3,000	psi
Gasket Factor	m	0.54	0.54	–
Minimum Yield Strength	S_y	141,000	150,000	psi
Minimum Ultimate Strength	S_u	174,000	185,000	psi
Basic Allowable Stress Limit	S_m	94,000	100,000	psi
Initial Temperature	T_i	70	70	°F
Temperature of Cask Lid at Bolts	T_l	293	86	°F
Temperature of Bolts	T_b	293	86	°F
Temperature of Cask Wall	T_c	293	86	°F
Temperature of Cask Lid Inner Surface	T_{li}	294	86	°F
Temperature of Cask Lid Outer Surface	T_{lo}	294	86	°F
Transport Package Internal Pressure	P_i	280	280	psia
Atmospheric Pressure	P_a	15	15	psia

4.5.2.3.5.2 Model AOS-100A Cask Lid Attachment Bolt NCT Results

Table 4-21 summarizes the forces and moments from individual loads. Table 4-22 documents the NCT load combinations.

Table 4-21. Model AOS-100A Cask Lid Attachment Bolt NCT Loads

Summary Bolt Loads from Individual Loads	Variable	Units	Temperature	
			(38°C) 100°F	(-40°C) -40°F
Preload				
Non-Prying Tensile Bolt Force Due to Preload	F_a	lbs.	45,714	45,714
Torsional Bolt Moment	M_t	lb-in	3,000	3,000
Gasket				
Non-Prying Tensile Bolt Force for Gasket Seating	F_a	lbs.	8,194	8,194
Non-Prying Tensile Bolt Force for Gasket Operation	F_a	lbs.	782	782
Torsional Bolt Moment	M_t	lb-in	538	538
Pressure				
Pressure inside the Cask Lid	P_{li}	psi	280.0	280.0
Pressure outside the Cask Lid	P_{lo}	psi	15.0	15.0
Pressure inside the Cask Wall	P_{ci}	psi	280.0	280.0
Pressure outside the Cask Wall	P_{co}	psi	15.0	15.0
Non-Prying Tensile Bolt Force	F_a	lbs.	2,203	2,203
Shear Bolt Force per Bolt	F_s	lbs.	4,495	4,495
Fixed-Edge Cask Lid Force	F_f	lb/in	932	932
Fixed-Edge Cask Lid Moment	M_f	(lb-in)/in	1,638	1,638
Temperature				
Temperature Change of Cask Lid at Bolts	T_l	°F	223.0	16.0
Temperature Change of Bolts	T_b	°F	223.0	16.0
Temperature Change of Cask Wall	T_c	°F	223.0	16.0
Temperature Change of Inner Surface of Cask Lid	T_{li}	°F	224.0	16.0
Temperature Change of Outer Surface of Cask Lid	T_{lo}	°F	224.0	16.0
Non-Prying Tensile Bolt Force	F_a	lbs.	7,083	445
Shear Bolt Force per Bolt	F_s	lbs.	0.0	0.0
Fixed-Edge Cask Lid Force	F_f	lb/in	0.0	0.0
Fixed-Edge Cask Lid Moment	M_f	(lb-in)/in	0.0	0.0

Table 4-21. Model AOS-100A Cask Lid Attachment Bolt NCT Loads (Continued)

Summary Bolt Loads from Individual Loads	Variable	Units	Temperature	
			(38°C) 100°F	(-40°C) -40°F
Impact				
Maximum Impact Acceleration	a_i	g	–	–
Impact Angle	x_i	°	–	–
Dynamic Load Factor	DLF	–	–	–
Non-Prying Axial Load Due to Impact	F_a	lbs.	–	–
Shear Load Due to Impact	F_s	lbs.	–	–
Fixed-Edge Load Due to Impact	F_f	lb/in	–	–
Fixed-Edge Moment Due to Impact	M_f	(lb-in)/in	–	–
Vibration				
Vibration Transmissibility of Acceleration (cask support to cask lid)	VTR	–	1.00	1.00
Maximum Axial Vibration Acceleration (g) at the Cask Support	ava	g	10.00	10.00
Maximum Transverse Vibration Acceleration (g) at the Cask Support	avt	g	5.00	5.00
Axial Load Due to Vibration	F_a	lbs.	75.00	75.00
Shear Load Due to Vibration	F_s	lbs.	37.50	37.50
Fixed-Edge Force	F_f	lb/in	23.76	23.76
Fixed-Edge Moment Due to Vibration	M_f	(lb-in)/in	41.78	41.78
Prying Action				
Bolt Length between Top and Bottom Surface of Cask Lid	L_b	in.	1.04	1.04
Constant1	C1	–	1.0	1.0
Constant2 (for outward loads)	C2	–	0.2965	0.2990
Bolt Preload per Unit Length of the Bolt Circle	P	lb/in	16,729	14,626
Non-Prying Tensile Bolt Force	B	lb/in	16,729	14,626
Combined Axial Load on Bolt Due to Prying	F_{ap-c}	lbs.	-35,159	-29,982

Table 4-22. Model AOS-100A Cask Lid Attachment Bolt NCT Load Combinations

Loads/Stresses	Variable	Units	Temperature	
			(38°C) 100°F	(-40°C) -40°F
Temperature and Preload Non-Prying Axial Load	F_{a-pt}	lbs.	52,797	46,159
Axial Load Less Temperature and Preload	F_{a-al}	lbs.	3,059	3,059
Combined Non-Prying Tensile Bolt Force (Greater of F_{a-pt} and F_{a-al})	F_{a-c}	lbs.	52,797	46,159
Prying Axial Load of Bolt	F_{ap-c}	lbs.	-35,159	-29,982
Total Tensile Bolt Load (F_{a-c} + F_{ap-c})	F_a	lbs.	17,638	16,177
Total Shear Bolt Force	F_s	lbs.	4,532	4,532
Total Bending Bolt Moment	M_{bb-c}	lb-in	673	668
Total Torsional Bolt Moment	M_t	lb-in	3,000	3,000
Diameter Used for Stress Calculations	D_{ba}	in.	0.767	0.767
Average Bolt Axial Stress	S_{ba}	psi	38,198	35,035
Average Bolt Shear Stress	S_{bs}	psi	9,816	9,816
Maximum Bending Stress	S_{bb}	psi	15,199	15,090
Maximum Shear Stress Due to Torsional Bolt Moment	S_{bt}	psi	33,896	33,896
Maximum Stress Intensity	S_{bi}	psi	102,440	100,773
Allowable Tensile Stress	S_m	psi	94,000	100,000
Allowable Shear Stress	$0.6\ S_m$	psi	56,400	60,000
Allowable Stress Intensity	$1.35\ S_m$	psi	126,900	135,000
Axial Stress Ratio	R_t	–	0.41	0.35
Shear Stress Ratio	R_s	–	0.17	0.16
Combined Stress Ratio	$R_t^2 + R_s^2$	–	0.20	0.15
Stress Intensity Ratio	R_i	–	0.81	0.75

4.5.2.3.5.3 Model AOS-100A Cask Lid Attachment Bolt HAC Results

Table 4-23 documents the HAC forces from individual loads. Table 4-24 summarizes the corresponding load combinations.

Table 4-23. Model AOS-100A Cask Lid Attachment Bolt HAC Loads

Summary Bolt Loads from Individual Loads	Variable	Units	Drop Type, by Temperature (T)					
			Head-On		Side		Cg/Corner	
			(38°C) 100°F	(-40°C) -40°F	(38°C) 100°F	(-40°C) -40°F	(38°C) 100°F	(-40°C) -40°F
Preload								
Non-Prying Tensile Bolt Force Due to Preload	F_a	lbs.	45,714	45,714	45,714	45,714	45,714	45,714
Torsional Bolt Moment	M_t	lb-in	3,000	3,000	3,000	3,000	3,000	3,000
Gasket								
Non-Prying Tensile Bolt Force for Gasket Seating	F_a	lbs.	8,194	8,194	8,194	8,194	8,194	8,194
Non-Prying Tensile Bolt Force for Gasket Operation	F_a	lbs.	782	782	782	782	782	782
Torsional Bolt Moment	M_t	lb-in	538	538	538	538	538	538
Pressure								
Pressure inside the Cask Lid	P_{li}	psi	280.0	280.0	280.0	280.0	280.0	280.0
Pressure outside the Cask Lid	P_{lo}	psi	15.0	15.0	15.0	15.0	15.0	15.0
Pressure inside the Cask Wall	P_{ci}	psi	280.0	280.0	280.0	280.0	280.0	280.0
Pressure outside the Cask Wall	P_{co}	psi	15.0	15.0	15.0	15.0	15.0	15.0
Non-Prying Tensile Bolt Force	F_a	lbs.	2,203	2,203	2,203	2,203	2,203	2,203
Shear Bolt Force per Bolt	F_s	lbs.	4,495	4,495	4,495	4,495	4,495	4,495
Fixed-Edge Cask Lid Force	F_f	lb/in	932	932	932	932	932	932
Fixed-Edge Cask Lid Moment	M_f	(lb-in)/in	1,638	1,638	1,638	1,638	1,638	1,638

Table 4-23. Model AOS-100A Cask Lid Attachment Bolt HAC Loads (Continued)

Summary Bolt Loads from Individual Loads	Variable	Units	Drop Type, by Temperature (T)					
			Head-On		Side		Cg/Corner	
			(38°C) 100°F	(-40°C) -40°F	(38°C) 100°F	(-40°C) -40°F	(38°C) 100°F	(-40°C) -40°F
Temperature								
Temperature Change of Cask Lid at Bolts	T_l	°F	223.0	16.0	223.0	16.0	223.0	16.0
Temperature Change of Bolts	T_b	°F	223.0	16.0	223.0	16.0	223.0	16.0
Temperature Change of Cask Wall	T_c	°F	223.0	16.0	223.0	16.0	223.0	16.0
Temperature Change of Inner Surface of Cask Lid	T_{li}	°F	224.0	16.0	224.0	16.0	224.0	16.0
Temperature Change of Outer Surface of Cask Lid	T_{lo}	°F	224.0	16.0	224.0	16.0	224.0	16.0
Non-Prying Tensile Bolt Force	F_a	lbs.	7,083	445	7,083	445	7,083	445
Shear Bolt Force per Bolt	F_s	lbs.	0.0	0.0	0.0	0.0	0.0	0.0
Fixed-Edge Cask Lid Force	F_f	lb/in	0.0	0.0	0.0	0.0	0.0	0.0
Fixed-Edge Cask Lid Moment	M_f	(lb-in)/in	0.0	0.0	0.0	0.0	0.0	0.0
Impact								
Maximum Impact Acceleration	a_i	g	156.0	218.0	172.0	240.0	113.0	158.0
Impact Angle	x_i	°	90.0	90.0	0.0	0.0	52.0	52.0
Dynamic Load Factor	DLF	–	1.15	1.15	1.15	1.15	1.15	1.15
Non-Prying Axial Load Due to Impact	F_a	lbs.	15,162	21,188	0	0	8,655	12,101
Shear Load Due to Impact	F_s	lbs.	0	0	1,290	1,800	522	730
Fixed-Edge Load Due to Impact	F_f	lb/in	4,804	6,714	0	0	2,742	3,834
Fixed-Edge Moment Due to Impact	M_f	(lb-in)/in	8,446	11,803	0	0	4,821	6,741

Table 4-23. Model AOS-100A Cask Lid Attachment Bolt HAC Loads (Continued)

Summary Bolt Loads from Individual Loads	Variable	Units	Drop Type, by Temperature (T)					
			Head-On		Side		Cg/Corner	
			(38°C) 100°F	(-40°C) -40°F	(38°C) 100°F	(-40°C) -40°F	(38°C) 100°F	(-40°C) -40°F
Vibration								
Vibration Transmissibility of Acceleration (cask support to cask lid)	VTR	–	–	–	–	–	–	–
Maximum Axial Vibration Acceleration (g) at the Cask Support	ava	g	–	–	–	–	–	–
Maximum Transverse Vibration Acceleration (g) at the Cask Support	avt	g	–	–	–	–	–	–
Axial Load Due to Vibration	F_a	lbs.	–	–	–	–	–	–
Shear Load Due to Vibration	F_s	lbs.	–	–	–	–	–	–
Fixed-Edge Force	F_f	lb/in	–	–	–	–	–	–
Fixed-Edge Moment Due to Vibration	M_f	(lb-in)/in	–	–	–	–	–	–
Prying Action								
Bolt Length	L_b	in	1.04	1.04	1.04	1.04	1.04	1.04
Constant1	C1	–	1.0	1.0	1.0	1.0	1.0	1.0
Constant2 (for outward loads)	C2	–	0.2965	0.2990	0.2965	0.2990	0.2965	0.2990
Bolt Preload per Unit Length of Bolt Circle	P	lb/in	16,729	14,626	16,729	14,626	16,729	14,626
Non-Prying Tensile Bolt Force	B	lb/in	16,729	14,626	16,729	14,626	16,729	14,626
Axial Load of Bolt Due to Prying	F_{ap-c}	lbs.	-7,325	8,895	-35,298	-30,120	-19,331	-7,837

Table 4-24. Model AOS-100A Cask Lid Attachment Bolt HAC Load Combinations

Loads/Stresses	Variable	Units	Drop Type, by Temperature (T)					
			Head-On		Side		Cg/Corner	
			(38°C) 100°F	(-40°C) -40°F	(38°C) 100°F	(-40°C) -40°F	(38°C) 100°F	(-40°C) -40°F
Temperature and Preload Non-Prying Axial Load	F_{a-pt}	lbs.	52,797	46,159	52,797	46,159	52,797	46,159
Axial Load Less Temperature and Preload	F_{a-al}	lbs.	18,146	24,172	2,984	2,984	11,639	15,085
Combined Non-Prying Tensile Bolt Force (Greater of F_{a-pt} and F_{a-al})	F_{a-c}	lbs.	52,797	46,159	52,797	46,159	52,797	46,159
Axial Load of Bolt Due to Prying Combined	F_{ap-c}	lbs.	-7,325	8,895	-35,298	-30,120	-19,331	-7,837
Total Tensile Bolt Load (F_{a-c} + F_{ap-c})	F_a	lbs.	45,472	55,054	17,499	16,039	33,466	38,322
Total Shear Bolt Force	F_s	lbs.	4,495	4,495	5,785	6,295	5,017	5,224
Total Bending Bolt Moment	M_{bb-c}	lb-in	4,038	5,343	656	651	2,586	3,331
Total Torsional Bolt Moment	M_t	lb-in	3,000	3,000	3,000	3,000	3,000	3,000
Diameter Used for Stress Calculations	D_{ba}	in.	0.767	0.767	0.767	0.767	0.767	0.767
Average Bolt Direct Stress	S_{ba}	psi	98,478	119,230	37,898	34,736	72,477	82,993
Average Bolt Shear Stress	S_{bs}	psi	9,735	9,735	12,528	13,633	10,865	11,314
Maximum Bending Stress	S_{bb}	psi	91,241	120,743	14,821	14,715	58,441	75,270
Total Tensile Stress	S_{bt}	psi	33,896	33,896	33,896	33,896	33,896	33,896
Allowable Direct Stress	Minimum of 0.7 S_u and S_y	psi	121,800	129,500	121,800	129,500	121,800	129,500
Allowable Shear Stress	Minimum of 0.42 S_u and 0.6 S_y	psi	73,080	77,700	73,080	77,700	73,080	77,700
Average Direct Stress Ratio	R_t	–	0.81	0.92	0.31	0.27	0.60	0.64
Shear Stress Ratio	R_s	–	0.13	0.13	0.17	0.18	0.15	0.15
Combined Axial and Shear Stress Ratio	$R_t^2 + R_s^2$	–	0.67	0.86	0.13	0.10	0.38	0.43

4.5.2.4 Cask Lid Attachment Bolt Thread Engagement Length

4.5.2.4.1 Model AOS-025A Cask Lid Attachment Bolt Thread Engagement Length

The required threaded engagement necessary for the threaded joint to carry the applied loads without the threads stripping is calculated using the methods presented in *Machinery's Handbook 26* (**[4.11]**, *Page 1490*). The Model AOS-025A cask lid attachment bolts are eight, 3/8 - 16 UNC, SB-637 bolts.

For materials of the same strength, the length of engagement to prevent stripping of external threads (L_e) is as follows:

$$L_e = \frac{2A_t}{\pi(Kn_{max})\left[\frac{1}{2}+0.57735n(Es_{min}-Kn_{max})\right]} = 0.250 \text{ in.}$$

where:

Es_{min} = 0.3287, Minimum pitch diameter of external threads, class 2A (**[4.11]**, *Page 1718*)

Ds_{min} = 0.3643, Minimum major diameter of external threads, class 2A (**[4.11]**, *Page 1718*)

En_{max} = 0.3387, Maximum pitch diameter of internal threads, class 3B (**[4.11]**, *Page 1718*)

Kn_{max} = 0.3182, Maximum minor diameter of internal threads, class 3B (**[4.11]**, *Page 1718*)

n = 16, Number of threads per inch

For steels over 100,000 psi ultimate tensile strength, the screw thread tensile stress area is calculated as follows:

$$A_t = \pi\left[\frac{Es_{min}}{2} - \frac{0.16238}{n}\right]^2 = 0.0747 \text{ in}^2$$

The length engagement (L_e) applies if the external and internal threads are made of materials of the same strength. If the materials of the internal and external threads do not have the same strength, the relative strength (J) is calculated to determine if the internal thread could strip before the bolt breaks. The relative strength is calculated as follows:

$$J = \frac{A_s \times S_{ut} \text{ of external thread material}}{A_n \times S_{ut2} \text{ of internal thread material}} = 1.385$$

where:

$$A_s = \pi n L_e \, Kn_{max} \left[\frac{1}{2n} + 0.57735(Es_{min} - Kn_{max})\right]$$

= 0.149 in^2, shear area of external threads

$$A_n = \pi n L_e \, Ds_{min} \left[\frac{1}{2n} + 0.57735(Ds_{min} - En_{max})\right]$$

= 0.211 in^2, shear area of internal threads

S_{ut} = 176.0 ksi, tensile strength of external threads

S_{ut2} = 90.0 ksi, tensile strength of internal threads (insert material)

Because the relative strength (J) is calculated to be greater than 1, the required length of engagement (Q_L) to prevent stripping of threads is calculated by multiplying the J factor times the calculated length of engagement (L_e):

$$Q_L = JL_e = 1.369 \times 0.250 \text{ in.} = 0.35 \text{ in.}$$

The actual length of engagement is calculated by subtracting the length of the cask lid attachment bolt that is embedded in the cask lid from the total bolt length (L_b = 0.63 in. – 0.15 in. = 0.48 in.). The actual length of engagement (L_b) is greater than the required length of engagement Q_L. Therefore, the engagement length is adequate.

4.5.2.4.2 Model AOS-050A Cask Lid Attachment Bolt Thread Engagement Length

The required threaded engagement necessary for the threaded joint to carry the applied loads without the threads stripping is calculated using the methods presented in *Machinery's Handbook 26* (**[4.11]**, *Page 1490*). The Model AOS-050A cask lid attachment bolts are ten, 1/2 - 13 UNC, SB-637 bolts.

For materials of the same strength, the length of engagement to prevent stripping of external threads (L_e) is as follows:

$$L_e = \frac{2A_t}{\pi(Kn_{max})\left[\frac{1}{2}+0.57735n(Es_{min}-Kn_{max})\right]} = 0.333 \text{ in.}$$

where:

Es_{min} = 0.4435, Minimum pitch diameter of external threads, class 2A (**[4.11]**, *Page 1719*)

Ds_{min} = 0.4876, Minimum major diameter of external threads, class 2A (**[4.11]**, *Page 1719*)

En_{max} = 0.4548, Maximum pitch diameter of internal threads, class 3B (**[4.11]**, *Page 1719*)

Kn_{max} = 0.4284, Maximum minor diameter of internal threads, class 3B (**[4.11]**, *Page 1719*)

n = 13, Number of threads per inch

For steels over 100,000 psi ultimate tensile strength, the screw thread tensile stress area is calculated as follows:

$$A_t = \pi\left[\frac{Es_{min}}{2} - \frac{0.16238}{n}\right]^2 = 0.1376 \text{ in}^2$$

The length engagement (L_e) applies if the external and internal threads are made of materials of the same strength. If the materials of the internal and external threads do not have the same strength, the relative strength (J) is calculated to determine the adequate length of engagement to prevent stripping of threads before the bolt breaks. The relative strength is calculated as follows:

$$J = \frac{A_s \times S_{ut} \text{ of external thread material}}{A_n \times S_{ut2} \text{ of internal thread material}} = 1.396$$

where:

$$A_s = \pi n L_e \, Kn_{max} \left[\frac{1}{2n} + 0.57735(Es_{min} - Kn_{max})\right]$$

= 0.275 in^2, shear area of external threads

$$A_n = \pi n L_e \, Ds_{min} \left[\frac{1}{2n} + 0.57735(Ds_{min} - En_{max})\right]$$

= 0.381 in^2, shear area of internal threads

S_{ut} = 174.0 ksi, tensile strength of external threads

S_{ut2} = 90.0 ksi, tensile strength of internal threads (insert material)

Because the relative strength (J) is calculated to be greater than 1, the required length of engagement (Q_L) to prevent stripping of threads is calculated by multiplying the J factor times the calculated length of engagement (L_e):

$$Q_L = JL_e = 1.396 \times 0.333 \text{ in.} = 0.47 \text{ in.}$$

The actual length of engagement is calculated by subtracting the length of the bolt embedded in the lid from the total bolt length (L_b = 1.0 in. – 0.41 in. = 0.59 in.). The actual length of engagement (L_b) is greater than the required length of engagement Q_L. Therefore, the engagement length is adequate.

4.5.2.4.3 Model AOS-100A Cask Lid Attachment Bolt Thread Engagement Length

The required threaded engagement necessary for the threaded joint to carry the applied loads without the threads stripping is calculated using the methods presented in *Machinery's Handbook 26* (**[4.11]**, *Page 1490*). The Model AOS-100A cask lid attachment bolts are fourteen, 7/8 - 9 UNC, SB-637 bolts.

For materials of the same strength, the length of engagement to prevent stripping of external threads (L_e) is as follows:

$$L_e = \frac{2A_t}{\pi(Kn_{max})\left[\frac{1}{2}+0.57735n(Es_{min}-Kn_{max})\right]} = 0.587 \text{ in.}$$

where:

Es_{min} = 0.7946, Minimum pitch diameter of external threads, class 2A (**[4.11]**, *Page 1723*)

Ds_{min} = 0.8592, Minimum major diameter of external threads, class 2A (**[4.11]**, *Page 1723*)

En_{max} = 0.8089, Maximum pitch diameter of internal threads, class 3B (**[4.11]**, *Page 1723*)

Kn_{max} = 0.7681, Maximum minor diameter of internal threads, class 3B (**[4.11]**, *Page 1723*)

n = 9, Number of threads per inch

For steels over 100,000 psi ultimate tensile strength, the screw thread tensile stress area is calculated as follows:

$$A_t = \pi\left[\frac{Es_{min}}{2} - \frac{0.16238}{n}\right]^2 = 0.4519 \text{ in}^2$$

The length engagement (L_e) applies if the external and internal threads are made of materials of the same strength. If the materials of the internal and external threads do not have the same strength, the relative strength (J) is calculated to determine if the internal thread could strip before the bolt breaks. The relative strength is calculated as follows:

$$J = \frac{A_s \times S_{ut} \text{ of external thread material}}{A_n \times S_{ut2} \text{ of internal thread material}} = 1.448$$

where:

$$A_s = \pi n L_e Kn_{max} \left[\frac{1}{2n} + 0.57735(Es_{min} - Kn_{max})\right]$$

= 0.904 in^2, shear area of external threads

$$A_n = \pi n L_e Ds_{min} \left[\frac{1}{2n} + 0.57735(Ds_{min} - En_{max})\right]$$

= 1.207 in^2, shear area of internal threads

S_{ut} = 174.0 ksi, tensile strength of external threads

S_{ut2} = 90.0 ksi, tensile strength of internal threads (insert material)

Because the relative strength (J) is calculated to be greater than 1, the required length of engagement (Q_L) to prevent stripping of threads is calculated by multiplying the J factor times the calculated length of engagement (L_e):

$$Q_L = JL_e = 1.448 \times 0.587 \text{ in.} = 0.85 \text{ in.}$$

The actual length of engagement is calculated by subtracting the length of the bolt embedded in the lid from the total bolt length (L_b = 2.25 in. – 1.04 in. = 1.21 in.). The actual length of engagement (L_b) is greater than the required length of engagement Q_L. Therefore, the engagement length is adequate.

4.5.2.5 Cask Lid Flange Separation Analysis

4.5.2.5.1 Model AOS-025A Cask Lid Flange Separation Analysis

The flange separation is evaluated based on the bolt elongation due to the clamp load of the cask lid attachment bolt. The clamp load is evaluated as the difference between the absolute sum of the applied loads (other than preload and temperature load) and prying load, and the absolute sum of the preload and temperature loads. The flange separation is greatest for the lowest preload torque allowable; therefore, a preload torque of 29 ft-lb is used in the calculations that follow.

Bolt Clamping Force (BCF):

$$BCF = | F_{a\text{-}al} | + | F_{ap\text{-}c} | - | F_{a\text{-}pt} |$$

where:

$F_{a\text{-}al}$ = Axial load less temperature and preload

$F_{ap\text{-}c}$ = Combined axial ;oad on bolt due to prying

$F_{a\text{-}pt}$ = Temperature and preload non-prying axial load

Bolt Displacement (BD):

$$BD = \frac{BCF \times L_b}{A \times E_b}$$

where:

BCF = Bolt clamping force

L_b = Length of bolt

A = Cross-sectional area of bolt

E_b = Modulus of elasticity of the bolt material

The flange separation evaluations are documented in Table 4-25 and Table 4-26 for NCT and HAC, respectively. Accordingly, the bolt displacement remains below the allowable flange separation value/ gasket recovery of 0.003 in. for both NCT and HAC.

Table 4-25. Model AOS-025A Cask Lid Flange Separation NCT Evaluation – 29-ft-lb Torque

Parameters	Variable	Units	Temperature	
			(38°C) 100°F	(-40°C) -40°F
Applied Load Less Temperature Load and Preload	$F_{a\text{-}al}$	lbs.	361	361
Load Due to Prying Action	$F_{ap\text{-}c}$	lbs.	-6,628	-5,514
Preload and Temperature Load	$F_{a\text{-}pt}$	lbs.	7,216	6,011
Bolt Clamping Force	BCF	lbs.	-228	-136
Bolt Length	L_b	in.	0.15	0.15
Modulus of Elasticity of Bolt	E_b	psi	28,000,000	29,200,000
Cross-Sectional Area of Bolt	BXA	in^2	0.0775	0.0775
Bolt Displacement	BD	in.	-0.000016	-0.000009
Allowable Flange Separation	BDA	in.	0.003	0.003

Table 4-26. Model AOS-025A Cask Lid Flange Separation HAC Evaluation – 29-ft-lb Torque

Parameters	Variable	Units	Drop Type, by Temperature (T)					
			Head-On		Side		Cg/Corner	
			(38°C) 100°F	(-40°C) -40°F	(38°C) 100°F	(-40°C) -40°F	(38°C) 100°F	(-40°C) -40°F
Applied Load Less Temperature Load and Preload	$F_{a\text{-}al}$	lbs.	2,926	3,974	359	359	2,833	3,805
Load Due to Prying Action	$F_{ap\text{-}c}$	lbs.	-1,167	2,181	-6,633	-5,519	-1,364	1,821
Preload and Temperature Load	$F_{a\text{-}pt}$	lbs.	7,216	6,011	7,216	6,011	7,216	6,011
Bolt Clamping Force	BCF	lbs.	-3,124	144	-225	-133	-3,020	-385
Bolt Length	L_b	in.	0.15	0.15	0.15	0.15	0.15	0.15
Modulus of Elasticity of Bolt	E_b	psi	28,000,000	29,200,000	28,000,000	29,200,000	28,000,000	29,200,000
Cross-Sectional Area of Bolt	BXA	in^2	0.0775	0.0775	0.0775	0.0775	0.0775	0.0775
Bolt Displacement	BD	in.	-0.000216	0.000010	-0.000016	-0.000009	-0.000209	-0.000026
Allowable Flange Separation	BDA	in.	0.003	0.003	0.003	0.003	0.003	0.003

4.5.2.5.2 Model AOS-050A Cask Lid Flange Separation Analysis

The flange separation is evaluated based on the bolt elongation due to the clamp load of the cask lid attachment bolt. The clamp load is evaluated as the difference between the absolute sum of the applied loads (other than preload and temperature load) and prying load, and the absolute sum of the preload and temperature loads. The flange separation is greatest for the lowest preload torque allowable; therefore, a preload torque of 62.5 ft-lb is used in the calculations that follow.

Bolt Clamping Force (BCF):

$$BCF = | F_{a\text{-}al} | + | F_{ap\text{-}c} | - | F_{a\text{-}pt} |$$

where:

$F_{a\text{-}al}$ = Axial load less temperature and preload

$F_{ap\text{-}c}$ = Combined axial ;oad on bolt due to prying

$F_{a\text{-}pt}$ = Temperature and preload non-prying axial load

Bolt Displacement (BD):

$$BD = \frac{BCF \times L_b}{A \times E_b}$$

where:

BCF = Bolt clamping force

L_b = Length of bolt

A = Cross-sectional area of bolt

E_b = Modulus of elasticity of the bolt material

The flange separation evaluations are documented in Table 4-27 and Table 4-28 for NCT and HAC, respectively. Accordingly, the bolt displacement remains below the allowable flange separation value/ gasket recovery of 0.003 in. for both NCT and HAC.

Table 4-27. Model AOS-050A Cask Lid Flange Separation NCT Evaluation – 62.5-ft-lb Torque

Parameters	Variable	Units	Temperature	
			(38°C) 100°F	(-40°C) -40°F
Applied Load Less Temperature Load and Preload	$F_{a\text{-}al}$	lbs.	693	693
Load Due to Prying Action	$F_{ap\text{-}c}$	lbs.	-9,841	-8,072
Preload and Temperature Load	$F_{a\text{-}pt}$	lbs.	12,240	10,136
Bolt Clamping Force	BCF	lbs.	-1,706	-1,372
Bolt Length	L_b	in.	0.41	0.41
Modulus of Elasticity of Bolt	E_b	psi	27,800,000	28,900,000
Cross-Sectional Area of Bolt	BXA	in^2	0.1419	0.1419
Bolt Displacement	BD	in.	-0.000177	-0.000137
Allowable Flange Separation	BDA	in.	0.003	0.003

Table 4-28. Model AOS-050A Cask Lid Flange Separation HAC Evaluation – 62.5-ft-lb Torque

Parameters	Variable	Units	Drop Type, by Temperature (T)					
			Head-On		Side		Cg/Corner	
			(38°C) 100°F	(-40°C) -40°F	(38°C) 100°F	(-40°C) -40°F	(38°C) 100°F	(-40°C) -40°F
Applied Load Less Temperature Load and Preload	$F_{a\text{-}al}$	lbs.	5,953	8,052	679	679	3,644	4,835
Load Due to Prying Action	$F_{ap\text{-}c}$	lbs.	41	5,737	-9,868	-8,098	-4,297	-300
Preload and Temperature Load	$F_{a\text{-}pt}$	lbs.	12,240	10,136	12,240	10,136	12,240	10,136
Bolt Clamping Force	BCF	lbs.	-6,246	3,653	-1,694	-1,360	-4,299	-5,001
Bolt Length	L_b	in.	0.41	0.41	0.41	0.41	0.41	0.41
Modulus of Elasticity of Bolt	E_b	psi	27,800,000	28,900,000	27,800,000	28,900,000	27,800,000	28,900,000
Cross-Sectional Area of Bolt	BXA	in^2	0.1419	0.1419	0.1419	0.1419	0.1419	0.1419
Bolt Displacement	BD	in.	-0.000649	0.000365	-0.000176	-0.000136	-0.000447	-0.000500
Allowable Flange Separation	BDA	in.	0.003	0.003	0.003	0.003	0.003	0.003

4.5.2.5.3 Model AOS-100A Cask Lid Flange Separation Analysis

The flange separation is evaluated based on the bolt elongation due to the clamp load of the cask lid attachment bolt. The clamp load is evaluated as the difference between the absolute sum of the applied loads (other than preload and temperature load) and prying load, and the absolute sum of the preload and temperature loads. The flange separation is greatest for the lowest preload torque allowable; therefore, a preload torque of 400 ft-lb is used in the calculations that follow.

Bolt Clamping Force (BCF):

$$BCF = | F_{a-al} | + | F_{ap-c} | - | F_{a-pt} |$$

where:

F_{a-al} = Axial load less temperature and preload

F_{ap-c} = Combined axial ;oad on bolt due to prying

F_{a-pt} = Temperature and preload non-prying axial load

Bolt Displacement (BD):

$$BD = \frac{BCF \times L_b}{A \times E_b}$$

where:

BCF = Bolt clamping force

L_b = Length of bolt

A = Cross-sectional area of bolt

E_b = Modulus of elasticity of the bolt material

The flange separation evaluations are documented in Table 4-29 and Table 4-30 for NCT and HAC, respectively, for cases that use 400-ft-lb torque. Accordingly, the bolt displacement remains below the allowable flange separation value/gasket recovery of 0.003 in. for both NCT and HAC.

Table 4-29. Model AOS-100A Cask Lid Flange Separation NCT Evaluation – 400-ft-lb Torque

Parameters	Variable	Units	Temperature	
			(38°C) 100°F	(-40°C) -40°F
Applied Load Less Temperature Load and Preload	$F_{a\text{-}al}$	lbs.	3,059	3,059
Load Due to Prying Action	$F_{ap\text{-}c}$	lbs.	-28,108	-22,943
Preload and Temperature Load	$F_{a\text{-}pt}$	lbs.	43,654	37,016
Bolt Clamping Force	BCF	lbs.	-12,487	-11,014
Bolt Length	L_b	in.	1.04	1.04
Modulus of Elasticity of Bolt	E_b	psi	27,800,000	28,900,000
Cross-Sectional Area of Bolt	BXA	in^2	0.4617	0.4617
Bolt Displacement	BD	in.	-0.00101	-0.00086
Allowable Flange Separation	BDA	in.	0.003	0.003

Table 4-30. Model AOS-100A Cask Lid Flange Separation HAC Evaluation – 400-ft-lb Torque

Parameters	Variable	Units	Drop Type, by Temperature (T)					
			Head-On		Side		Cg/Corner	
			(38°C) 100°F	(-40°C) -40°F	(38°C) 100°F	(-40°C) -40°F	(38°C) 100°F	(-40°C) -40°F
Applied Load Less Temperature Load and Preload	$F_{a\text{-}al}$	lbs.	18,146	24,172	2,984	2,984	11,639	15,085
Load Due to Prying Action	$F_{ap\text{-}c}$	lbs.	-273	1,5933	-28,246	-23,081	-12,279	-799
Preload and Temperature Load	$F_{a\text{-}pt}$	lbs.	43,654	37,016	43,654	37,016	43,654	37,016
Bolt Clamping Force	BCF	lbs.	-25,235	3,090	-12,424	-10,951	-19,736	-21,132
Bolt Length	L_b	in.	1.04	1.04	1.04	1.04	1.04	1.04
Modulus of Elasticity of Bolt	E_b	psi	27,800,000	28,900,000	27,800,000	28,900,000	27,800,000	28,900,000
Cross-Sectional Area of Bolt	BXA	in^2	0.4617	0.4617	0.4617	0.4617	0.4617	0.4617
Bolt Displacement	BD	in.	-0.00204	0.00024	-0.00101	-0.00085	-0.00160	-0.00165
Allowable Flange Separation	BDA	in.	0.003	0.003	0.003	0.003	0.003	0.003

4.5.2.6 Cask Lid Attachment Bolt Fatigue Analysis

Fatigue analysis is completed for NCT, using a minimum fatigue reduction factor of 4 and ASME fatigue curves I-9.4 **[4.13]** with elastic modulus adjustment per *NUREG/CR-6007* **[4.6]**, *Table 6.2*. The maximum cumulative usage factor due to alternating stress intensity should be less than 1.

4.5.2.6.1 Model AOS-025A Cask Lid Attachment Bolt Fatigue Analysis

The fatigue analysis identifies two stress cycles – Normal operation and vibration cycles. Normal operation loads include preload, temperature, and pressure. The vibration loads are documented based on the applied axial and transverse vibration acceleration loads.

4.5.2.6.1.1 Normal Operation Cycles

Fatigue due to operating loads is documented based on the maximum NCT cases. The direct stress is obtained by combining the axial and bending stresses. The shear stress is obtained by combining the average shear load and torsional bolt moment. The maximum principal stress (S_1) is calculated from the combined direct and shear stress. Summary of normal operation cycles is documented in Table 4-31.

$$S_1 = \frac{\sigma}{2} \pm \sqrt{\left(\frac{\sigma}{2}\right)^2 + \tau^2} = 40{,}785.2 \text{ psi}$$

where:

$\sigma = S_{ba} + S_{bb} = 11{,}046$ psi (direct stress, Table 4-12)

$\tau = S_{bs} + S_{bt} = 34{,}827$ psi (shear stress, Table 4-12)

The corresponding alternating stresses (S_a) are calculated using a fatigue reduction factor (RF) of 4 **[4.12]**. Also, because the fatigue curve (**[4.13]**, *ASME Section III*, *Figure I-9.4*) is based on a modulus of elasticity of 30 × 10^3 ksi, which is different than the modulus of elasticity of the bolt materials, a ratio of the modulus of elasticities is considered in calculating the alternating stress per **[4.12]**, *NB-3232.3*.

$$S_a = RF\left(\frac{S_1}{2}\right)\left(\frac{E_{dc}}{E_a}\right) = 87{,}396.9 \text{ psi}$$

where:

RF = 4, Fatigue strength reduction factor **[4.12]**

E_{dc} = 30 × 10^3 ksi, Modulus of elasticity on design fatigue curve **[4.13]**

E_a = 28.0 × 10^3 ksi, Modulus of elasticity of the bolt materials

Using the alternating stress calculated and the fatigue curve for a maximum nominal stress ≤ 2.7 S_m in **[4.13]**, *ASME Section III*, *Figure I-9.4*, the corresponding fatigue limits are calculated by interpolating the tabular data provided in **[4.13]**, *ASME Section III*, *Table I-9.0*. The estimated fatigue limit, N_1, for the 87.4 ksi alternating stress is 1,313 cycles. Based on a weekly transport for five (5) years, the number of normal operation cycles, n_1, is 52 cycles/year × 5 years = 260 cycles. The corresponding usage factor (U_1) for normal operating cycles is as follows:

$$U_1 = \frac{n_1}{N_1} = 0.20$$

where:

n_1 = 260 cycles, operating cycles

N_1 = 1,313 cycles, allowable cycles

4.5.2.6.1.2 Vibration Cycles

Fatigue due to vibration loads are documented based on the applied axial and transverse vibration acceleration loads. The maximum principal stress (S_1) is calculated from the combined direct and shear stress. Summary of vibration cycles is documented in Table 4-31.

$$S_1 = \frac{\sigma}{2} \pm \sqrt{\left(\frac{\sigma}{2}\right)^2 + \tau^2} = 38.9 \text{ psi}$$

where:

σ = S_{ba} = 1.2732 F_a / D^2 = 32.3 psi, direct stress

τ = S_{bs} = 1.2732 F_s / D^2 = 16.1 psi, shear stress

F_a = 2.50 lbs., axial load due to vibration (refer to Table 4-11)

F_s = 1.25 lbs., shear load due to vibration (refer to Table 4-11)

D = 0.314 in. (bolt diameter for tensile stress (D_{ba}); refer to Table 4-12)

The corresponding alternating stresses (S_a) are calculated using a fatigue reduction factor (RF) of 4 **[4.12]**. Also, because the fatigue curve (**[4.13]**, *ASME Section III*, *Figure I-9.4*) is based on a modulus of elasticity of 30 × 10^3 ksi, which is different than the modulus of elasticity of the bolt materials, a ratio of the modulus of elasticities is considered in calculating the alternating stress per **[4.12]**, *NB-3232.3*.

$$S_a = RF\left(\frac{S_1}{2}\right)\left(\frac{E_{dc}}{E_a}\right) = 83.4 \text{ psi}$$

where:

RF = 4, Fatigue strength reduction factor **[4.12]**

E_{dc} = 30 × 10^3 ksi, Modulus of elasticity on design fatigue curve **[4.13]**

E_a = 28.0 × 10^3 ksi, Modulus of elasticity of the bolt materials

Using the alternating stress calculated and the fatigue curve for a maximum nominal stress ≤ 2.7 S_m in **[4.13]**, *ASME Section III*, *Figure I-9.4*, the corresponding fatigue limits are calculated by interpolating the tabular data provided in **[4.13]**, *ASME Section III*, *Table I-9.0*. The estimated fatigue limit for the 0.08 ksi alternating stress is 3.4E+20 cycles. The vibration cycles are estimated based on an infinite cycle (1.0E+07). Using 1.0 × 10^7 vibration cycles, n_1, and maximum allowable cycles, N_1, of 3.4E+20 cycles, the corresponding usage factor (U_1) for vibration is approximately 0.00. The summary results of vibration cycles are presented in Table 4-31.

$$U_2 = \frac{n_2}{N_2} = 0.00$$

4.5.2.6.1.3 Cumulative Usage Factor

Based on a weekly transport for five (5) years, the Model AOS-025A cask lid attachment bolts are expected to undergo 260 normal operating cycles and infinite (1.0×10^7) vibration cycles. The corresponding allowables are 1,313 normal operating cycles and 3.4E+20 vibration cycles. Under NCT, this analysis predicts that the Model AOS-025A cask lid attachment bolts can serve for five (5) years with a cumulative usage factor of 0.20, as documented in Table 4-31.

$$U = \frac{n_1}{N_1} + \frac{n_2}{N_2} = 0.20 + 0.00 = 0.20$$

Table 4-31. Model AOS-025A Cask Lid Attachment Bolt Fatigue Analysis Results

Parameter	Variable	Units	Normal Operation Cycles	Vibration Cycles	Total Usage Factor
Fatigue Strength Reduction Factor	RF	–	4	4	
Modulus of Elasticity Provided on Design Curve	E_{dc}	psi	3.00E+07	3.00E+07	
Modulus of Elasticity Used in Analysis	E_a	psi	2.80E+07	2.80E+07	
Ratio of Modulus of Elasticity	E_{dc} / E_a	–	1.07	1.07	
Direct Stress	σ	psi	11,045.8	32.3	
Shear Stress	τ	psi	34,827.2	16.1	
Maximum Principal Stress	S_1	psi	40,785.2	38.9	
Alternating Stress	S_a	psi	87,396.9	83.4	
Number of Usage Cycles	n	cycles	260	1.0E+07	
Maximum Allowable Number of Cycles	N	cycles	1,313	3.4E+20	
Usage Factor	U	–	0.20	0.00	0.20

4.5.2.6.2 Model AOS-050A Cask Lid Attachment Bolt Fatigue Analysis

The fatigue analysis identifies two stress cycles – Normal operation and vibration cycles. Normal operation loads include preload, temperature, and pressure. The vibration loads are documented based on the applied axial and transverse vibration acceleration loads.

4.5.2.6.2.1 Normal Operation Cycles

Fatigue due to operating loads is documented based on the maximum NCT cases. The direct stress is obtained by combining the axial and bending stresses. The shear stress is obtained by combining the average shear load and torsional bolt moment. The maximum principal stress (S_1) is calculated from the combined direct and shear stress. Summary of normal operation cycles is documented in Table 4-32.

$$S_1 = \frac{\sigma}{2} \pm \sqrt{\left(\frac{\sigma}{2}\right)^2 + \tau^2} = 42{,}333 \text{ psi}$$

where:

σ = $S_{ba} + S_{bb}$ = 22,551 psi (direct stress, Table 4-17)

τ = $S_{bs} + S_{bt}$ = 28,938 psi (shear stress, Table 4-17)

The corresponding alternating stresses (S_a) are calculated using a fatigue reduction factor (RF) of 4 **[4.12]** Also, because the fatigue curve (**[4.13]**, *ASME Section III*, *Figure I-9.4*) is based on a modulus of elasticity of 30 × 10^3 ksi, which is different than the modulus of elasticity of the bolt materials, a ratio of the modulus of elasticities is considered in calculating the alternating stress per **[4.12]**, *NB-3232.3*.

$$S_a = RF\left(\frac{S_1}{2}\right)\left(\frac{E_{dc}}{E_a}\right) = 91{,}365 \text{ psi}$$

where:

RF = 4, Fatigue strength reduction factor **[4.12]**

E_{dc} = 30 × 10^3 ksi, Modulus of elasticity on design fatigue curve **[4.13]**

E_a = 27.8 × 10^3 ksi, Modulus of elasticity of the bolt materials

Using the alternating stress calculated and the fatigue curve for a maximum nominal stress ≤ 2.7 S_m in **[4.13]**, *ASME Section III*, *Figure I-9.4*, the corresponding fatigue limits are calculated by interpolating the tabular data provided in **[4.13]**, *ASME Section III*, *Table I-9.0*. The estimated fatigue limit, N_1, for the 91.4 ksi alternating stress is 1,383 cycles. Based on a weekly transport for five (5) years, the number of normal operation cycles, n_1, is 52 cycles/year × 5 years = 260 cycles. The corresponding usage factor (U_1) for normal operating cycles is as follows:

$$U_1 = \frac{n_1}{N_1} = 0.19$$

where:

n_1 = 260 cycles, operating cycles

N_1 = 1,383 cycles, allowable cycles

4.5.2.6.2.2 Vibration Cycles

Fatigue due to vibration loads are documented based on the applied axial and transverse vibration acceleration loads. The maximum principal stress (S_1) is calculated from the combined direct and shear stress. Summary of vibration cycles is documented in Table 4-32.

$$S_1 = \frac{\sigma}{2} \pm \sqrt{\left(\frac{\sigma}{2}\right)^2 + \tau^2} = 119.1 \text{ psi}$$

where:

σ = S_{ba} = 1.2732 F_a / D^2 = 98.7 psi, direct stress

τ = S_{bs} = 1.2732 F_s / D^2 = 49.3 psi, shear stress

F_a = 14.00 lbs., axial load due to vibration (refer to Table 4-16)

F_s = 7.00 lbs., shear load due to vibration (refer to Table 4-16)

D = 0.425 in. (bolt diameter for tensile stress (D_{ba}); refer to Table 4-17)

The corresponding alternating stresses (S_a) are calculated using a fatigue reduction factor (RF) of 4 **[4.12]**. Also, because the fatigue curve (**[4.13]**, *ASME Section III*, *Figure I-9.4*) is based on a modulus of elasticity of 30 × 10^3 ksi, which is different than the modulus of elasticity of the bolt materials, a ratio of the modulus of elasticities is considered in calculating the alternating stress per **[4.12]**, *NB-3232.3*.

$$S_a = RF\left(\frac{S_1}{2}\right)\left(\frac{E_{dc}}{E_a}\right) = 257.0 \text{ psi}$$

where:

RF = 4, Fatigue strength reduction factor **[4.12]**

E_{dc} = 30 × 10^3 ksi, Modulus of elasticity on design fatigue curve **[4.13]**

E_a = 27.8 × 10^3 ksi, Modulus of elasticity of the bolt materials

Using the alternating stress calculated and the fatigue curve for a maximum nominal stress ≤ 2.7 S_m in **[4.13]**, *ASME Section III*, *Figure I-9.4*, the corresponding fatigue limits are calculated by interpolating the tabular data provided in **[4.13]**, *ASME Section III*, *Table I-9.0*. The estimated fatigue limit for the 0.26 ksi alternating stress is 2.1E+17 cycles. The vibration cycles are estimated based on an infinite cycle (1.0E+07). Using 1.0 × 10^7 vibration cycles, n_1, and maximum allowable cycles, N_1, of 2.1E+17 cycles, the corresponding usage factor (U_1) for vibration is approximately 0.00. The summary results of vibration cycles are presented in Table 4-32.

$$U_2 = \frac{n_2}{N_2} = 0.00$$

4.5.2.6.2.3 Cumulative Usage Factor

Based on a weekly transport for five (5) years, the Model AOS-050A cask lid attachment bolts are expected to undergo 260 normal operating cycles and infinite (1.0×10^7) vibration cycles. The corresponding allowables are 1,383 normal operating cycles and 2.1E+17 vibration cycles. Under NCT, this analysis predicts that the Model AOS-050A cask lid attachment bolts can serve for five (5) years with a cumulative usage factor of 0.19, as documented in Table 4-32.

$$U = \frac{n_1}{N_1} + \frac{n_2}{N_2} = 0.19 + 0.00 = 0.19$$

Table 4-32. Model AOS-050A Cask Lid Attachment Bolt Fatigue Analysis Results

Parameter	Variable	Units	Normal Operation Cycles	Vibration Cycles	Total Usage Factor
Fatigue Strength Reduction Factor	RF	–	4	4	
Modulus of Elasticity Provided on Design Curve	E_{dc}	psi	3.00E+07	3.00E+07	
Modulus of Elasticity Used in Analysis	E_a	psi	2.78E+07	2.78E+07	
Ratio of Modulus of Elasticity	E_{dc} / E_a	–	1.08	1.08	
Direct Stress	σ	psi	21,487.4	98.7	
Shear Stress	τ	psi	26,649.9	49.3	
Maximum Principal Stress	S_1	psi	42,333	119.1	
Alternating Stress	S_a	psi	91,365	257.0	
Number of Usage Cycles	n	cycles	260	1.0E+07	
Maximum Allowable Number of Cycles	N	cycles	1,383	2.1E+17	
Usage Factor	U	–	0.19	0.00	0.19

4.5.2.6.3 Model AOS-100A Cask Lid Attachment Bolt Fatigue Analysis

The fatigue analysis identifies two stress cycles – Normal operation and vibration cycles. Normal operation loads include preload, temperature, and pressure. The vibration loads are documented based on the applied axial and transverse vibration acceleration loads.

4.5.2.6.3.1 Normal Operation Cycles

Fatigue due to operating loads is documented based on the maximum NCT cases. The direct stress is obtained by combining the axial and bending stresses. The shear stress is obtained by combining the average shear load and torsional bolt moment. The maximum principal stress (S_1) is calculated from the combined direct and shear stress. Summary of normal operation cycles is documented in Table 4-33.

$$S_1 = \frac{\sigma}{2} \pm \sqrt{\left(\frac{\sigma}{2}\right)^2 + \tau^2} = 77{,}918.1 \text{ psi}$$

where:

σ = $S_{ba} + S_{bb}$ = 53,397 psi (direct stress, Table 4-22)

τ = $S_{bs} + S_{bt}$ = 43,712 psi (shear stress, Table 4-22)

The corresponding alternating stresses (S_a) are calculated using a fatigue reduction factor (RF) of 4 **[4.12]**. Also, because the fatigue curve (**[4.13]**, *ASME Section III*, *Figure I-9.4*) is based on a modulus of elasticity of 30 × 10^3 ksi, which is different than the modulus of elasticity of the bolt materials, a ratio of the modulus of elasticities is considered in calculating the alternating stress per **[4.12]**, *NB-3232.3*.

$$S_a = RF\left(\frac{S_1}{2}\right)\left(\frac{E_{dc}}{E_a}\right) = 168{,}168.6 \text{ psi}$$

where:

RF = 4, Fatigue strength reduction factor **[4.12]**

E_{dc} = 30 × 10^3 ksi, Modulus of elasticity on design fatigue curve **[4.13]**

E_a = 27.8 × 10^3 ksi, Modulus of elasticity of the bolt materials

Using the alternating stress calculated and the fatigue curve for a maximum nominal stress ≤ 2.7 S_m in **[4.13]**, *ASME Section III*, *Figure I-9.4*, the corresponding fatigue limits are calculated by interpolating the tabular data provided in **[4.13]**, *ASME Section III*, *Table I-9.0*. The estimated fatigue limit, N_1, for the 168.2 ksi alternating stress is 360 cycles. Based on a weekly transport for five (5) years, the number of normal operation cycles, n_1, is 52 cycles/year × 5 years = 260 cycles. The corresponding usage factor (U_1) for normal operating cycles is as follows:

$$U_1 = \frac{n_1}{N_1} = 0.72$$

where:

n_1 = 260 cycles, operating cycles

N_1 = 360 cycles, allowable cycles

4.5.2.6.3.2 Vibration Cycles

Fatigue due to vibration loads are documented based on the applied axial and transverse vibration acceleration loads. The maximum principal stress (S_1) is calculated from the combined direct and shear stress. Summary of vibration cycles is documented in Table 4-33.

$$S_1 = \frac{\sigma}{2} \pm \sqrt{\left(\frac{\sigma}{2}\right)^2 + \tau^2} = 196.1 \text{ psi}$$

where:

σ = S_{ba} = 1.2732 F_a / D^2 = 162.4 psi, direct stress

τ = S_{bs} = 1.2732 F_s / D^2 = 81.2 psi, shear stress

F_a = 75.00 lbs., axial load due to vibration (refer to Table 4-21)

F_s = 37.50 lbs., shear load due to vibration (refer to Table 4-21)

D = 0.767 in. (bolt diameter for tensile stress (D_{ba}); refer to Table 4-22)

The corresponding alternating stresses (S_a) are calculated using a fatigue reduction factor (RF) of 4 **[4.12]**. Also, because the fatigue curve (**[4.13]**, *ASME Section III*, *Figure I-9.4*) is based on a modulus of elasticity of 30 × 10^3 ksi, which is different than the modulus of elasticity of the bolt materials, a ratio of the modulus of elasticities is considered in calculating the alternating stress per **[4.12]**, *NB-3232.3*.

$$S_a = RF\left(\frac{S_1}{2}\right)\left(\frac{E_{dc}}{E_a}\right) = 423.2 \text{ psi}$$

where:

RF = 4, Fatigue strength reduction factor **[4.12]**

E_{dc} = 30 × 10^3 ksi, Modulus of elasticity on design fatigue curve **[4.13]**

E_a = 27.8 × 10^3 ksi, Modulus of elasticity of the bolt materials

Using the alternating stress calculated and the fatigue curve for a maximum nominal stress ≤ 2.7 S_m in **[4.13]**, *ASME Section III*, *Figure I-9.4*, the corresponding fatigue limits are calculated by interpolating the tabular data provided in **[4.13]**, *ASME Section III*, *Table I-9.0*. The estimated fatigue limit for the 0.4 ksi alternating stress is 7.8E+15 cycles. The vibration cycles are estimated based on an infinite cycle (1.0E+07). Using 1.0 × 10^7 vibration cycles, n_1, and maximum allowable cycles, N_1, of 7.8E+15, the corresponding usage factor (U_1) for vibration is approximately 0.00. The summary results of vibration cycles are presented in Table 4-33.

$$U_2 = \frac{n_2}{N_2} = 0.00$$

4.5.2.6.3.3 Cumulative Usage Factor

Based on a weekly transport for five (5) years, the Model AOS-100A cask lid attachment bolts are expected to undergo 260 normal operating cycles and infinite (1.0 × 10^7) vibration cycles. The corresponding allowables are 360 normal operating cycles and 7.82E+15 vibration cycles. Under NCT, this analysis predicts that the Model AOS-100A cask lid attachment bolts can serve for five (5) years with a cumulative usage factor of 0.72, as documented in Table 4-33.

$$U = \frac{n_1}{N_1} + \frac{n_2}{N_2} = 0.72 + 0.00 = 0.72$$

Table 4-33. Model AOS-100A Cask Lid Attachment Bolt Fatigue Analysis Results

Parameter	Variable	Units	Normal Operation Cycles	Vibration Cycles	Total Usage Factor
Fatigue Strength Reduction Factor	RF	–	4	4	
Modulus of Elasticity Provided on Design Curve	E_{dc}	psi	3.00E+07	3.00E+07	
Modulus of Elasticity Used in Analysis	E_a	psi	2.78E+07	2.78E+07	
Ratio of Modulus of Elasticity	E_{dc} / E_a	–	1.08	1.08	
Direct Stress	σ	psi	53,396.5	162.4	
Shear Stress	τ	psi	43,711.3	81.2	
Maximum Principal Stress	S_1	psi	77,918.1	196.1	
Alternating Stress	S_a	psi	168,168.6	423.2	
Number of Usage Cycles	n	cycles	260	1.0E+07	
Maximum Allowable Number of Cycles	N	cycles	360	7.8E+15	
Usage Factor	U	–	0.72	0.00	0.72

4.5.3 DELETED

CONTENT DELETED

4.6 REFERENCES

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

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

[4.4] American National Standards Institute, *ANSI N14.5-2014*, "Radioactive Materials – Leakage Tests on Packages for Shipment," June 19, 2014.

[4.5] American Society of Mechanical Engineers, *ASME Boiler and Pressure Vessel Code (BPVC)*, Section III, Division 1, 2004, No Addenda.

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[4.9] U.S. Nuclear Regulatory Commission (NRC), "Methods for Impact Analysis of Shipping Container," *NUREG/CR-3966*, November 1987.

[4.10] Blevins PhD, R. D., *Formulas for Natural Frequency and Mode Shape*, New York: Van Nostrand Reinhold Co., 1979.

[4.11] Oberg, E., F. D. Jones, H. L. Horton, H. H. Ryffell, and R. M. Heald, *Machinery's Handbook 26: A Reference Book for the Mechanical Engineer, Designer, Manufacturing Engineer, Draftsman, Toolmaker, and Machinist*, 26th Ed., New York: Industrial Press, Inc., 2000.

[4.12] American Society of Mechanical Engineers, *ASME Boiler and Pressure Vessel Code (BPVC),* Section III - Rules for Construction of Nuclear Facility Components - Division 1 - Subsection NB - Class 1 Components, 2004.

[4.13] American Society of Mechanical Engineers, *ASME Boiler and Pressure Vessel Code (BPVC)*, "Rules For Construction of Nuclear Facility Components," Section III, Division 1 – Appendices, 2004.

[4.14] Orano, TLI Engineering & Packaging Services Division, "Bolting Evaluation of AOS Transport Packages," *Calculation Note No. CN-15008-22-201 Rev. 1.v1*, June 9, 2023.

7 PACKAGE OPERATIONS

The information within this chapter provides the operations used to load the AOS Transport Packaging System and prepare it for transport. These operations describe the fundamental steps needed to ensure the requirements of this SAR. The transport packages should be operated using detailed written procedures that are based upon, and consistent with, the operations described in this chapter and the certification drawings listed in Table 1-5, "AOS Transport Packaging System Certification Drawing List – All Models." During actual operation, these procedures can be supplemented with engineering personnel, training classes, and/or site-specific procedures, as applicable.

Figure 7-1 and Figure 7-2 provide isometric views of Models AOS-025A and AOS-050A, respectively. Figure 7-3 provides an isometric view of Models AOS-100A and AOS-100B. Figure 7-3a provides an isometric view of Model AOS-100A-S.

Notes: *Unless indicated otherwise, all information related to the Model AOS-100A is also applicable to Models AOS-100B and AOS-100A-S.*

Package Operations as specified in this chapter also include the information specified by the certification drawings. (Refer to Table 1-5, "AOS Transport Packaging System Certification Drawing List – All Models.")

7.1 PACKAGE LOADING

Note: *The operational steps provided in this section apply to all AOS Radioactive Material Transport Packaging System models (Models AOS-025A, AOS-050A, AOS-100A, AOS-100B, and AOS-100A-S). Any step specific to a given Model is identified within the step.*

Part of the transport package loading preparation is to perform a Pre-Shipment Engineering Evaluation following *IAEA TS-R-1, Paragraph 502*, *10 CFR 71.87*, and *49 CFR 173.475* (References **[7.1]**, **[7.2]**, and **[7.3]**, respectively). The evaluation is used to ensure that the packaging, with its proposed contents, satisfies the applicable requirements of the transport package's license or certificate. This evaluation includes, but is not limited to, the review of the following:

- Proposed contents' isotopic composition, quantities, and decay heat;
- Proposed contents' form, weight, and geometry. If the content is defined as *Special form*, verify its certification from the competent authorities;
- Identify shoring device to be used. All structural shoring materials used within the cask cavity must have a melting point greater than (i) 600°F for Co-60 in metallic form and Cs-137 in the form of cesium chloride and (ii) 900°F for all other contents;
- Shielding requirements (use of additional shielding devices may be required for shipment);
- Structural requirements;
- Thermal requirements;
- Pressure requirements;
- Shipping hardware (such as liners, racks, dividers, baskets, and shoring devices);
- Maintenance records.
- Personnel qualification.
- Certification Drawing requirements.

In addition, operations at the loading facility must safely support a range of activities, from receiving and inspecting the package, to preparing the loaded transport package for shipment. Each loading facility must provide fully trained personnel and detailed operating procedures to cover these activities.

7.1.1 Preparation for Loading

7.1.1.1 Receiving and Inspecting the Empty Transport Package

To receive and inspect the empty transport package:

a. Position the transport vehicle in the Receiving Inspection area.

b. Visually inspect the transport package for damage and proper labeling and marking. Refer to the shipping paper for shipment category and compare the marking and labels on the package to the requirement of Reference **[7.3]**.

**Table 7-1. Additional Required Shielding –
Models AOS-025A, AOS-050A, AOS-100A, and AOS-100A-S**

Model	Component	Certification Drawing[a]	Comments
AOS-025A	Liner	183C8485	Shielding liner is mandatory for all contents. (Refer to the current revision of the current revision of the NRC Certificate of Compliance 9316.)
AOS-050A	Axial Shielding Plates[b]	183C8519	Used when shipping Ir-192 and Ir-194 isotopes. (Refer to the current revision of the NRC Certificate of Compliance 9316.)
AOS-100A AOS-100A-S	Axial Shielding Plates	183C8491	Used when additional shielding is required for Co-60. (Refer to the current revision of the current revision of the NRC Certificate of Compliance 9316.)
	Cavity Spacer Plates	183C8518	

a. *Refer to Table 1-5, "AOS Transport Packaging System Certification Drawing List – All Models," for drawing revision levels.*

b. *If the Model AOS-050A axial shielding plates include threaded screw holes, each hole must be filled with a setscrew during shipment.*

7.1.2.3 Installing the Cask Lid

Note: *Visually inspect the cask and lid sealing surfaces, as well as the cask lid seal to be used, for damage that can prevent proper sealing of the sealing joint. Refer to Subsection 8.2.2, "Leakage Tests [8.4]," for detailed inspection of these items. If the metallic cask lid seal is replaced, prior to the shipment of Normal Form material, a Maintenance Test must be performed, in accordance with ANSI N14.5 (Reference* **[7.8]***). The elastomeric seal option is acceptable for use only with Special Form contents, in which the cask contents provide containment for the radioactive contents.*

To install the cask lid, after verifying that the cask lid seal is properly installed, use proper rigging to slowly lower the cask lid onto the cask. Carefully monitor this operation to ensure that the cask lid is properly aligned. During the placement of the cask lid, two lid guide pins may be installed in the cask lid threaded holes perpendicular to each other to maintain alignment of the cask lid attachment bolt holes with the cask lid threaded holes.

The cask lid attachment bolts must be lubricated with a lubricant such as Neolube No. 2 (note that the lubricant must be approved by AOS).

7.1.3 Preparation for Transport

7.1.3.1 Securing the Cask Lid

To secure the cask lid, in preparation for transport:

Note: *Torque sequence is stamped on top surface of the cask lid, about the bolt location.*

a. Lubricate the cask lid attachment bolts with a lubricant such as Neolube No. 2. The lubricant must be approved by AOS. In the case of wet loading, the lubricant must be applied after the cask has been removed from the pool and dried.

b. Torque the cask lid attachment bolts (refer to Table 7-2), using one of the two conditions listed below.

   1. **If the cask was dry loaded** – Torque the cask lid attachment bolts in a crisscross pattern, with a final pass all the way around, to ensure even seal compression after the elastomeric seal has been visually inspected and installed, –or– a new metallic seal has been installed.

   2. **If the cask was wet loaded** – To torque the cask lid attachment bolts:

      a. Install the cask lid and a minimum of at least five (5) bolts in the cask lid, as the cask breaks the water's surface. Note that this step may be skipped with the approval of Radiation Protection.

      b. Drain the cask over the pool area. After the water has drained from the cask, move the cask to the decontamination pad.

      c. Remove the bolts (previously installed for the transfer) and cask lid.

      d. Dry the cask lid attachment bolts and then lubricate with a lubricant such as Neolube No. 2.

      e. Dry the sealing surfaces and the bolt threaded holes.

      f. Install the cask lid elastomeric seal after it has been visually inspected, –or– a new cask lid metallic seal onto the cask lid, then re-install the bolts and torque the cask lid attachment bolts in a crisscross pattern, with a final pass all the way around, to ensure even seal compression.

Note: *For shipments of Special Form material, a Maintenance Leak test is not necessary after replacing a cask lid elastomeric seal, provided that a Periodic Leak test has been performed on the cask's containment system within the past 12 months.*

Table 7-2. Cask Lid Attachment Bolt Size and Preload Torque – All Models[a]

Model	Function	Bolt Size / ASME and ANSI Standards	Preload Torque	
			N-m	ft-lb
AOS-025	Cask Lid Attachment Bolt	3/8-16 UNC-2A / ASME SB-637, UNS N07718	39 to 47	29 to 35
AOS-050		1/2-13 UNC-2A / ASME SB-637, UNS N07718	85 to 92	62.5 to 68
AOS-100		7/8-9 UNC-2A / ASME SB-637, UNS N07718	542 to 678	400 to 500

a. Refer to Table 1-5, "AOS Transport Packaging System Certification Drawing List – All Models."

Figure 7-4 illustrates a typical Leak testing setup (vacuum drying system and its basic components) that can be used for all AOS Radioactive Material Transport Packaging System models (Models AOS-025A, AOS-050A, AOS-100A, AOS-100B, and AOS-100A-S).

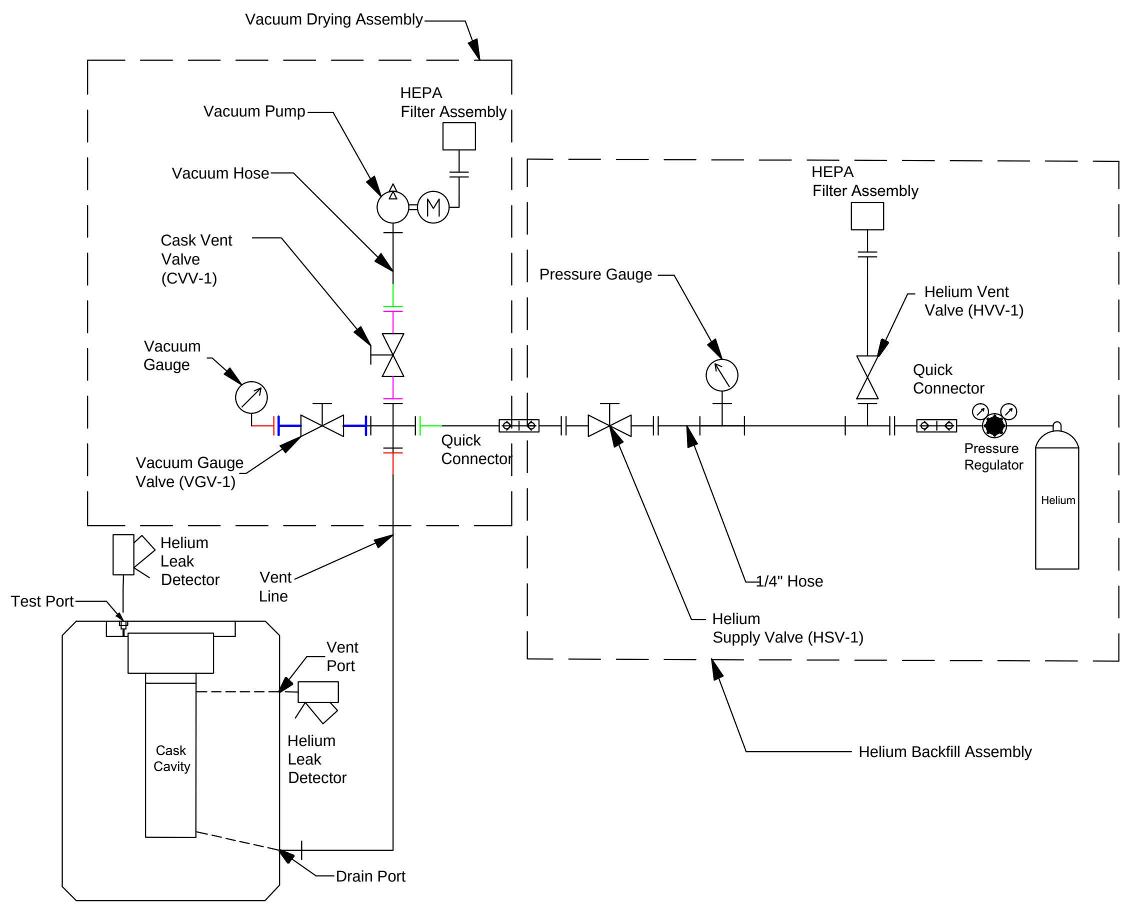

Figure 7-4. Typical Vacuum Drying System Setup and Equipment

8.1.1 Visual Inspections and Measurements

Visual examinations of all component surfaces, including welds and dimensional inspections, are conducted during packaging fabrication. These inspections, as well any other NDE inspections, are conducted according to approved written procedures. Their objectives are to identify harmful discontinuities or indications (such as overlaps, seams, cracks, porosity, crevices, and excessive oxidation), and to verify that the component or item critical dimensions are met, as specified in the certification drawings. (Refer to Table 1-5, "AOS Transport Packaging System Certification Drawing List – All Models," for a complete list.)

Visual and dimensional inspection results are recorded in accordance with the Purchaser's approved Quality Assurance and Fabrication plan. Refer to Subsection 2.3.2, "Examination," for additional details.

8.1.2 Weld Examinations

All welds within the cask component and impact limiters are visually inspected and liquid-penetrant tested (root and final passes). Also, the weld within the containment boundary must be ultrasonically examined and liquid-penetrant tested. These inspections are conducted to ensure that no cracks, incomplete fusion, nor lack of penetration exist. Parts that do not meet the established criteria are repaired or replaced, in accordance with written procedures issued by the Fabricator and approved by AOS.

The Model AOS-025, AOS-050, and AOS-100 transport packages use an ASME Code corner type C weld. This weld configuration is presented in Figure 4-2, "Typical Corner Cask Cavity Shell Weld Joint Configuration – All Models."

8.1.3 Structural and Pressure Tests

In addition to the test described in Subsection 8.1.2, the cask cavity is hydrostatically tested, to verify that the containment boundary can support the Design Pressure, per the requirements of NB6200, Subsection NB, Section III, of the ASME Code **[8.2]**. The Test Pressure is 1.5 times (1.5x) the Design Pressure. If this test were to fail, each component of the containment boundary must be evaluated and replaced, if necessary.

Table 8-2. Type 304 and 316 Material Requirements (Continued)

Definition	Requirements	Test Frequency	Remarks
Sensitization Test	ASTM A262 Practice A - Modified – Material having ditching greater than 5% is unacceptable. Can be waived by AOS for material not exposed to reactor water environments at elevated temperatures for extended periods of time.	**Inventory Material** – 10% of Supplied Pieces **New Material** – One per Heat and Heat Treat Lot	After final solution heat treatment
Intergranular Attack	Surface sample after pickling or if pickling is not used after final heat treatment – IGA or pitting in excess of 0.025 mm (0.001 in.) deep is unacceptable.	**Inventory Material** – 10% of Supplied Pieces **New Material** – One per Heat and Heat Treat Lot	After final solution heat treatment and oxide removal (if applicable)
Non-Destructive Examination	As required by the Base Specification and/or applicable ASME Section III requirements (Reference [8.2]).	100%	–

a. Nitrogen can be added, as necessary (up to the limits of the Base Specification), to achieve mechanical properties.

Table 8-4. Casting Pipe/Casting Material Requirements (Type CPF-8, CF-8)

Definition	Requirements	Test Frequency	Remarks
Base Specification			
Suffix T	ASME SA-451/ASTM A 451 Grade CPF8	–	Cast Pipe
Suffix U	ASME SA-351/ASTM A 351 Grade CF8	–	Casting
Chemistry Modification	As required by the ASME Specification.	One Chemical Analysis Required per Heat	–
Ferrite Content	Controlled within the allowable limits of the Base Specification, to produce a minimum ferrite content of 5%, as determined magnetically by Practice ASTM A800, S1.	One Analysis Required per Heat and Heat Treat Lot	Ferrite to be measured on an actual casting, after final solution heat treatment
Heat Treatment	Solution Heat Treat at 1,066 to 1,149°C (1,950 to 2,100°F) for 15 minutes/25 mm (15 minutes/1 in.) of thickness, but not less than 15 minutes, in accordance with the Base Specification.	One per Heat and Heat Treat Lot	Certification Statement
Mechanical Tests	Properties at Room Temperature, as required by the Base Specification.	One per Heat and Heat Treat Lot	After final solution heat treatment
Hardness Test	As required by the Base Specification.	One per Heat and Heat Treat Lot	After final solution heat treatment
Sensitization Test	Not required.	–	–
Intergranular Attack (IGA)	Surface sample after pickling or if pickling is not used after final heat treatment. IGA or pitting in excess of 0.025 mm (0.001 in.) deep is unacceptable.	**Inventory Material** – 10% of Supplied Pieces **New Material** – One per Heat and Heat Treat Lot	After final solution heat treatment and oxide removal (if applicable)
Non-Destructive Examination	As required by the Base Specification, Radiography per NB-2575, and additional applicable requirements of ASME Section III (Reference [8.2]).	100%	–
Weld Repair	Procedures require AOS approval prior to performance of the repair work. Repairs to castings subsequent to solution annealing must be documented and submitted to AOS.	–	Buyer approval required for repair procedure

Table 8-5. LAST-A-FOAM FR-3700 Series Foams – Testing Program

Type of Test[a]	Test Description	Applicable Reference	Number of Samples	Nominal Value	Tolerance (of Nominal)	Sample size (in.)
Formulation	Density, pcf	ASTM D1622-03	3	18, 8, and 11[b]	Each ±15% Increment ±10%	2 × 2 × 1
	Static Crush Strength, psi[c]	General Plastics Manufacturing Company, TM-9704, Rev. K	3[d]	Report Value	Report Value	1 × 1 × 1 and 2 × 2 × 2
	Flame Retardancy	ASTM D1622-03	3	Burn length ≤ 6 in.	–	0.5 × 3 × 6
	Intumescence	General Plastics Manufacturing Company, 9952037-00 and TM-9704, Rev. K	2	50%	Minimum	2 × 2 × 2
	Leachable Chlorides	General Plastics Manufacturing Company, GP-TM9510, Rev. B and EPA 300.0	1	1 ppm	< 1 ppm	2 × 2 × 2
	Thermal Conductivity, Btu-in/(ft^2-°F-h)	ASTM D1622-03	1	0.349	Each ±15%	8.0 diameter × 1.0 L
	Specific Heat, Btu/lb-°F	ASTM E1269-05	1	0.351	Each ±20%	As Required
	Water Absorption	ASTM E1269-05	3	0.05 lbs. of water per ft^2 in 96 hours	Not to exceed nominal	6 × 6 × 3
	Chemical Composition	–	1 per formulation	Report Value	Report Value	As Required

Table 8-5. LAST-A-FOAM FR-3700 Series Foams – Testing Program (Continued)

Type of Test[a]	Test Description	Applicable Reference	Number of Samples	Nominal Value	Tolerance (of Nominal)	Sample size (in.)
Batch	Density, pcf	ASTM D1622-03	3	18, 8, and 11[b]	Each ±15% Increment ±10%	2 × 2 × 1
	Static Crush Strength, psi[e]	General Plastics Manufacturing Company, TM-9704, Rev. K	3[f]	General Plastics Manufacturing Company, Technical Specification	Increment ±15%	2 × 2 × 1
	Flame Retardancy	14CFR14.25.853	3	Burn length ≤ 6 in.	–	0.5 × 3 × 6
	Intumescence	General Plastics Manufacturing Company, 9952037-00 and GP-TM9510, Rev. B	3	50%	Minimum	2 × 2 × 2
	Leachable Chlorides	General Plastics Manufacturing Company, GP-TM9510, Rev. B & EPA 300.0	2	1 ppm	< 1 ppm	2 × 2 × 2
Pour	Static Crush Strength, psi[e]	General Plastics Manufacturing Company, TM-9704, Rev. K	3[f]	General Plastics Manufacturing Company, Technical Specification	Increment ±15%	2 × 2 × 1
	Density, pcf	ASTM D1622-03	3	18, 8, and 11[b]	Each ±15% Increment ±10%	2 × 2 × 1

a. *Formulation tests are conducted upon initial order or formulation change. Batch tests are conducted upon each batch required to fulfill each impact limiter. Pour tests are conducted upon each pour of every batch.*

b. *Density nominal values of 18, 8, and 11 pcf are associated with the Model AOS-025, AOS-050, and AOS-100, respectively.*

c. *The foam manufacturer will perform the Static Crush Strength test. In addition, a dynamic test will be performed by an independent testing laboratory as part of the Dedication Process toward a safety "Category A." The dynamic test shall be per ASTM D1621-10, and will follow the recommendation of this Standard, with the exception of the strain rate. The test will use a controlled dynamic strain rate of 60s^{-1}. The values obtained from this test must be less than or equal to the corresponding values in Table 8-6 and Table 8-7.*

d. *Three (3) samples are tested at -40, 75, and 250°F, at strains of 10, 40, and 60% in each direction; Parallel to Direction of Rise and Perpendicular to Direction of Rise.*

e. *Strain Rate value for this test is approximately 0.14 in./min. Each sample shall meet the tolerance for the indicated test. In cases where multiple samples are taken, the indicated tolerance applies to the numerical average result of the samples. For example, the results of each Static Crush test must be ±20% of the nominal value, and the average of the three samples must be ±15% of the nominal value.*

f. *Three (3) samples are tested at 75°F, at strains of 10, 40, and 60% in each direction; Parallel to Direction of Rise and Perpendicular to Direction of Rise.*

8.4 REFERENCES

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

[8.2] American Society of Mechanical Engineers, *ASME Boiler and Pressure Vessel Code (BPVC)*, Section III, Division 1, 2004, No Addenda.

[8.3] DELETED.

[8.4] American National Standards Institute, *ANSI N14.5-2014*, “Radioactive Materials – Leakage Tests on Packages for Shipment,” June 19, 2014.

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

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[8.7] NUREG/CR-6407, *Classification of Transportation Packaging and Dry Spent Fuel Storage System Components According to Importance to Safety,* Idaho National Engineering Laboratory, Idaho Falls, Idaho, February, 1996.

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