

3.5.2.3 Hypothetical Accident Conditions of Transport Results – Model AOS-165

Table 3-88 lists the tables and figures in this appendix that present the Model AOS-165 transport package results under Hypothetical Accident conditions of transport, for Load Cases 111 through 116. Each table provides a list of temperatures at each monitoring node. Also listed are the maximum temperatures within each transport package component.

Table 3-89 lists the temperature monitoring points (nodes) for the Model AOS-165 transport package, under Normal and Hypothetical Accident (Fire) conditions of transport. Figure 3-118 illustrates the location of each node on the transport package, under Fire conditions.

Table 3-88. Hypothetical Accident Conditions of Transport Results – Model AOS-165

Load Case	Description	Results Table	Temperature versus Time	Entire Model	Cask Model
111	Fire at 30 Minutes, 1,475°F Ambient, Maximum Decay Heat	Table 3-90	Figure 3-119	Figure 3-120	Figure 3-121
112	Fire at 60 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation	Table 3-91	-	Figure 3-122	Figure 3-123
113	Fire at 90 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation	Table 3-92	-	Figure 3-124	Figure 3-125
114	Fire at 120 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation	Table 3-93	-	Figure 3-126	Figure 3-127
115	Fire at 150 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation	Table 3-94	-	Figure 3-128	Figure 3-129
116	Fire at 180 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation	Table 3-95	-	Figure 3-130	Figure 3-131

Table 3-89. Temperature Monitoring Points, All Conditions of Transport – Model AOS-165

Nodal Location	LIBRA Model Nodal Number	
	Normal Conditions	Fire Conditions
1	5001	5001
2	4532	4532
3	4227	4227
4	4752	4752
5	4838	4838
6	4995	4995
7	3309	3309
8	3419	3419
9	678	678
10	2537	2537
11	1888	1888
12	583	583
13	3001	3001
14	3148	3148
15	7533	7533
16	7377	7377
17	7371	7371
18	6942	6942
19	6267	6267
20	6121	6121
21	6001	6001
22	9501	15481
23	9950	16630
24	10014	16694
25	10781	18111
26	9091	1153
27	8463	9785
28	8462	9571
29	8197	8197
30	9711	15451
31	9821	15961
32	10158	17032
33	10605	17743
34	9102	11051
35	8578	9900
36	8225	8673
37	8001	8225

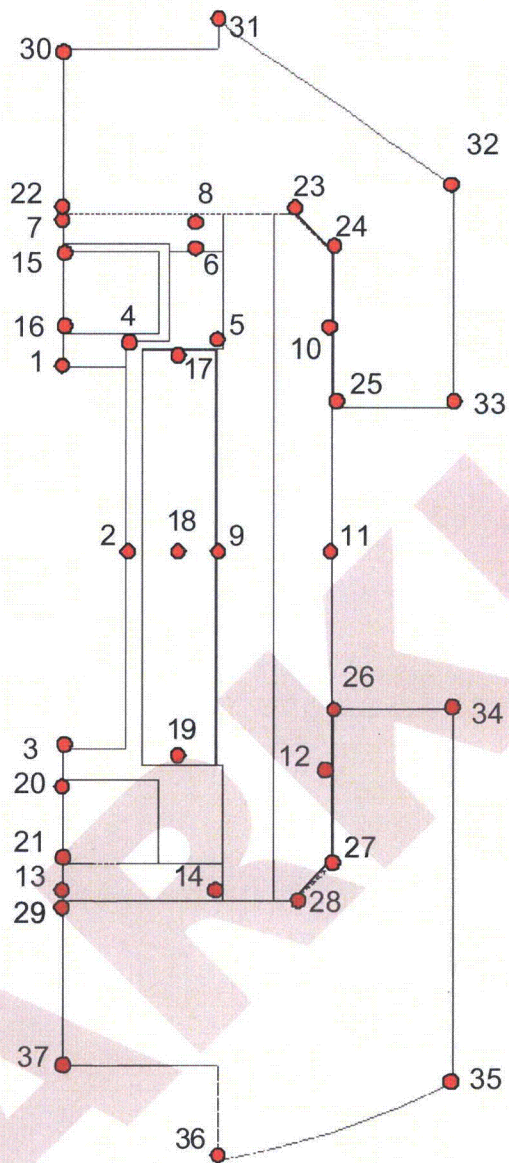


Figure 3-118. Selected Nodal Locations for Fire Conditions of Transport – Model AOS-165

Table 3-90. Load Case 111 – Fire at 30 Minutes, 1,475°F Ambient, Maximum Decay Heat – Model AOS-165

Location	Node	Temp (C)	Temp (F)
-----	----	-----	-----
1	5001	376.56	709.80
2	4532	348.89	660.00
3	4227	363.56	686.40
4	4752	333.89	633.00
5	4838	303.44	578.20
6	4995	301.28	574.30
7	3309	308.28	586.90
8	3419	301.28	574.30
9	678	310.44	590.80
10	2537	300.39	572.70
11	1888	522.44	972.40
12	583	300.61	573.10
13	3001	307.11	584.80
14	3148	299.11	570.40
15	7533	319.83	607.70
16	7377	325.67	618.20
17	7371	312.33	594.20
18	6942	315.17	599.30
19	6267	312.61	594.70
20	6121	315.56	600.00
21	6001	310.61	591.10
22	15481	307.89	586.20
23	16630	291.61	556.90
24	16694	287.39	549.30
25	18111	652.22	1206.00
26	11531	651.11	1204.00
27	9785	289.56	553.20
28	9571	293.56	560.40
29	8197	306.83	584.30
30	15451	791.11	1456.00
31	15961	798.33	1469.00
32	17022	793.33	1460.00
33	17743	795.56	1464.00
34	11051	797.22	1467.00
35	9900	795.56	1464.00
36	8673	797.22	1467.00
37	8225	793.89	1461.00

Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp (C)	Max_Temp (F)
Outside Shell	101	2894	1855	5.2244E+02	9.7240E+02
Bottom Plate	3001	3232	3120	3.0844E+02	5.8720E+02
Lid	3233	3424	3233	3.0944E+02	5.8900E+02
Shell Cavity	4001	4998	4227	3.6356E+02	6.8640E+02
Plug	5001	5404	5001	3.7656E+02	7.0980E+02
Tungsten Alloy	6001	7656	7377	3.2567E+02	6.1820E+02
LAST-A-FOAM	8001	18126	15929	7.9833E+02	1.4690E+03

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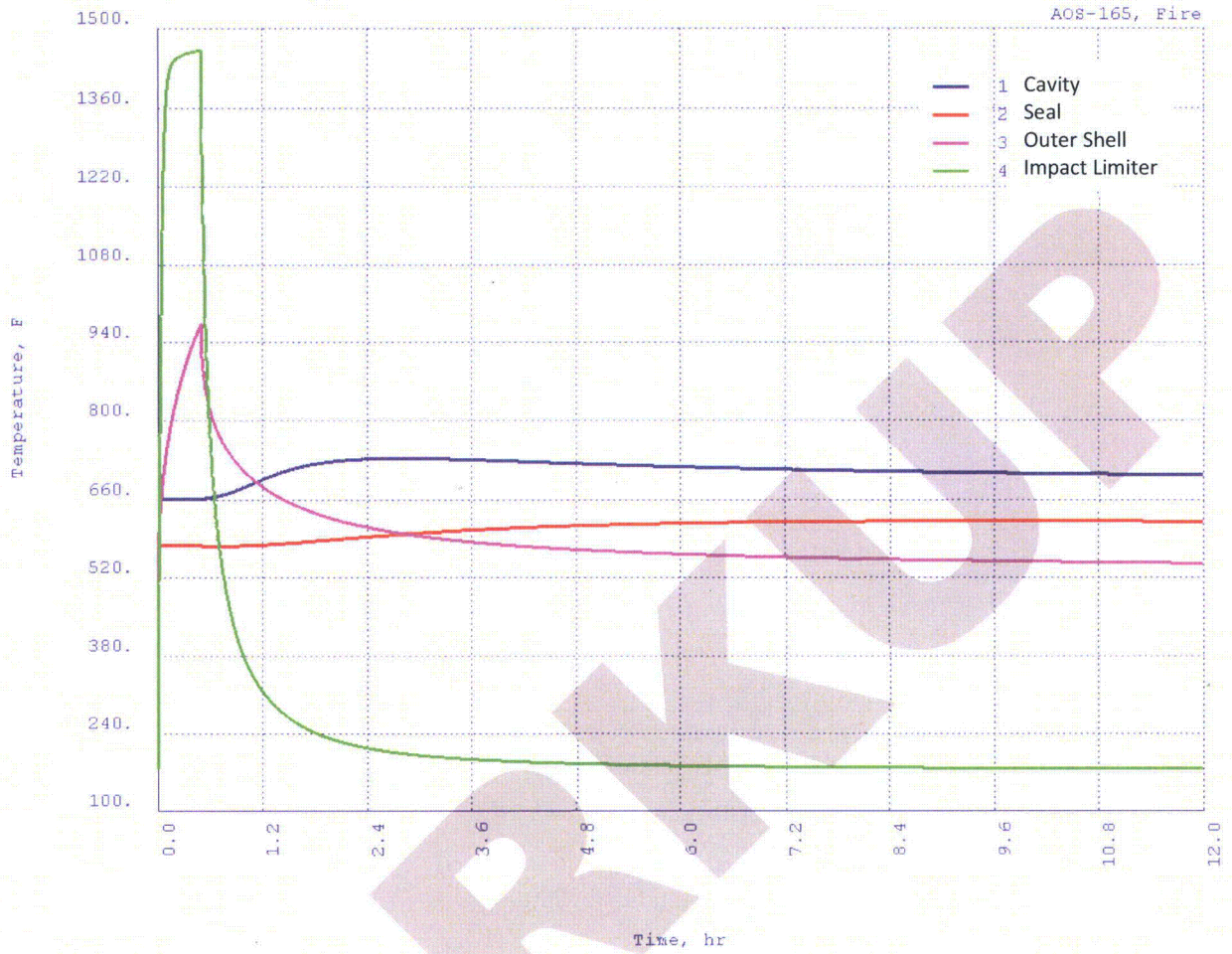


Figure 3-119. Load Case 111 – Fire at 30 Minutes, 1,475°F Ambient, Maximum Decay Heat, Temperature versus Time – Model AOS-165

VECTOR 1
 MIN 1.6947E+02
 MAX 1.4694E+03

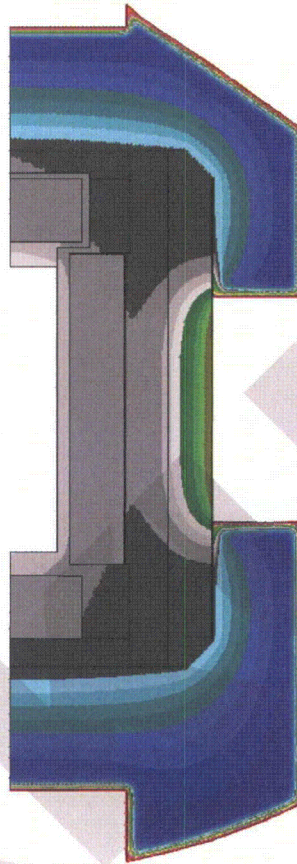
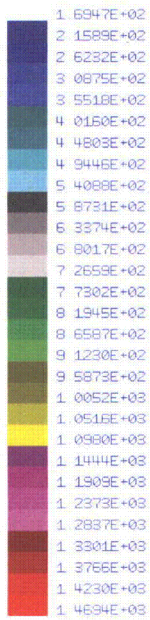


Figure 3-120. Load Case 111 – Fire at 30 Minutes, 1,475°F Ambient, Maximum Decay Heat, Entire Model – Model AOS-165

VECTOR: 1
MIN: 5.5632E+02
MAX: 9.7242E+02

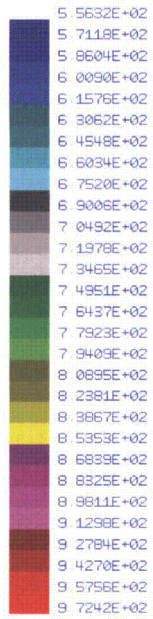


Figure 3-121. Load Case 111 – Fire at 30 Minutes, 1,475°F Ambient, Maximum Decay Heat, Cask Model – Model AOS-165

Table 3-91. Load Case 112 – Fire at 60 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation – Model AOS-165

Location	Node	Temp (C)	Temp (F)
1	5001	376.94	710.50
2	4532	360.33	680.60
3	4227	364.39	687.90
4	4752	337.00	638.60
5	4838	310.11	590.20
6	4995	301.83	575.30
7	3309	308.28	586.90
8	3419	301.39	574.50
9	678	340.89	645.60
10	2537	313.39	596.10
11	1888	374.83	706.70
12	583	313.61	596.50
13	3001	307.17	584.90
14	3148	299.50	571.10
15	7533	320.06	608.10
16	7377	325.94	618.70
17	7371	322.06	611.70
18	6942	333.00	631.40
19	6267	322.06	611.70
20	6121	316.11	601.00
21	6001	311.00	591.80
22	15481	307.89	586.20
23	16630	292.50	558.50
24	16694	289.83	553.70
25	18111	267.56	513.60
26	11531	263.94	507.10
27	9785	292.22	558.00
28	9571	294.61	562.30
29	8197	306.83	584.30
30	15451	192.56	378.60
31	15961	196.06	384.90
32	17022	188.83	371.90
33	17743	182.50	360.50
34	11051	172.78	343.00
35	9900	181.28	358.30
36	8673	194.78	382.60
37	8225	183.56	362.40

Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp (C)	Max_Temp (F)
Outside Shell	101	2894	1884	3.8061E+02	7.1710E+02
Bottom Plate	3001	3232	3120	3.0856E+02	5.8740E+02
Lid	3233	3424	3233	3.0944E+02	5.8900E+02
Shell Cavity	4001	4998	4227	3.6439E+02	6.8790E+02
Plug	5001	5404	5001	3.7694E+02	7.1050E+02
Tungsten Alloy	6001	7656	6432	3.3572E+02	6.3630E+02
LAST-A-FOAM	8001	18126	15841	3.6828E+02	6.9490E+02

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VECTOR: 1
MIN: 1.7824E+02
MAX: 7.1711E+02

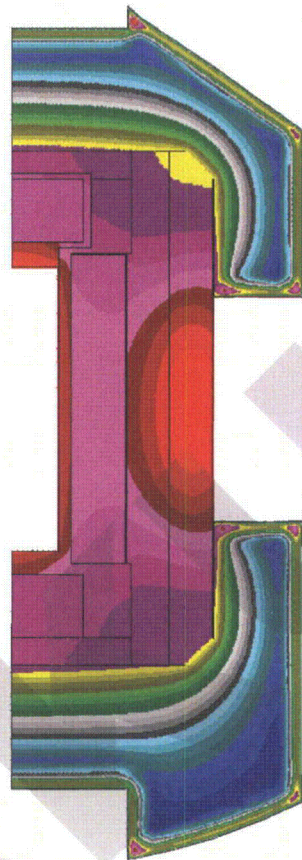
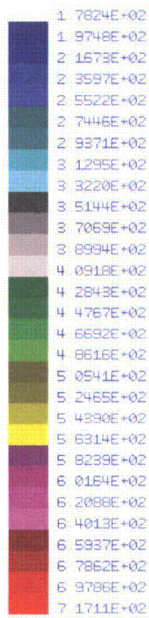


Figure 3-122. Load Case 112 – Fire at 60 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Entire Model – Model AOS-165

VECTOR: 1
MIN: 5.6055E+02
MAX: 7.1711E+02

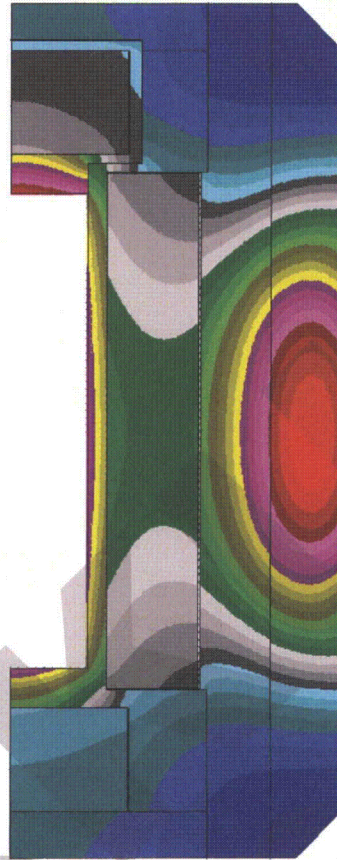
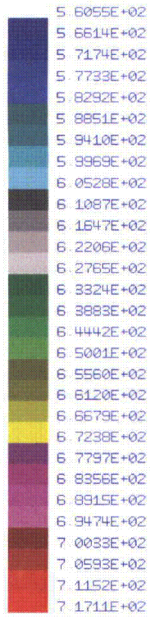


Figure 3-123. Load Case 112 – Fire at 60 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Cask Model – Model AOS-165

Table 3-92. Load Case 113 – Fire at 90 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation – Model AOS-165

Location	Node	Temp (C)	Temp (F)
-----	-----	-----	-----
1	5001	379.28	714.70
2	4532	376.56	709.80
3	4227	368.44	695.20
4	4752	343.89	651.00
5	4838	317.56	603.60
6	4995	304.22	579.60
7	3309	308.44	587.20
8	3419	302.39	576.30
9	678	349.61	661.30
10	2537	313.78	596.80
11	1888	345.22	653.40
12	583	314.50	598.10
13	3001	307.72	585.90
14	3148	301.39	574.50
15	7533	321.33	610.40
16	7377	327.61	621.70
17	7371	333.39	632.10
18	6942	347.61	657.70
19	6267	333.00	631.40
20	6121	318.94	606.10
21	6001	313.11	595.60
22	15481	308.06	586.50
23	16630	295.61	564.10
24	16694	293.83	560.90
25	18111	235.17	455.30
26	11531	233.28	451.90
27	9785	296.28	565.30
28	9571	297.89	568.20
29	8197	307.33	585.20
30	15451	129.83	265.70
31	15961	133.33	272.00
32	17022	130.61	267.10
33	17743	124.00	255.20
34	11051	116.06	240.90
35	9900	124.33	255.80
36	8673	135.11	275.20
37	8225	121.67	251.00

Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp (C)	Max_Temp (F)
Outside Shell	101	2894	1884	3.8061E+02	7.1710E+02
Bottom Plate	3001	3232	3120	3.0856E+02	5.8740E+02
Lid	3233	3424	3233	3.0944E+02	5.8900E+02
Shell Cavity	4001	4998	4227	3.6439E+02	6.8790E+02
Plug	5001	5404	5001	3.7694E+02	7.1050E+02
Tungsten Alloy	6001	7656	6432	3.3572E+02	6.3630E+02
LAST-A-FOAM	8001	18126	15841	3.6828E+02	6.9490E+02

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VECTOR 2
 MIN 1.8533E+02
 MAX 7.1469E+02

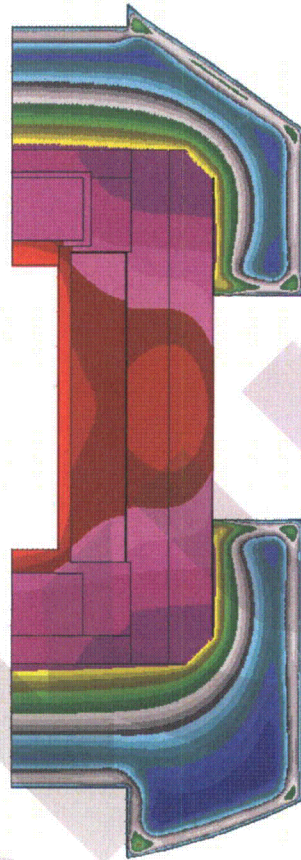
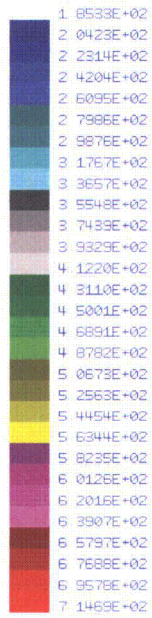


Figure 3-124. Load Case 113 – Fire at 90 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Entire Model – Model AOS-165

VECTOR: 2
MIN: 5.6674E+02
MAX: 7.1469E+02

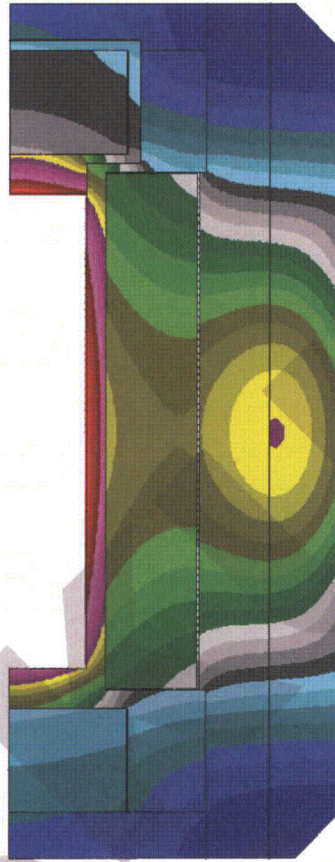
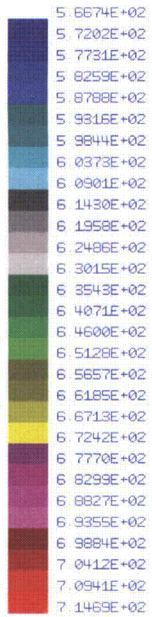


Figure 3-125. Load Case 113 – Fire at 90 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Cask Model – Model AOS-165

Table 3-93. Load Case 114 – Fire at 120 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation – Model AOS-165

Location	Node	Temp (C)	Temp (F)
1	5001	383.17	721.70
2	4532	384.94	724.90
3	4227	374.11	705.40
4	4752	349.72	661.50
5	4838	322.56	612.60
6	4995	307.67	585.80
7	3309	309.22	588.60
8	3419	304.56	580.20
9	678	349.94	661.90
10	2537	313.44	596.20
11	1888	328.78	623.80
12	583	314.33	597.80
13	3001	309.50	589.10
14	3148	304.39	579.90
15	7533	323.94	615.10
16	7377	330.61	627.10
17	7371	339.89	643.80
18	6942	353.50	668.30
19	6267	339.28	642.70
20	6121	323.17	613.70
21	6001	316.67	602.00
22	15481	308.78	587.80
23	16630	299.33	570.80
24	16694	297.39	567.30
25	18111	223.78	434.80
26	11531	222.72	432.90
27	9785	299.83	571.70
28	9571	301.61	574.90
29	8197	309.00	588.20
30	15451	105.33	221.60
31	15961	109.50	229.10
32	17022	109.22	228.60
33	17743	102.78	217.00
34	11051	96.72	206.10
35	9900	104.28	219.70
36	8673	113.22	235.80
37	8225	98.83	209.90

Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp (C)	Max_Temp (F)
Outside Shell	101	2894	1884	3.8061E+02	7.1710E+02
Bottom Plate	3001	3232	3120	3.0856E+02	5.8740E+02
Lid	3233	3424	3233	3.0944E+02	5.8900E+02
Shell Cavity	4001	4998	4227	3.6439E+02	6.8790E+02
Plug	5001	5404	5001	3.7694E+02	7.1050E+02
Tungsten Alloy	6001	7656	6432	3.3572E+02	6.3630E+02
LAST-A-FOAM	8001	18126	15841	3.6828E+02	6.9490E+02

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VECTOR 3
 MIN 1 9914E+02
 MAX 7 2491E+02

1	9914E+02
2	1792E+02
2	3669E+02
2	5547E+02
2	7425E+02
2	9303E+02
3	1180E+02
3	3058E+02
3	4936E+02
3	6814E+02
3	8691E+02
4	0569E+02
4	2447E+02
4	4325E+02
4	6202E+02
4	8080E+02
4	9958E+02
5	1836E+02
5	3714E+02
5	5591E+02
5	7469E+02
5	9347E+02
6	1225E+02
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6	4980E+02
6	6858E+02
6	8736E+02
7	0613E+02
7	2491E+02

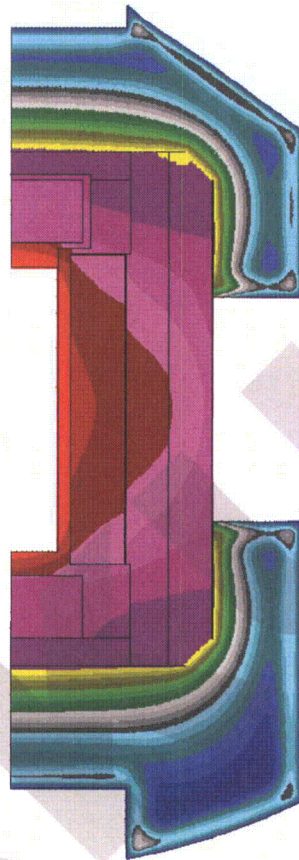


Figure 3-126. Load Case 114 – Fire at 120 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Entire Model – Model AOS-165

VECTOR: 3
MIN: 5 7353E+02
MAX: 7 2491E+02

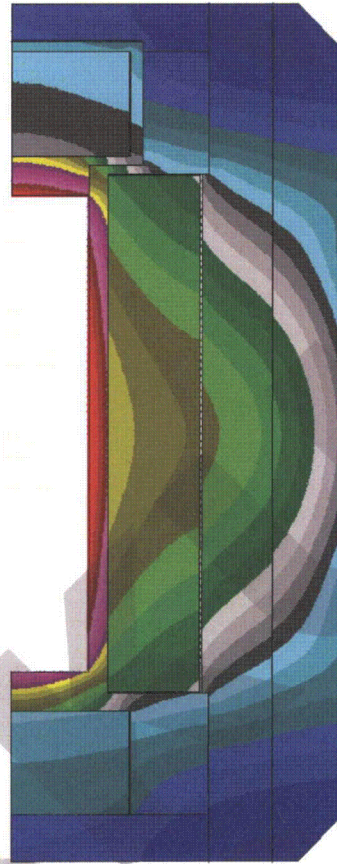
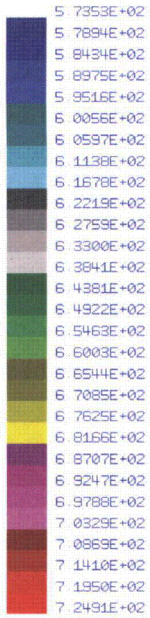


Figure 3-127. Load Case 114 – Fire at 120 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Cask Model – Model AOS-165

Table 3-94. Load Case 115 – Fire at 150 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation – Model AOS-165

Location	Node	Temp (C)	Temp (F)
1	5001	387.06	728.70
2	4532	387.78	730.00
3	4227	378.94	714.10
4	4752	353.61	668.50
5	4838	325.61	618.10
6	4995	311.17	592.10
7	3309	310.94	591.70
8	3419	307.39	585.30
9	678	348.00	658.40
10	2537	313.17	595.70
11	1888	318.39	605.10
12	583	314.22	597.60
13	3001	312.39	594.30
14	3148	307.61	585.70
15	7533	327.11	620.80
16	7377	334.00	633.20
17	7371	342.89	649.20
18	6942	354.94	670.90
19	6267	342.28	648.10
20	6121	327.28	621.10
21	6001	320.50	608.90
22	15481	310.44	590.80
23	16630	302.61	576.70
24	16694	300.22	572.40
25	18111	218.06	424.50
26	11531	217.50	423.50
27	9785	302.67	576.80
28	9571	304.89	580.80
29	8197	311.78	593.20
30	15451	93.33	200.00
31	15961	98.06	208.50
32	17022	98.94	210.10
33	17743	92.67	198.80
34	11051	87.89	190.20
35	9900	95.00	203.00
36	8673	102.78	217.00
37	8225	88.11	190.60

Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp (C)	Max_Temp (F)
Outside Shell	101	2894	1884	3.8061E+02	7.1710E+02
Bottom Plate	3001	3232	3120	3.0856E+02	5.8740E+02
Lid	3233	3424	3233	3.0944E+02	5.8900E+02
Shell Cavity	4001	4998	4227	3.6439E+02	6.8790E+02
Plug	5001	5404	5001	3.7694E+02	7.1050E+02
Tungsten Alloy	6001	7656	6432	3.3572E+02	6.3630E+02
LAST-A-FOAM	8001	18126	15841	3.6828E+02	6.9490E+02

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VECTOR: 4
 MIN: 1.9009E+02
 MAX: 7.3005E+02

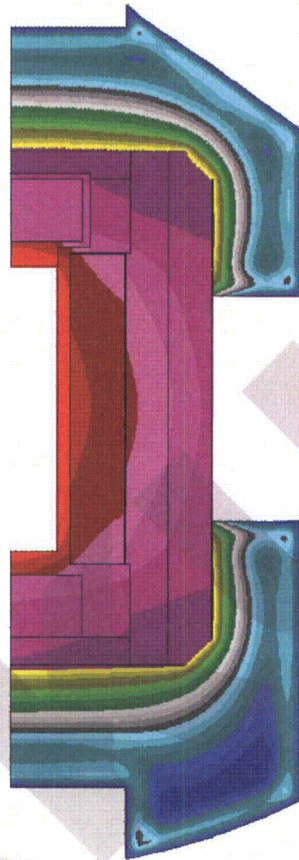
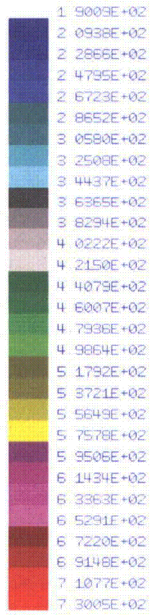


Figure 3-128. Load Case 115 – Fire at 150 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Entire Model – Model AOS-165

VECTOR: 4
MIN: 5.7942E+02
MAX: 7.3005E+02

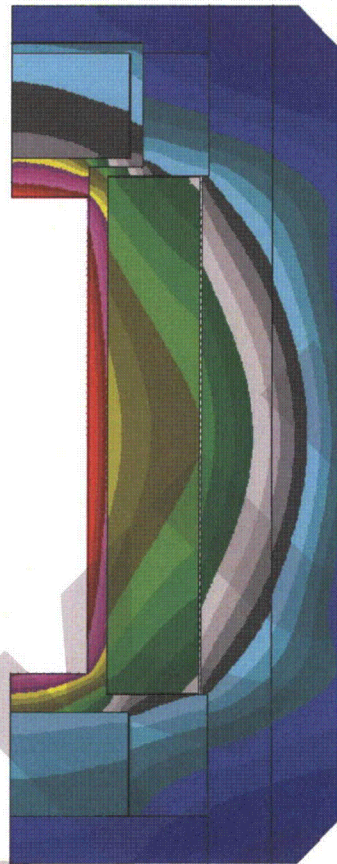
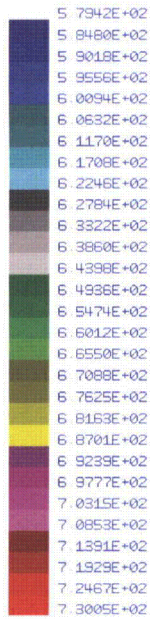


Figure 3-129. Load Case 115 – Fire at 150 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Cask Model – Model AOS-165

Table 3-95. Load Case 116 – Fire at 180 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation – Model AOS-165

Location	Node	Temp (C)	Temp (F)
1	5001	390.33	734.60
2	4532	387.94	730.30
3	4227	382.50	720.50
4	4752	356.11	673.00
5	4838	327.44	621.40
6	4995	314.22	597.60
7	3309	313.33	596.00
8	3419	310.33	590.60
9	678	345.39	653.70
10	2537	313.11	595.60
11	1888	311.28	592.30
12	583	314.22	597.60
13	3001	315.67	600.20
14	3148	310.72	591.30
15	7533	330.28	626.50
16	7377	337.22	639.00
17	7371	344.00	651.20
18	6942	354.33	669.80
19	6267	343.44	650.20
20	6121	330.78	627.40
21	6001	324.00	615.20
22	15481	312.78	595.00
23	16630	305.33	581.60
24	16694	302.61	576.70
25	18111	214.67	418.40
26	11531	214.39	417.90
27	9785	304.94	580.90
28	9571	307.61	585.70
29	8197	315.00	599.00
30	15451	86.50	187.70
31	15961	91.78	197.20
32	17022	93.22	199.80
33	17743	87.00	188.60
34	11051	83.17	181.70
35	9900	90.00	194.00
36	8673	97.00	206.60
37	8225	82.17	179.90

Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp (C)	Max_Temp (F)
Outside Shell	101	2894	1884	3.8061E+02	7.1710E+02
Bottom Plate	3001	3232	3120	3.0856E+02	5.8740E+02
Lid	3233	3424	3233	3.0944E+02	5.8900E+02
Shell Cavity	4001	4998	4227	3.6439E+02	6.8790E+02
Plug	5001	5404	5001	3.7694E+02	7.1050E+02
Tungsten Alloy	6001	7656	6432	3.3572E+02	6.3630E+02
LAST-A-FOAM	8001	18126	15841	3.6828E+02	6.9490E+02

MARKED

VECTOR: 5
MIN: 1.7989E+02
MAX: 7.3465E+02

1	7989E+02
1	9970E+02
2	1352E+02
2	3933E+02
2	5914E+02
2	7895E+02
2	9877E+02
3	1858E+02
3	3839E+02
3	5821E+02
3	7802E+02
3	9783E+02
4	1764E+02
4	3746E+02
4	5727E+02
4	7708E+02
4	9689E+02
5	1671E+02
5	3652E+02
5	5633E+02
5	7615E+02
5	9596E+02
6	1577E+02
6	3558E+02
6	5540E+02
6	7521E+02
6	9502E+02
7	1484E+02
7	3465E+02

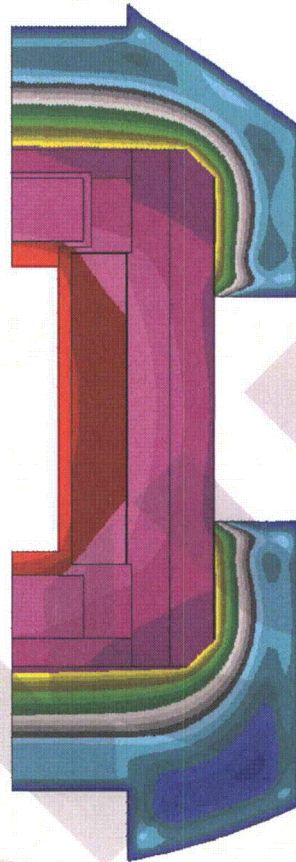


Figure 3-130. Load Case 116 – Fire at 180 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Entire Model – Model AOS-165

VECTOR: 5
MIN: 5.8432E+02
MAX: 7.3465E+02

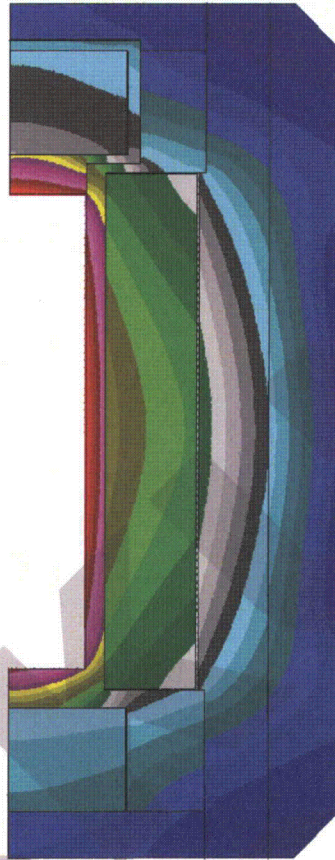
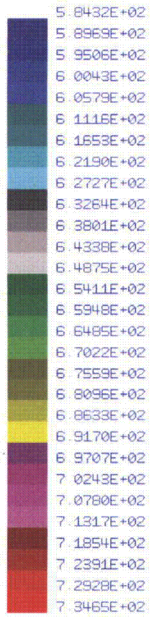


Figure 3-131. Load Case 116 – Fire at 180 Minutes, 100°F, Maximum Decay Heat, Maximum Insolation, Cask Model – Model AOS-165

3.5.3 LIBRA Finite Element Program Heat Transfer Module

3.5.3.1 Description of the LIBRA Heat Transfer Program

The LIBRA heat transfer program performs steady-state and transient analyses of two- and three-dimensional structures. The LIBRA heat transfer code is compatible with the structural code in that essentially the same model can be used for both structural and thermal analyses, and temperature fields determined in thermal analyses can be saved and applied in subsequent structural analyses.

For transient thermal problems the user can control the integration scheme by specifying the integration parameter. A zero (0) value of this parameter gives an explicit integration scheme, while values between zero (0) and one (1) give implicit schemes. Usually, a value of one (1) for the integration parameter was used, and this value corresponds to a backward difference integration technique.

The LIBRA user can specify property changes at user-directed intervals in transient problems. At such times, the LIBRA code passes control to a user-written subroutine, which allows the introduction of temperature-dependent properties. This program feature was widely used in the analysis of the transport package.

3.5.3.2 Qualification and Verification of LIBRA Program

To assess the accuracy of the LIBRA computer program, a qualification and verification program was conducted. The program included verification against exact solution type of problems and benchmarking in the thermal area. The GE Model 2000 heat tests were performed to verify thermal properties used in the analytical model. In particular, the Model 2000 heat tests were used to validate thermal conduction properties for cask structural and shielding materials. The LIBRA program accuracy is demonstrated by a number of verification problems, described below, and by tests applied to the Model AOS-165A transport package.

3.5.3.3 Heat Transfer Problems with Exact Solution

Six example problems were solved analytically and by application of the LIBRA heat transfer program. The problems solved included plane and axisymmetric (2D) geometry and involved convective, radiative, and fixed temperature boundary conditions. In all problems solved, both steady-state and transient problems, agreement between the analytical solutions and the LIBRA program was within 1%. Table 3-96 summarizes these problems and the comparison of results.

3.5.3.4 Heat Transfer Benchmarking Test

A thermal test was performed on a GE Model 2000 transport package. The content heat load was simulated by electric heaters. Thermocouples were placed at strategic locations:

- Inside the cask cavity,
- On the outside cask surface,
- On the inside overpack surfaces, and
- Exterior to overpack structure.

Temperatures were periodically recorded as the heater power was varied from 0 to 3 kW. Steady-state temperatures were recorded for various heater powers from 1 to 3 kW.

A finite element model of the package was developed and was applied to a thermal analysis using the LIBRA Heat Transfer Program. A comparison of heat test (HT) and LIBRA results are provided in Table 3-97.

A more detailed description of the GE Model 2000 heat tests is provided in Appendix 3.5.3.5.

Table 3-96. Summary of Heat Transfer Exact Solution Properties and their Results

Problem Type	Problem Statement	Theory	LIBRA	References
Transient conduction	Concrete wall at initial temperature (T_i), suddenly exposed on one side to hot gas at (T_g).	X L $T(^{\circ}F)$ 0.000 508.8 0.167 538.2 0.333 625.3 0.500 766.3 0.667 954.7 0.833 1,180.7 1.000 1,431.8	$T(^{\circ}F)$ 507 535 622 763 952 1,180 1,430	Kreith, Frank, <i>Principles of Heat Transfer</i> , International Textbook Company, Pennsylvania, 2nd Ed., 1969, Example 4-4.
Steady-state conduction	Concrete slab has its two surfaces maintained at T_1 and T_2 . Obtain heat transfer rate.	120 Btu/h-ft ²	120 Btu/h-ft ²	Gebhart, Benjamin, <i>Heat Transfer, The McGraw-Hill Companies</i> , New York, 2nd Ed., 1971, Example 2-1.
Internal heat generation/ steady-state	A uniformly heat-generating plate of thickness t , subjected to a temperature T_1 on inside and T_2 on the other side.	X L $T(^{\circ}F)$ 0.000 141 0.125 330 0.250 471 0.375 562 0.500 605 0.625 599 0.750 544 0.875 440 1.000 288	$T(^{\circ}F)$ 142 331 471 562 605 599 544 440 287	Garret, J. K., <i>THTD Verification Manual</i> , General Electric Company, San Jose, CA, 1980.
Conduction with radiation and convection boundaries	A plate has a heat flux on one side, and the other side radiates to two sinks.	Surface Temperature 659.7°F	Surface Temperature 659.7°F	Ibid.
Axisymmetric (2D), transient conduction	An infinitely long rod of radius R having a uniform initial temperature T_{∞} is plunged suddenly into a bath at T_{∞} .	r/R $T(^{\circ}F)$ 0.8 6.6 0.1 87.0 0.2 87.6 0.3 88.5 0.4 89.7 0.5 91.2 0.6 92.8 0.7 94.6 0.8 96.5 0.9 98.3 1.0 100.0	$T(^{\circ}F)$ 86.6 87.0 87.6 88.5 89.7 91.2 92.9 94.7 96.5 98.3 100.0	

Table 3-96. Summary of Heat Transfer Exact Solution Properties and their Results (Continued)

Problem Type	Problem Statement	Theory	LIBRA	References	
Axisymmetric (2D), transient conduction with convective boundary	A rod having a uniform initial temperature T_i is quenched in an oil bath at T_∞ .	r/R	T(°F)	T(°F)	Ibid, Example 5-13.
		0	490.0	490	
		0.1	489.0	488	
		0.2	485.7	485	
		0.3	480.2	479	
		0.4	472.6	472	
		0.5	462.9	462	
		0.6	451.3	450	
		0.7	437.8	437	
		0.8	422.5	421	
		0.9	405.6	404	
		1.0	387.2	386	

Table 3-97. Comparison of Heat Test GE Model 2000 and LIBRA Results

Location	p = 1.1 kW		p = 2 kW		p = 3 kW	
	HT (°F)	LIBRA (°F)	HT (°F)	LIBRA (°F)	HT (°F)	LIBRA (°F)
Cavity	264	248	395	372	527	474
Cask Surface	166	179	243	256	319	308
Inside Jacket	101	99	139	138	168	158
Outside Jacket	80	82	98	107	102	111

3.5.3.5 GE Model 2000 Heat Test Description

The GE Model 2000 heat tests were conducted outside, using a test structure only partially enclosed by plywood. In addition, tests were conducted over an extended time period, during which the ambient temperature varied by over 20°F. Consequently, test convective values could not be accurately identified. However, thermal conduction values can be evaluated without accurate convection properties, by matching test and analytical temperature patterns. To this end, approximate ambient temperature and convection values were applied in the analysis of the test event. While the approximate convection properties produced the consistently low temperature correlation, the calculated temperature patterns correlated well with test results validating the model.

The Model AOS-165A test was performed under a more controlled environment, and the correlation between analytical and test temperatures were very good. Accuracy of the LIBRA code is further demonstrated by the following eight solutions, presented in the LIBRA program verification documentation. These problems were chosen to exercise the LIBRA program elements and features used in the AOS thermal analyses. The LIBRA input models for these problems are contained on the **LIBRA** program CD, **Libra64** folder, **verification** sub-folder.

ver_prob.1 (Main 12, Elements 34 & 32)

Axisymmetric, steady-state heat transfer of Carbon resistor, graphite core and michanite conductor, model 1. Solution from Edwards, Denny, and Mills, *Transfer Processes*, 2nd Ed., p. 27 [3.15].

graphite temperature = 368.8
Libra node 15 temperature = 368.5

ver_prob.2 (Main 12, Elements 34 & 32)

Axisymmetric, steady-state heat transfer of Carbon resistor, graphite core and michanite conductor, model 2. Solution from Edwards, Denny, and Mills, *Transfer Processes*, 2nd Ed., p. 27 [3.15].

graphite temperature = 368.8
Libra node 39 temperature = 368.5

ver_prob.3 (Main 12, Elements 34 & 32)

Axisymmetric, steady-state heat transfer of Carbon resistor, graphite core and michanite conductor, model 3. Solution from Edwards, Denny, and Mills, *Transfer Processes*, 2nd Ed., p. 27 [3.15].

graphite temperature = 368.8
Libra node 39 temperature = 368.5

ver_prob.4 (Main 12, Elements 34 & 32)

Axisymmetric, steady-state heat transfer of Carbon resistor, graphite core and michanite conductor, model 4. Solution from Edwards, Denny, and Mills, *Transfer Processes*, 2nd Ed., p. 27 [3.15].

core temperature = 434.8
Libra node 6 temperature = 434.8

ver_prob.5 (Main 12, Elements 34 & 32)

Axisymmetric, transient heat transfer of copper wire initially at 300 deg immersed in water. Solution from Kreith, *Principals of Heat Transfer*, 2nd Ed., p. 131 [3.14].

Item	Theory	Libra
time step 16 temp	173.7	175.2
time step 32 temp	127.1	128.3
time step 48 temp	110.0	110.6
time step 64 temp	103.7	104.0
time step 90 temp	101.4	101.5

ver_prob.6 (Main 12, Elements 34 & 32)

Axisymmetric, transient heat transfer of copper wire initially at 300 deg, immersed in air. Solution from Kreith, *Principals of Heat Transfer*, 2nd Ed., p. 131 [3.14].

Item	Theory	Libra
temperature @ time step 32	217.5	217.3
temperature @ time step 64	169.0	168.8
temperature @ time step 96	140.5	140.3
temperature @ time step 128	123.8	123.7
temperature @ time step 160	114.0	113.9

ver_prob.7 (Main 12, Elements 34 & 32)

Transient heat transfer of concrete wall initially at 100 deg exposed to gas at 1,600 deg. Solution from Kreith, *Principals of Heat Transfer*, 2nd Ed., p. 151 [3.14].

Item	Theory	Libra
temperature @ x/L 0.0	500.8578	500.5
temperature @ x/L 0.2	543.3878	543.1
temperature @ x/L 0.4	668.5285	668.5
temperature @ x/L 0.6	868.4861	868.7
temperature @ x/L 0.8	1129.25	1130.0
temperature @ x/L 1.0	1430.378	1431.1

ver_prob.8 (Main 12, Element 34)

Steady-state heat transfer of two-layer furnace wall. Solution from Kreith, *Principals of Heat Transfer*, 2nd Ed., p. 34 [3.14].

temperature @ inside surface = 2957.0, Libra node 1 = 2957.3
temperature @ outside surface = 336.0, Libra node 50 = 335.8

3.5.4 Tungsten Alloy versus Carbon Steel Materials Comparison

Temperature results are presented for the Model AOS-100B transport package's cask, using tungsten alloy or carbon steel (shielding material). Table 3-98 lists the figures associated with Load Cases 102, and 111 through 115.

Note: Results data is not included for Load Case 116.

Comparative results are shown for each shielding material with the same loading. The loading conditions evaluated are:

- 400W decay heat plus insolation
- 5-hour fire transient – 30-minute fire at 1,475°F and 4.5-hour cool down at 100°F, 400W decay heat

Table 3-98. Tungsten Alloy versus Carbon Steel Shielding Results – Models AOS-100B

Load Case	Description	Temperature versus Time	Entire Model	Cask Model
102	100°F Ambient, 400W Decay Heat, Maximum Insolation	-	Figure 3-133	Figure 3-134
111	Fire at 30 Minutes, 1,475°F Ambient, 400W Decay Heat	Figure 3-135	Figure 3-136	Figure 3-137
112	Fire at 60 Minutes, 100°F, 400W Decay Heat, Maximum Insolation	-	Figure 3-138	Figure 3-139
113	Fire at 90 Minutes, 100°F, 400W Decay Heat, Maximum Insolation	-	Figure 3-140	Figure 3-141
114	Fire at 120 Minutes, 100°F, 400W Decay Heat, Maximum Insolation	-	Figure 3-142	Figure 3-143
115	Fire at 150 Minutes, 100°F, 400W Decay Heat, Maximum Insolation	-	Figure 3-144	Figure 3-145

Table 3-99 lists the carbon steel (~ 0.5% carbon) properties used for this testing [3.13].

Table 3-99. Carbon Steel Properties

Temperature (°C)	Conductivity (W/m-°C)	Thermal Diffusivity (m ² /hr)	Specific Heat (KJ/kg-°C)
Material: SA-105, Carbon Steel Forging			
21.1	60.75	0.06457	0.4324
37.8	60.06	0.06262	0.4408
65.6	59.02	0.05992	0.4527
93.3	58.15	0.05695	0.4693
121.1	56.94	0.05435	0.4815
148.9	55.90	0.05212	0.4930
204.4	53.48	0.04757	0.5167
260.0	51.06	0.04385	0.5351
315.6	48.46	0.04023	0.5537
343.3	47.25	0.03846	0.5646
371.1	46.04	0.03660	0.5780
398.9	44.83	0.03475	0.5929
426.7	43.61	0.03298	0.6078
454.4	42.40	0.03112	0.6262
482.2	41.19	0.02945	0.6483

Density = 7,832.8 kg/m³
 = 0.283 lb/in³

The conductivity property as a function of temperature is defined as:

$$K = 3.003 - 1.027E-3 T - 1.249E-7 T^2$$

where:

K = Conductivity - Btu/hr-in-°F

T = Temperature - °F

The specific heat property as a function of temperature is defined as:

$$C_p = 0.1009 + 4.847E-5 T + 9.493E-9 T^2$$

where:

C_p = Specific heat - Btu/lb-°F

T = Temperature, °F

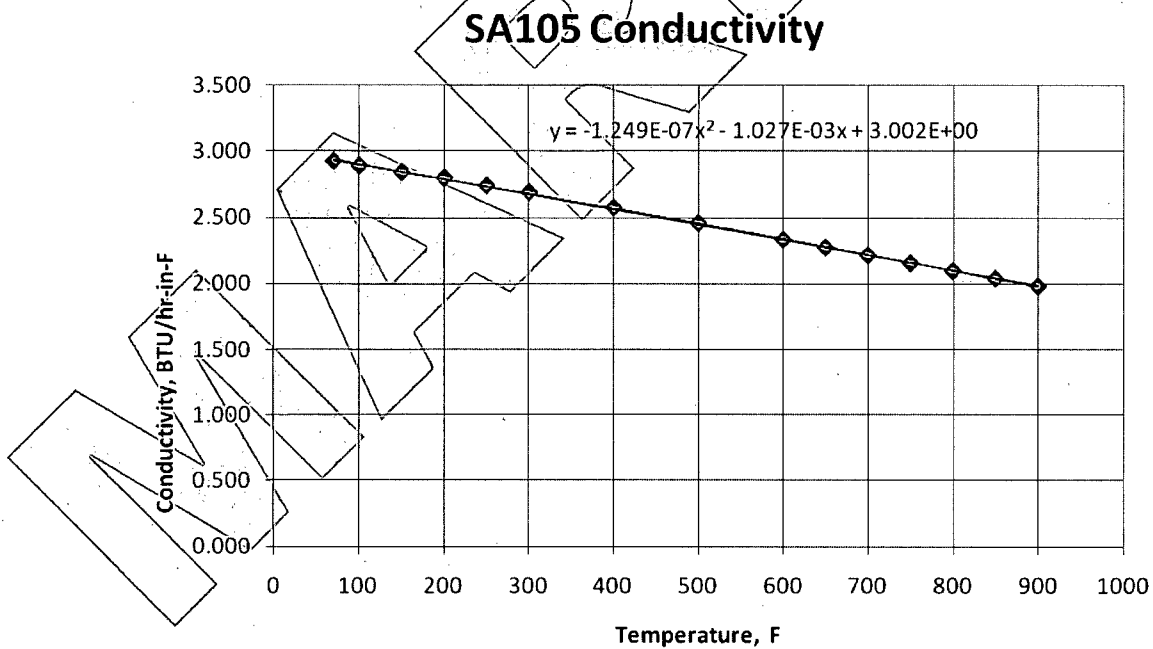
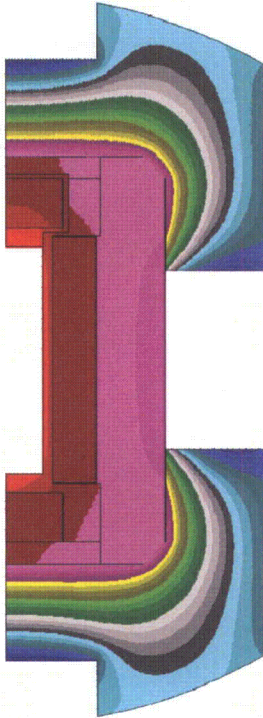


Figure 3-132. Carbon Steel Conductivity (~ 0.5% Carbon) – Model AOS-100B

Tungsten Alloy

VECTOR 1
 MIN 1 4605E+02
 MAX 2 6189E+02

- 1 4605E+02
- 1 5018E+02
- 1 5432E+02
- 1 5846E+02
- 1 6260E+02
- 1 6673E+02
- 1 7087E+02
- 1 7501E+02
- 1 7915E+02
- 1 8328E+02
- 1 8742E+02
- 1 9156E+02
- 1 9570E+02
- 1 9983E+02
- 2 0397E+02
- 2 0811E+02
- 2 1224E+02
- 2 1638E+02
- 2 2052E+02
- 2 2466E+02
- 2 2879E+02
- 2 3293E+02
- 2 3707E+02
- 2 4121E+02
- 2 4534E+02
- 2 4948E+02
- 2 5362E+02
- 2 5776E+02
- 2 6189E+02



Carbon Steel

VECTOR 1
 MIN 1 4605E+02
 MAX 2 6223E+02

- 1 4605E+02
- 1 5020E+02
- 1 5435E+02
- 1 5850E+02
- 1 6264E+02
- 1 6679E+02
- 1 7094E+02
- 1 7509E+02
- 1 7924E+02
- 1 8339E+02
- 1 8754E+02
- 1 9169E+02
- 1 9584E+02
- 1 9999E+02
- 2 0414E+02
- 2 0829E+02
- 2 1244E+02
- 2 1659E+02
- 2 2074E+02
- 2 2489E+02
- 2 2904E+02
- 2 3318E+02
- 2 3733E+02
- 2 4148E+02
- 2 4563E+02
- 2 4978E+02
- 2 5393E+02
- 2 5808E+02
- 2 6223E+02

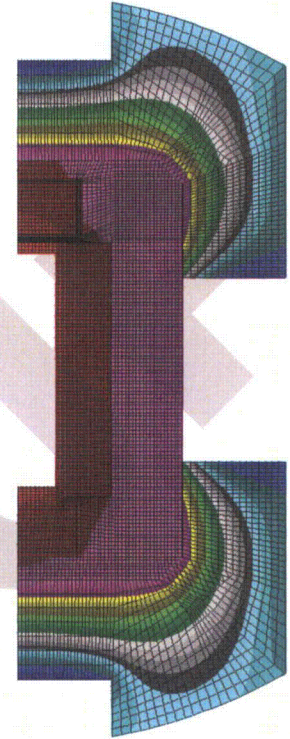


Figure 3-133. Load Case 102 – 100°F Ambient, 400W Decay Heat, Maximum Insolation, Entire Model – Tungsten Alloy (Model AOS-100A) and Carbon Steel (Model AOS-100B)

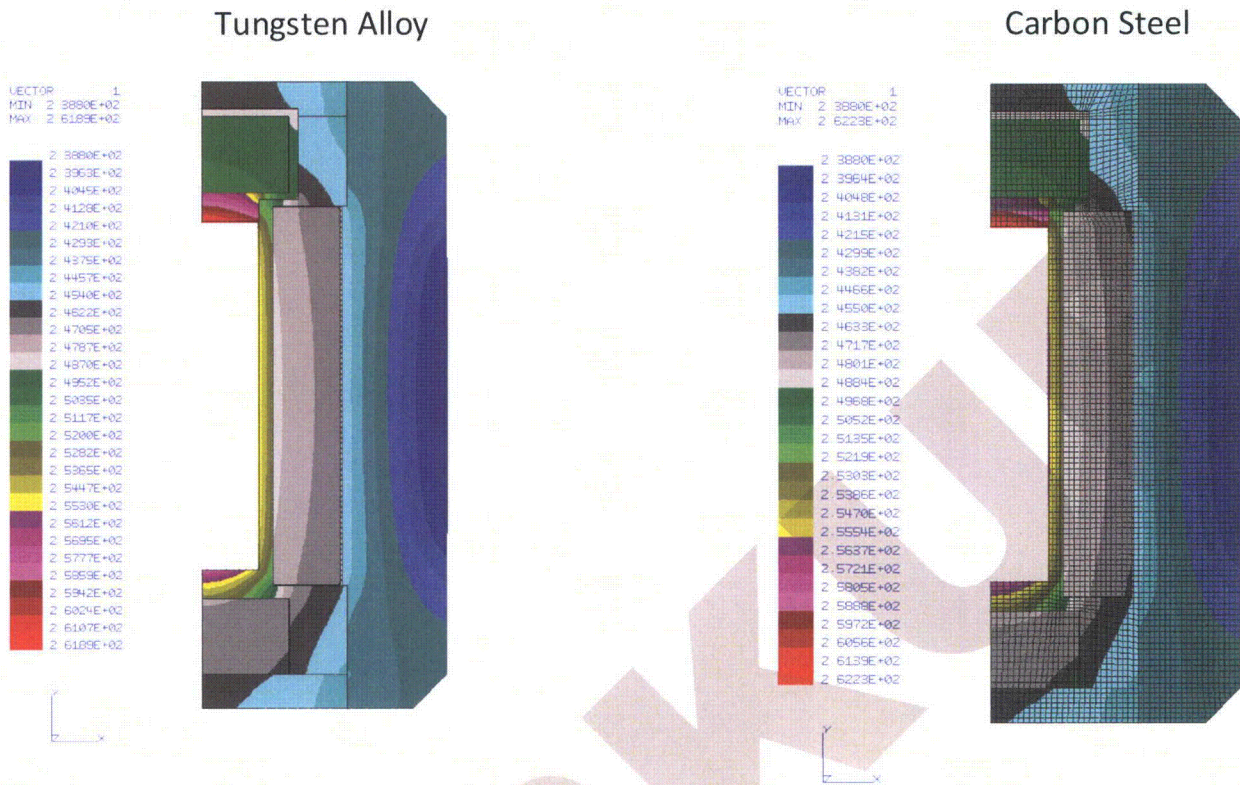
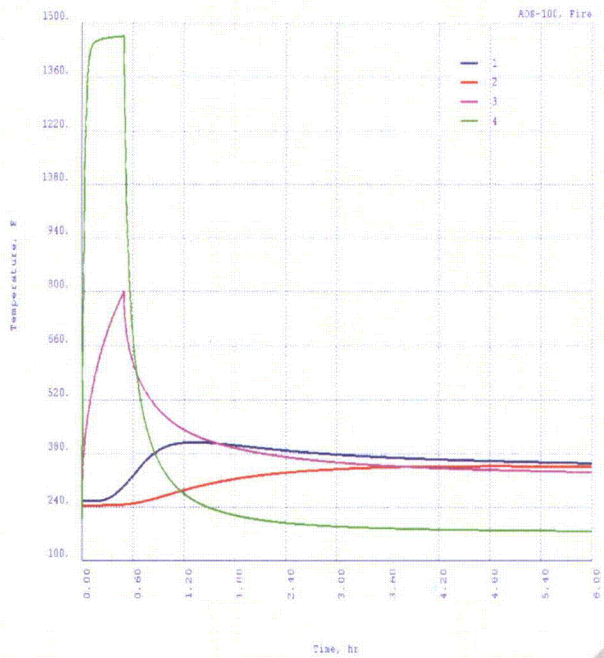


Figure 3-134. Load Case 102 – 100°F Ambient, 400W Decay Heat, Maximum Insolation, Cask Model – Tungsten Alloy (Model AOS-100A) and Carbon Steel (Model AOS-100B)

Tungsten Alloy



Carbon Steel

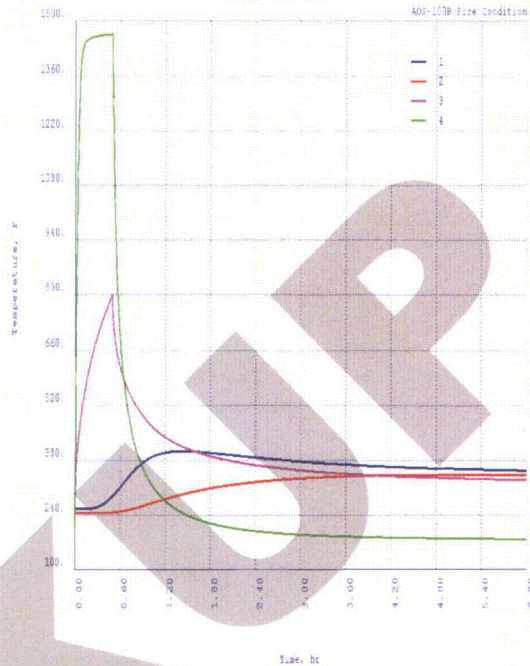


Figure 3-135. 5-Hour Fire Transient, Fire at 30 Minutes, 1,475°F Ambient, 4.5-Hour Cool Down at 100°F – Tungsten Alloy (Model AOS-100A) and Carbon Steel (Model AOS-100B)



Figure 3-136. Load Case 111 – Fire at 30 Minutes, 1,475°F Ambient, 400W Decay Heat, Entire Model – Tungsten Alloy (Model AOS-100A) and Carbon Steel (Model AOS-100B)

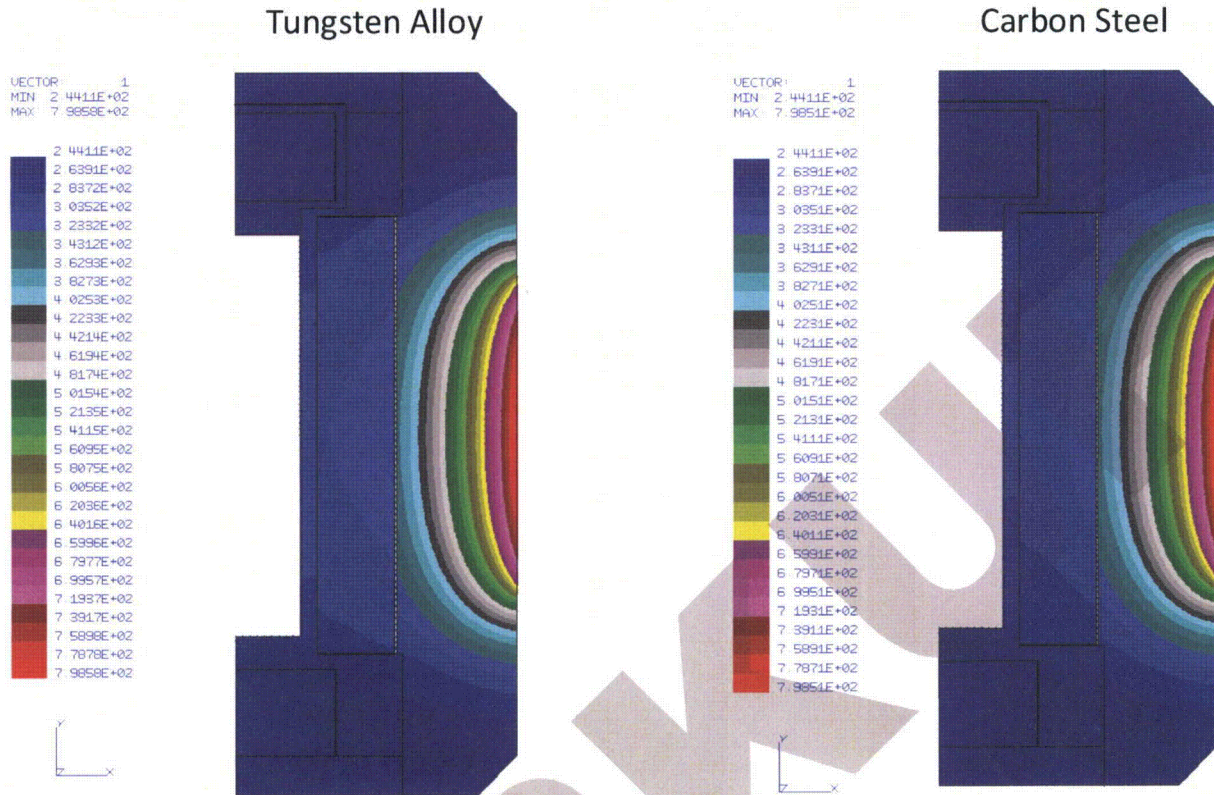
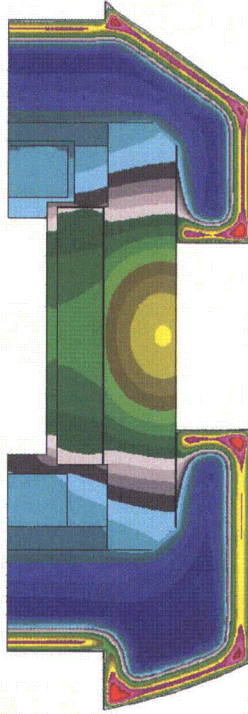


Figure 3-137. Load Case 111 – Fire at 30 Minutes, 1,475°F Ambient, 400W Decay Heat, Cask Model – Tungsten Alloy (Model AOS-100A) and Carbon Steel (Model AOS-100B)

Tungsten Alloy

VECTOR 1
 MIN 1 6809E+02
 MAX 6 1981E+02

- 1 6809E+02
- 1 8423E+02
- 2 0036E+02
- 2 1649E+02
- 2 3262E+02
- 2 4876E+02
- 2 6489E+02
- 2 8102E+02
- 2 9715E+02
- 3 1329E+02
- 3 2942E+02
- 3 4555E+02
- 3 6168E+02
- 3 7782E+02
- 3 9395E+02
- 4 1008E+02
- 4 2621E+02
- 4 4235E+02
- 4 5848E+02
- 4 7461E+02
- 4 9074E+02
- 5 0688E+02
- 5 2301E+02
- 5 3914E+02
- 5 5528E+02
- 5 7141E+02
- 5 8754E+02
- 6 0367E+02
- 6 1981E+02



Carbon Steel

VECTOR 1
 MIN 1 6810E+02
 MAX 6 1980E+02

- 1 6810E+02
- 1 8423E+02
- 2 0036E+02
- 2 1649E+02
- 2 3262E+02
- 2 4876E+02
- 2 6489E+02
- 2 8102E+02
- 2 9715E+02
- 3 1329E+02
- 3 2942E+02
- 3 4555E+02
- 3 6168E+02
- 3 7782E+02
- 3 9395E+02
- 4 1008E+02
- 4 2621E+02
- 4 4235E+02
- 4 5848E+02
- 4 7461E+02
- 4 9074E+02
- 5 0688E+02
- 5 2301E+02
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- 5 7141E+02
- 5 8754E+02
- 6 0367E+02
- 6 1980E+02

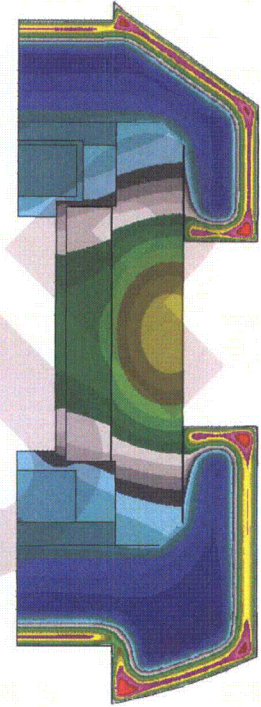
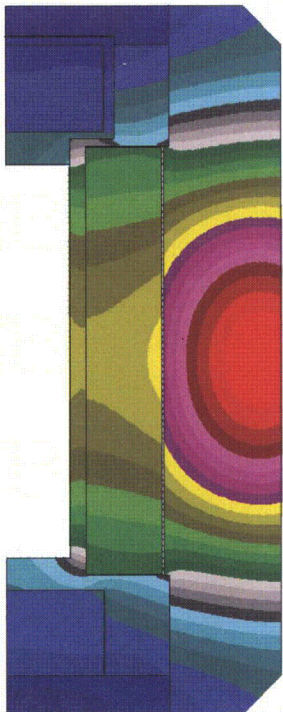


Figure 3-138. Load Case 112 – Fire at 60 Minutes, 100°F, 400W Decay Heat, Maximum Insolation, Entire Model – Tungsten Alloy (Model AOS-100A) and Carbon Steel (Model AOS-100B)

Tungsten Alloy

VECTOR: 1
 MIN: 2 4933E+02
 MAX: 4 7565E+02

- 2 4933E+02
- 2 5741E+02
- 2 6549E+02
- 2 7357E+02
- 2 8165E+02
- 2 8974E+02
- 2 9782E+02
- 3 0591E+02
- 3 1399E+02
- 3 2207E+02
- 3 3015E+02
- 3 3824E+02
- 3 4632E+02
- 3 5441E+02
- 3 6249E+02
- 3 7057E+02
- 3 7865E+02
- 3 8674E+02
- 3 9482E+02
- 4 0290E+02
- 4 1098E+02
- 4 1907E+02
- 4 2715E+02
- 4 3524E+02
- 4 4332E+02
- 4 5140E+02
- 4 5948E+02
- 4 6757E+02
- 4 7565E+02



Carbon Steel

VECTOR: 1
 MIN: 2 4848E+02
 MAX: 4 7385E+02

- 2 4848E+02
- 2 5653E+02
- 2 6458E+02
- 2 7263E+02
- 2 8067E+02
- 2 8872E+02
- 2 9677E+02
- 3 0482E+02
- 3 1287E+02
- 3 2092E+02
- 3 2897E+02
- 3 3702E+02
- 3 4507E+02
- 3 5311E+02
- 3 6116E+02
- 3 6921E+02
- 3 7726E+02
- 3 8531E+02
- 3 9336E+02
- 4 0141E+02
- 4 0946E+02
- 4 1751E+02
- 4 2556E+02
- 4 3360E+02
- 4 4165E+02
- 4 4970E+02
- 4 5775E+02
- 4 6580E+02
- 4 7385E+02



Figure 3-139. Load Case 112 – Fire at 60 Minutes, 100°F, 400W Decay Heat, Maximum Insolation, Cask Model – Tungsten Alloy (Model AOS-100A) and Carbon Steel (Model AOS-100B)

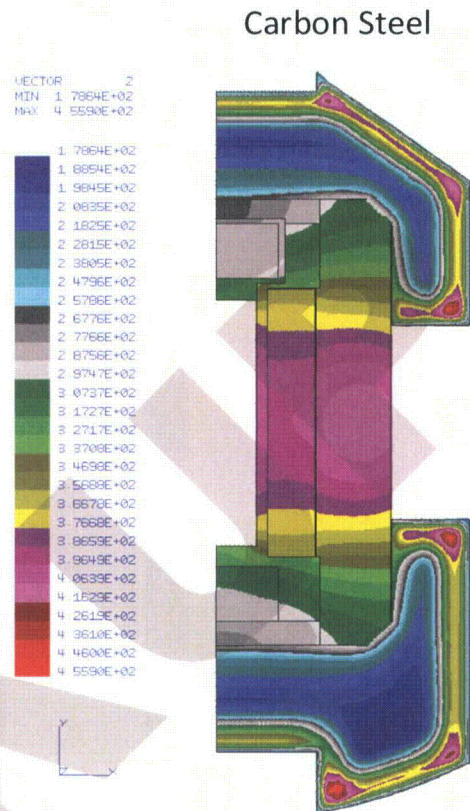
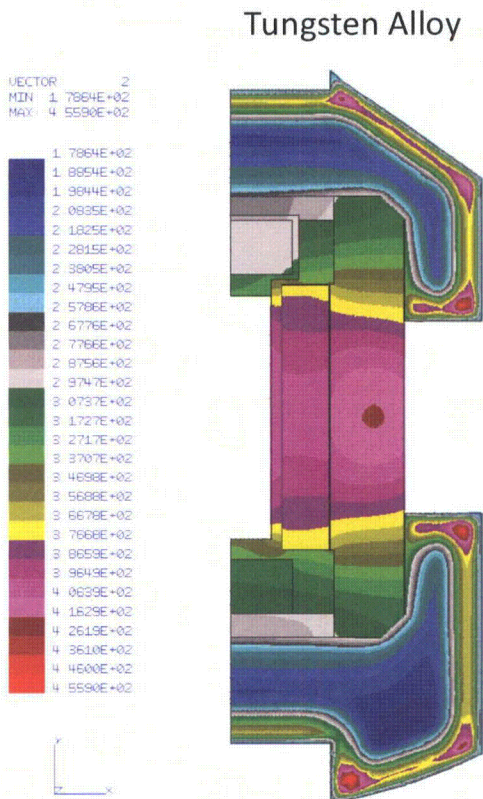
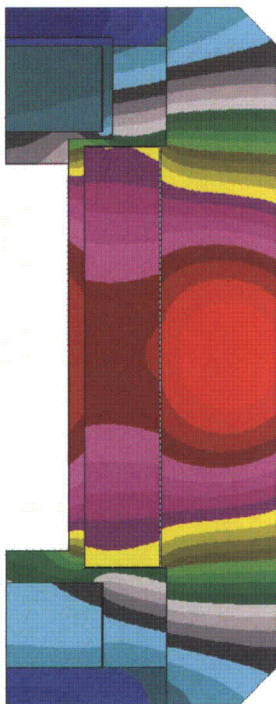


Figure 3-140. Load Case 113 – Fire at 90 Minutes, 100°F, 400W Decay Heat, Maximum Insolation, Entire Model – Tungsten Alloy (Model AOS-100A) and Carbon Steel (Model AOS-100B)

Tungsten Alloy

VECTOR 2
MIN: 2 6808E+02
MAX: 4 1689E+02

- 2 6808E+02
- 2 7339E+02
- 2 7871E+02
- 2 8402E+02
- 2 8934E+02
- 2 9465E+02
- 2 9997E+02
- 3 0528E+02
- 3 1060E+02
- 3 1591E+02
- 3 2123E+02
- 3 2654E+02
- 3 3185E+02
- 3 3717E+02
- 3 4248E+02
- 3 4780E+02
- 3 5311E+02
- 3 5843E+02
- 3 6374E+02
- 3 6906E+02
- 3 7437E+02
- 3 7969E+02
- 3 8500E+02
- 3 9031E+02
- 3 9563E+02
- 4 0094E+02
- 4 0626E+02
- 4 1157E+02
- 4 1689E+02



Carbon Steel

VECTOR 2
MIN: 2 6465E+02
MAX: 4 1316E+02

- 2 6465E+02
- 2 6995E+02
- 2 7526E+02
- 2 8056E+02
- 2 8587E+02
- 2 9117E+02
- 2 9647E+02
- 3 0178E+02
- 3 0708E+02
- 3 1239E+02
- 3 1769E+02
- 3 2299E+02
- 3 2830E+02
- 3 3360E+02
- 3 3890E+02
- 3 4421E+02
- 3 4951E+02
- 3 5482E+02
- 3 6012E+02
- 3 6542E+02
- 3 7073E+02
- 3 7603E+02
- 3 8134E+02
- 3 8664E+02
- 3 9194E+02
- 3 9725E+02
- 4 0255E+02
- 4 0785E+02
- 4 1316E+02

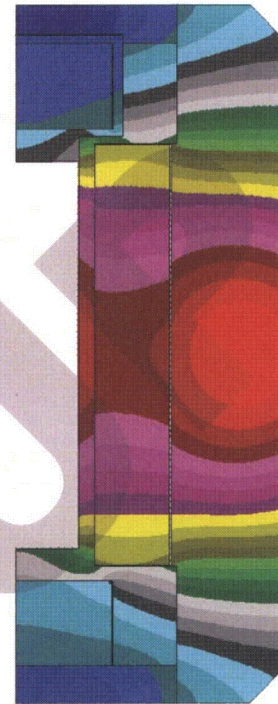
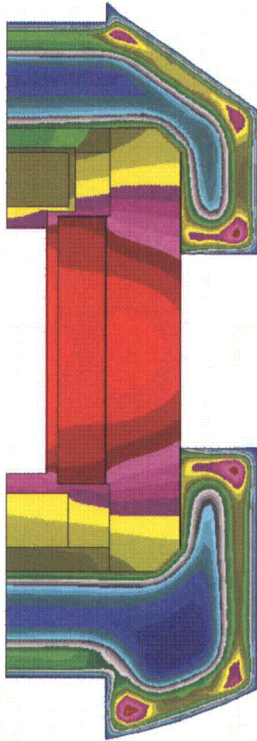


Figure 3-141. Load Case 113 – Fire at 90 Minutes, 100°F, 400W Decay Heat, Maximum Insolation, Cask Model – Tungsten Alloy (Model AOS-100A) and Carbon Steel (Model AOS-100B)

Tungsten Alloy

VECTOR: 3
 MIN: 1 8444E+02
 MAX: 3 9527E+02

- 1 8444E+02
- 1 9137E+02
- 1 9950E+02
- 2 0703E+02
- 2 1458E+02
- 2 2209E+02
- 2 2962E+02
- 2 3715E+02
- 2 4468E+02
- 2 5221E+02
- 2 5974E+02
- 2 6727E+02
- 2 7480E+02
- 2 8233E+02
- 2 8986E+02
- 2 9738E+02
- 3 0491E+02
- 3 1244E+02
- 3 1997E+02
- 3 2750E+02
- 3 3503E+02
- 3 4256E+02
- 3 5009E+02
- 3 5762E+02
- 3 6515E+02
- 3 7268E+02
- 3 8021E+02
- 3 8774E+02
- 3 9527E+02



Carbon Steel

VECTOR: 3
 MIN: 1 8445E+02
 MAX: 3 9380E+02

- 1 8445E+02
- 1 9132E+02
- 1 9940E+02
- 2 0688E+02
- 2 1435E+02
- 2 2183E+02
- 2 2931E+02
- 2 3678E+02
- 2 4426E+02
- 2 5174E+02
- 2 5922E+02
- 2 6669E+02
- 2 7417E+02
- 2 8165E+02
- 2 8912E+02
- 2 9660E+02
- 3 0408E+02
- 3 1155E+02
- 3 1903E+02
- 3 2651E+02
- 3 3398E+02
- 3 4146E+02
- 3 4894E+02
- 3 5642E+02
- 3 6389E+02
- 3 7137E+02
- 3 7885E+02
- 3 8632E+02
- 3 9380E+02

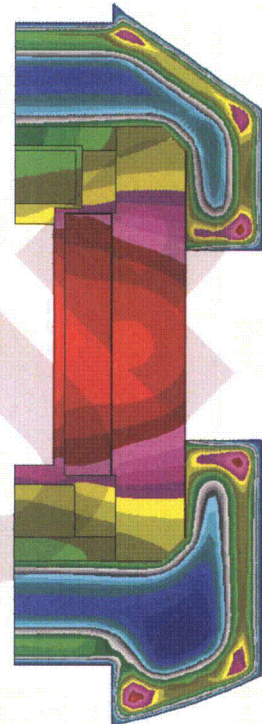
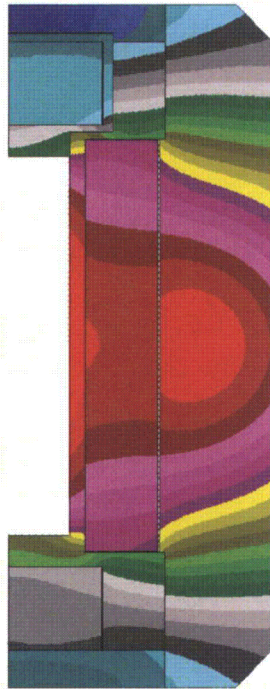


Figure 3-142. Load Case 114 – Fire at 120 Minutes, 100°F, 400W Decay Heat, Maximum Insolation, Entire Model – Tungsten Alloy (Model AOS-100A) and Carbon Steel (Model AOS-100B)

Tungsten Alloy

VECTOR 3
 MIN 2 9205E+02
 MAX 3 9527E+02

- 2 9205E+02
- 2 9574E+02
- 2 9942E+02
- 3 0311E+02
- 3 0690E+02
- 3 1048E+02
- 3 1417E+02
- 3 1786E+02
- 3 2154E+02
- 3 2523E+02
- 3 2891E+02
- 3 3260E+02
- 3 3629E+02
- 3 3997E+02
- 3 4366E+02
- 3 4735E+02
- 3 5103E+02
- 3 5472E+02
- 3 5840E+02
- 3 6209E+02
- 3 6578E+02
- 3 6946E+02
- 3 7315E+02
- 3 7683E+02
- 3 8052E+02
- 3 8421E+02
- 3 8790E+02
- 3 9158E+02
- 3 9527E+02



Carbon Steel

VECTOR 3
 MIN 2 8631E+02
 MAX 3 9380E+02

- 2 8631E+02
- 2 9015E+02
- 2 9399E+02
- 2 9783E+02
- 3 0166E+02
- 3 0550E+02
- 3 0934E+02
- 3 1318E+02
- 3 1702E+02
- 3 2086E+02
- 3 2470E+02
- 3 2854E+02
- 3 3238E+02
- 3 3622E+02
- 3 4005E+02
- 3 4389E+02
- 3 4773E+02
- 3 5157E+02
- 3 5541E+02
- 3 5925E+02
- 3 6309E+02
- 3 6693E+02
- 3 7077E+02
- 3 7461E+02
- 3 7844E+02
- 3 8228E+02
- 3 8612E+02
- 3 8996E+02
- 3 9380E+02

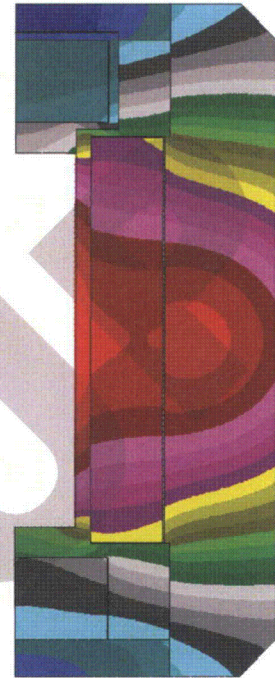


Figure 3-143. Load Case 114 – Fire at 120 Minutes, 100°F, 400W Decay Heat, Maximum Insolation, Cask Model – Tungsten Alloy (Model AOS-100A) and Carbon Steel (Model AOS-100B)

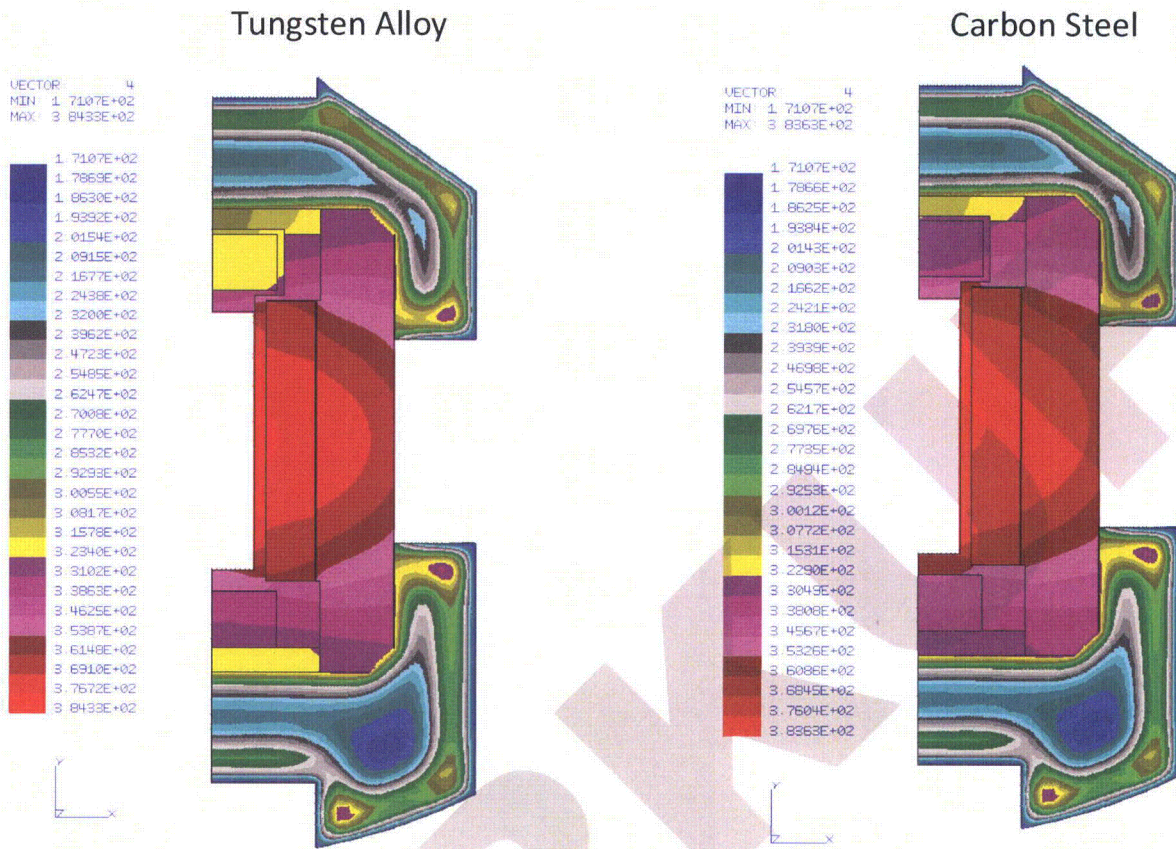


Figure 3-144. Load Case 115 – Fire at 150 Minutes, 100°F, 400W Decay Heat, Maximum Insolation, Entire Model – Tungsten Alloy (Model AOS-100A) and Carbon Steel (Model AOS-100B)

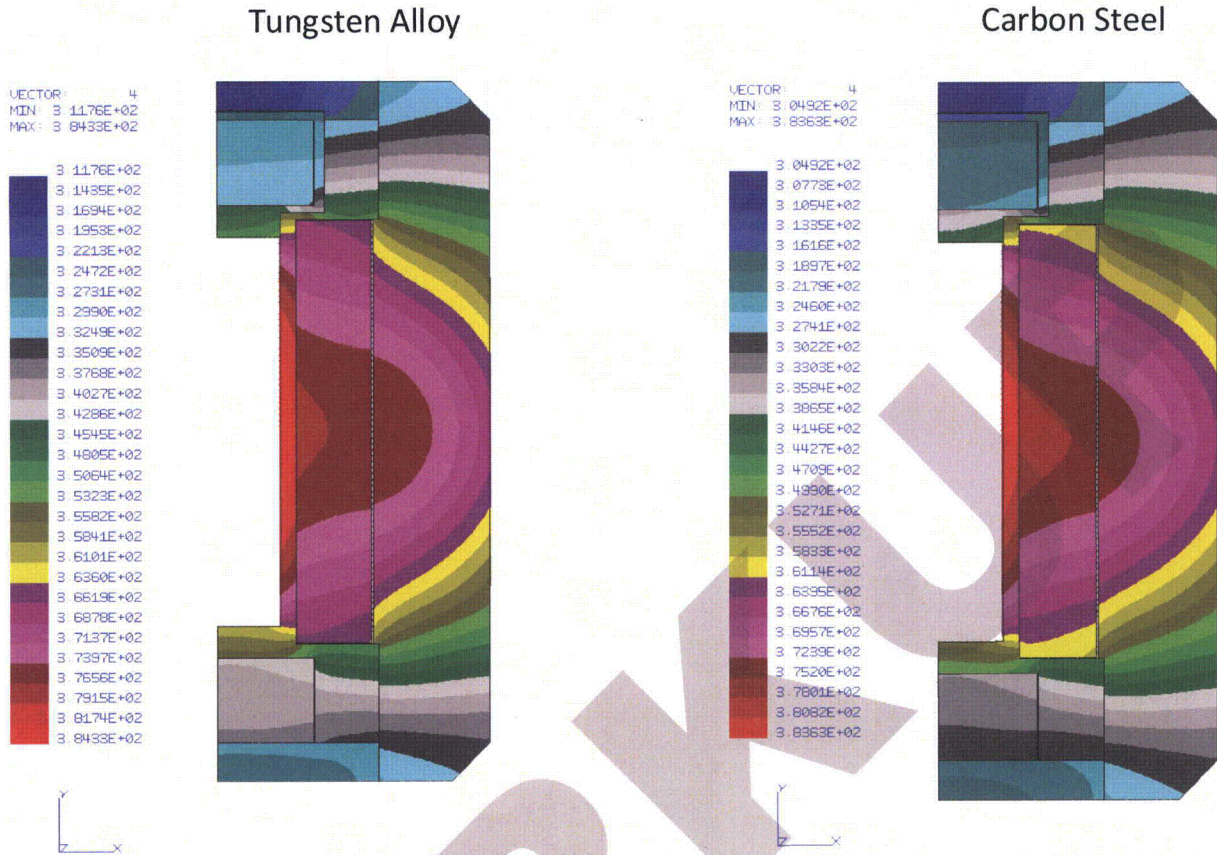


Figure 3-145. Load Case 115 – Fire at 150 Minutes, 100°F, 400W Decay Heat, Maximum Insolation, Cask Model – Tungsten Alloy (Model AOS-100A) and Carbon Steel (Model AOS-100B)

MARBLE

3.5.5 Material Properties Correlation between the Equations Provided in the Test and the LIBRA Input File

TI Load Case_111 - 100F Ambient, Max Decay Heat, max Insolation
*

mc	12	31	32	33	34
cnd	1	0.0,	0.0,	0.0	0.0
cnd	2	8.1185,	0.0,	0.0	0.0
cnd	3	13.688,	0.0,	0.0	0.0
cnd	103	13.70,	0.0,	0.0	0.0
cnd	4	18.10,	0.0,	0.0	0.0
cnd	104	18.10,	0.0,	0.0	0.0
cnd	5	19.88,	0.0,	0.0	0.0
cnd	6	0.0,	3.22,	0.0	0.0
cnd	106	0.0,	3.226,	0.0	0.0
cnd	7	4.6058,	3.226,	0.0	0.0
cnd	8	6.6528,	3.226,	0.0	0.0
cnd	9	8.188,	3.226,	0.0	0.0
cnd	109	8.25,	3.22,	0.0	0.0
cnd	1009	8.25,	3.226,	0.0	0.0
cnd	10	13.688,	3.22,	0.0	0.0
cnd	110	13.688,	3.226,	0.0	0.0
cnd	1010	13.70,	3.22,	0.0	0.0
cnd	11	18.10,	3.22,	0.0	0.0
cnd	111	18.10,	3.22,	0.0	0.0
cnd	12	19.6,	3.22,	0.0	0.0
cnd	13	23.1,	3.22,	0.0	0.0
cnd	14	0.0,	10.446,	0.0	0.0
cnd	114	0.0,	10.456,	0.0	0.0
cnd	15	5.36,	10.446,	0.0	0.0
cnd	115	5.36,	10.456,	0.0	0.0
cnd	16	6.725,	10.446,	0.0	0.0
cnd	116	6.725,	10.456,	0.0	0.0
cnd	17	8.188,	10.446,	0.0	0.0
cnd	117	8.25,	10.456,	0.0	0.0
cnd	18	13.1936,	9.664,	0.0	0.0
cnd	19	13.688,	9.5815,	0.0	0.0
cnd	20	5.36,	12.024,	0.0	0.0
cnd	21	6.725,	11.70,	0.0	0.0
cnd	121	6.730,	11.763,	0.0	0.0
cnd	22	8.25,	11.70,	0.0	0.0
cnd	122	8.25,	11.763,	0.0	0.0
cnd	23	13.20,	11.70,	0.0	0.0
cnd	123	13.075,	11.763,	0.0	0.0
cnd	1023	13.20,	11.71,	0.0	0.0
cnd	24	13.688,	11.70,	0.0	0.0
cnd	124	13.70,	11.71,	0.0	0.0
cnd	25	18.10,	11.71,	0.0	0.0
cnd	125	18.10,	11.71,	0.0	0.0
cnd	26	23.10,	11.71,	0.0	0.0
cnd	27	0.0,	13.20,	0.0	0.0
cnd	28	5.36,	13.20,	0.0	0.0
cnd	29	6.725,	13.20,	0.0	0.0

cnd 129	6.730,	13.20,	0.0
cnd 30	8.25,	13.20,	0.0
cnd 31	13.075,	13.2262,	0.0
cnd 51	0.0,	46.20,	0.0
cnd 52	5.344,	46.20,	0.0
cnd 152	5.36,	46.20,	0.0
cnd 53	6.725,	46.20,	0.0
cnd 153	6.730,	46.20,	0.0
cnd 54	8.25,	46.20,	0.0
cnd 55	10.18,	46.20,	0.0
cnd 56	13.075,	46.20,	0.0
cnd 57	0.0,	47.70,	0.0
cnd 58	5.344,	47.70,	0.0
cnd 158	5.36,	47.70,	0.0
cnd 59	6.725,	47.70,	0.0
cnd 159	6.730,	47.637,	0.0
cnd 60	8.25,	47.637,	0.0
cnd 160	8.25,	47.70,	0.0
cnd 61	9.125,	47.637,	0.0
cnd 161	9.125,	47.70,	0.0
cnd 62	13.075,	47.637,	0.0
cnd 162	13.20,	47.69,	0.0
cnd 1062	13.20,	47.70,	0.0
cnd 63	13.688,	47.70,	0.0
cnd 163	13.70,	47.69,	0.0
cnd 64	18.10,	47.69,	0.0
cnd 164	18.10,	47.69,	0.0
cnd 65	23.10,	47.69,	0.0
cnd 66	0.0,	48.327,	0.0
cnd 67	5.344,	48.327,	0.0
cnd 167	5.36,	48.317,	0.0
cnd 68	6.725,	48.317,	0.0
cnd 168	6.725,	48.327,	0.0
cnd 69	8.25,	48.317,	0.0
cnd 169	8.25,	48.327,	0.0
cnd 70	9.125,	48.317,	0.0
cnd 170	9.075,	48.327,	0.0
cnd 71	13.0361,	49.16566,	0.0
cnd 72	13.688,	49.3071,	0.0
cnd 73	0.0,	48.944,	0.0
cnd 173	0.0,	48.954,	0.0
cnd 74	5.344,	48.944,	0.0
cnd 174	5.344,	48.954,	0.0
cnd 75	6.96914,	48.944,	0.0
cnd 76	8.188,	48.954,	0.0
cnd 176	8.25,	48.944,	0.0
cnd 78	9.075,	48.944,	0.0
cnd 178	9.125,	48.944,	0.0
cnd 79	13.688,	50.9243,	0.0
cnd 80	0.0,	56.174,	0.0
cnd 180	0.0,	56.18,	0.0
cnd 81	5.0417,	56.174,	0.0
cnd 82	8.188,	56.174,	0.0
cnd 182	8.25,	56.18,	0.0

cnd 83	9.075,	56.18,	0.0
cnd 183	9.125,	56.174,	0.0
cnd 1083	9.125,	56.18,	0.0
cnd 84	13.688,	56.174,	0.0
cnd 184	13.688,	56.18,	0.0
cnd 1084	13.70,	56.18,	0.0
cnd 85	18.10,	56.18,	0.0
cnd 185	18.10,	56.18,	0.0
cnd 86	19.60,	56.18,	0.0
cnd 87	23.1,	56.18,	0.0
cnd 88	0.0,	56.862,	0.0
cnd 188	0.0,	56.893,	0.0
cnd 89	8.25,	56.862,	0.0
cnd 189	8.25,	56.893,	0.0
cnd 90	9.075,	56.862,	0.0
cnd 190	9.125,	56.893,	0.0
cnd 92	13.688,	57.5657,	0.0
cnd 93	0.0,	59.40,	0.0
cnd 94	8.496,	59.40,	0.0
cnd 95	10.384,	59.40,	0.0
cnd 96	13.688,	59.40,	0.0
cnd 196	13.70,	59.40,	0.0
cnd 97	18.10,	59.40,	0.0
cnd 197	18.10,	59.40,	0.0
cnd 98	19.88,	59.40,	0.0
cnd 401	5.36,	42.2,	0.0
cnd 402	6.725,	42.2,	0.0
cnd 403	5.36,	43.2,	0.0
cnd 404	6.725,	43.2,	0.0
* impact limiter			
cnd 201	0.0,	-.02,	0.0
cnd 202	0.0,	-14.19,	0.0
cnd 203	13.70,	-.02,	0.0
cnd 204	13.35,	-14.19,	0.0
cnd 205	13.35,	-22.39,	0.0
cnd 2050	14.101,	-22.251,	0.0
cnd 206	18.10,	-.02,	0.0
cnd 207	20.0442,	-7.4535,	0.0
cnd 208	24.808,	-19.366,	0.0
cnd 2080	21.856,	-20.333,	0.0
cnd 209	19.92,	-.02,	0.0
cnd 210	22.2703,	-5.2050,	0.0
cnd 211	28.66,	-17.896,	0.0
cnd 2110	31.125,	-16.825,	0.0
cnd 212	26.1625,	-3.0625,	0.0
cnd 213	33.55,	-15.66,	0.0
cnd 214	23.3,	3.18,	0.0
cnd 215	30.375,	.8180,	0.0
cnd 216	33.55,	-.38,	0.0
cnd 217	23.3,	11.71,	0.0
cnd 218	30.375,	11.71,	0.0
cnd 219	33.55,	11.71,	0.0
cnd 220	23.3,	16.71,	0.0
cnd 221	30.375,	16.71,	0.0

BREAKUP

cnd 222	33.55,	16.71,	0.0
cnd 223	23.3,	42.69,	0.0
cnd 224	32.0,	42.69,	0.0
cnd 225	33.55,	42.69,	0.0
cnd 226	23.3,	47.69,	0.0
cnd 227	32.0,	47.69,	0.0
cnd 228	33.55,	47.69,	0.0
cnd 229	23.3,	56.22,	0.0
cnd 230	32.0,	60.5,	0.0
cnd 231	33.55,	61.83,	0.0
cnd 232	27.6,	63.7,	0.0
cnd 233	29.03,	65.04,	0.0
cnd 234	19.92,	59.42,	0.0
cnd 235	24.8,	66.1,	0.0
cnd 236	25.37,	67.65,	0.0
cnd 237	18.10,	59.42,	0.0
cnd 238	21.6,	68.6,	0.0
cnd 239	22.06,	70.00,	0.0
cnd 240	13.70,	59.42,	0.0
cnd 241	13.35,	73.59,	0.0
cnd 242	13.35,	76.19,	0.0
cnd 243	0.0,	59.42,	0.0
cnd 244	0.0,	73.59,	0.0
cnd 301	0.0,	-12.7,	0.0
cnd 302	13.35,	-12.7,	0.0
cnd 303	14.85,	-12.7,	0.0
cnd 304	14.85,	-14.19,	0.0
cnd 305	13.35,	-20.9,	0.0
cnd 306	14.85,	-20.9,	0.0
cnd 307	14.85,	-22.103,	0.0
cnd 308	27.9,	-16.3,	0.0
cnd 309	32.,	-14,	0.0
cnd 310	31.9,	0.2,	0.0
cnd 311	31.9,	11.71,	0.0
cnd 312	23.3,	15.21,	0.0
cnd 313	30.375,	15.21,	0.0
cnd 314	31.9,	15.21,	0.0
cnd 315	33.55,	15.21,	0.0
cnd 316	31.9,	16.71,	0.0
cnd 320	0.0,	72.1,	0.0
cnd 321	13.35,	72.1,	0.0
cnd 322	14.85,	74.8,	0.0
cnd 323	14.85,	73.5,	0.0
cnd 324	14.85,	72.1,	0.0
cnd 325	23.3,	44.2,	0.0
cnd 326	32.0,	44.2,	0.0
cnd 327	33.55,	44.2,	0.0

*		node/element range
*	part 1 Outer Stainless Steel shell	101 - 3000 - 101/1
*	part 2 Top+bottom plates	3001 - 4000 - 102/2
*	part 3 cavity Inner shell	4001 - 5000 - 103/3
*	part 4 Inner plug	5001 - 6000 - 104/4
*	part 5 Tungsten cylinder	6001 - 8000 - 105/5
*	impact limiter foam	8001 - 11000 - 106/6

* part 1 outer ss shell, prop/mat=101/1

G10

10,8, 101,101, 34,101,,1 *Identify the NM for the Element that creates.*
103,4,11,1010 *See G10 record, attached.*

-1

G10

4,8, -1,-1, 34,101,,1
104,5,12,111

-1

G9

8,8,8, -1,-1, 31,34,101,,1
5,13,12

-1

G10

10,17, -1,-1, 34,101,,1
1010,11,25,124

-1

G10

11,17, -1,-1, 34,101,,1
111,13,26,125

-1

G10

2,73, -1,-1, 34,101,,1
1023,124,163,162

-1

G10

10,73, -1,-1, 34,101,,1
124,25,64,163

-1

G10

11,73, -1,-1, 34,101,,1
125,26,65,164

-1

G10

10,22, -1,-1, 34,101,,1
163,64,85,1084

-1

G10

11,22, -1,-1, 34,101,,1
164,65,87,185

-1

G10

10,8, -1,-1, 34,101,,1
1084,85,97,196

-1

G10

4,8, -1,-1, 34,101,,1
185,86,98,197

-1

G9

8,8,8, -1,-1, 31,34,101,,1

87,98,86
-1
* part 2
* bottom cover plate, prop/mat 102/2
G10
17,8, 3001,3001, 34,102,,1
1,2,109,6
-1
G10
12,8, -1,-1, 34,102,,1
2,3,10,109
-1
* lid cover plate
G10
19,5, -1,-1, 34,102,,1
188,189,94,93
-1
G10
5,5, -1,-1, 34,102,,1
189,190,95,94
-1
G10
8,4, -1,-1, 34,102,,1
1083,184,92,190
-1
G10
8,5, -1,-1, 34,102,,1
190,92,96,95
-1
* part 3 cavity inner shell, prop/mat 103/3
G10
12,13, 4001,4001, 34,103,,1
1009,110,19,117
-1
G10
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114,115,28,27
-1
G10
5,5, -1,-1, 34,103,,1
115,116,21,20
-1
G10
4,5, -1,-1, 34,103,,1
116,117,22,21
-1
G10
11,5, -1,-1, 34,103,,1
117,18,23,22
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G10

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 18,19,24,23
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 5,59, -1;-1, 34,103,,1
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 403,404,53,152
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 G10
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 152,53,59,158
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 G10
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 158,59,68,167
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 G10
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 59,160,69,68
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 G10
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 160,161,70,69
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 161,1062,71,70
 -1
 G10
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 1062,63,72,71
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 G10
 8,5, -1,-1, 34,103,,1
 70,72,79,178
 -1
 G10
 8,14, -1,-1, 34,103,,1
 178,79,84,183
 -1

DRAFT

* part 4 - plug cylinder shell, prop/mat-104/4

*

G10

12,4, 5001,5001, 34,104,,1
51,52,58,57

-1

G10

12,5, -1,-1, 34,104,,1
57,58,67,66

-1

G10

12,5, -1,-1, 34,104,,1
66,67,74,73

-1

G10

5,5, -1,-1, 34,104,,1
67,168,75,74

-1

G10

4,5, -1,-1, 34,104,,1
168,169,176,75

-1

G10

5,5, -1,-1, 34,104,,1
169,170,78,176

-1

G10

5,14, -1,-1, 34,104,,1
176,78,83,182

-1

G10

19,4, -1,-1, 34,104,,1
180,182,89,88

-1

G10

5,4, -1,-1, 34,104,,1
182,83,90,89

-1

* part 5 Tungsten, prop/mat=105/5

* Tungsten at bottom

G10

10,13, 6001,6001, 34,105,,1
106,7,15,14

-1

G10

5,13, -1,-1, 34,105,,1
7,8,16,15

-1

G10

4,13, -1,-1, 34,105,,1
8,9,17,16

```

-1
* side tungsten
G10
  4,4,  -1,-1,      34,105,,1
  121,122,30,129
-1
G10
  11,4,  -1,-1,     34,105,,1
  122,123,31,30
-1
G10
  4,67,  -1,-1,     34,105,,1
  129,30,54,153
-1
G10
  11,67,  -1,-1,    34,105,,1
  30,31,56,54
-1
G10
  4,4,  -1,-1,      34,105,,1
  153,54,60,159
-1
G10
  5,4,  -1,-1,      34,105,,1
  54,55,61,60
-1
G10
  7,4,  -1,-1,      34,105,,1
  55,56,62,61
-1
* Tungsten in plug
G10
  12,14,  -1,-1,     34,105,,1
  173,174,81,80
-1
G10
  8,14,  -1,-1,     34,105,,1
  174,76,82,81
-1
*
* impact limiter
* bottom section
G10
  28,8,  8001,8001,   34,106,,1
  301,302,203,201
-1
G10
  28,16,  -1,-1,     34,106,,1
  202,204,302,301
-1
G10

```

ALWAYS BRKUP

	16,16, -1,-1,	34,106,,1
	205,307,306,305	
	5,2050	
-1		
G10		
	16,6, -1,-1,	34,106,,1
	305,306,304,204	
-1		
G10		
	16,16, -1,-1,	34,106,,1
	204,304,303,302	
-1		
g8		
	16,8,10,8 -1,-1,	31,34,106,,1
	302,303,206,203	
-1		
G8		
	11,7,11,16 -1,-1,	31,34,106,,1
	304,308,210,303	
-1		
G9		
	8,8,8 -1,-1,	31,34,106,,1
	206,303,207	
-1		
G10		
	4,8 -1,-1,	34,106,,1
	207,210,209,206	
-1		
G9		
	6,11,11 -1,-1,	31,34,106,,1
	304,306,308	
-1		
G10		
	11,16 -1,-1,	34,106,,1
	307,211,308,306	
	5,2080	
-1		
G9		
	8,8,8 -1,-1,	31,34,106,,1
	214,209,212	
-1		
G9		
	8,8,8 -1,-1,	31,34,106,,1
	209,210,212	
-1		
G9		
	8,8,8 -1,-1,	31,34,106,,1
	212,215,214	
-1		
G10		
	8,16, -1,-1,	34,106,,1

DRAFT

211,213,309,308
 5,2110
 -1
 G10
 8,7, -1,-1, 34,106,,1
 308,309,212,210
 -1
 G10
 8,16, -1,-1, 34,106,,1
 213,216,310,309
 -1
 G10
 8,7, -1,-1, 34,106,,1
 309,310,215,212
 -1
 G10
 17,16 -1,-1, 34,106,,1
 216,219,311,310
 -1
 G10
 17,7 -1,-1, 34,106,,1
 310,311,218,215
 -1
 G10
 17,8 -1,-1, 34,106,,1
 215,218,217,214
 -1
 G10
 8,16 -1,-1, 34,106,,1
 219,315,314,311
 -1
 G10
 8,7 -1,-1, 34,106,,1
 311,314,313,218
 -1
 G10
 8,8 -1,-1, 34,106,,1
 218,313,312,217
 -1
 G10
 16,16 -1,-1, 34,106,,1
 315,222,316,314
 -1
 G10
 16,7 -1,-1, 34,106,,1
 314,316,221,313
 -1
 G10
 16,8 -1,-1, 34,106,,1
 313,221,220,312
 -1

BREAKUP

* top section

G10

30,16, 15001,15001, 34,1060,,1
320,321,241,244

-1

G10

30,8, -1,-1, 34,1060,,1
243,240,321,320

-1

G10

16,16, -1,-1, 34,1060,,1
241,323,322,242

-1

G10

16,16, -1,-1, 34,1060,,1
321,324,323,241

-1

G8

10,8,16,8 -1,-1, 31,34,1060,,1
240,237,324,321

-1

G10

8,16, -1,-1, 34,1060,,1
323,238,239,322

-1

G9

8,8,8, -1,-1, 31,34,1060,,1
237,238,324

-1

G9

8,8,16, -1,-1, 31,34,1060,,1
324,238,323

-1

G10

4,16 -1,-1, 34,1060,,1
238,235,236,239

-1

G10

4,8 -1,-1, 34,1060,,1
237,234,235,238

-1

G9

8,8,8 -1,-1, 31,34,1060,,1
234,229,232

-1

G9

8,8,8 -1,-1, 31,34,1060,,1
235,234,232

-1

G9

8,8,8 -1,-1, 31,34,1060,,1

```

229,230,232
-1
G10
  8,16,      -1,-1,      34,1060,,1
  235,232,233,236
-1
G10
  8,16      -1,-1,      34,1060,,1
  232,230,231,233
-1
G10
  22,16     -1,-1,      34,1060,,1
  228,231,230,227
-1
G10
  22,8      -1,-1,      34,1060,,1
  227,230,229,226
-1
G10
  8,16      -1,-1,      34,1060,,1
  327,228,227,326
-1
G10
  8,8       -1,-1,      34,1060,,1
  326,227,226,325
-1
G10
  16,16     -1,-1,      34,1060,,1
  225,327,326,224
-1
G10
  16,8      -1,-1,      34,1060,,1
  224,326,325,223
-1
*
scale 0.606061,,101,18126
* interface surface 1D elements, type 33
* el,#,type,prop,n1,n2,total,incr1,incr2
* tungsten gaps pr=151 pressure contact,152=steel wool
* bottom 0.0 gaps
el  20001,33,151, 3120,6001, 10,1,1
el  20011,33,151, 3130,6132,  4,1,1
el  20015,33,151, 3134,6197,  3,1,1
el  20018,33,151, 6121,4157, 10,1,1
el  20028,33,151, 6192,4238,  4,1,1
el  20032,33,151, 6245,4263,  2,1,1
el  20034,33,151, 6247,4145
* gap steel wool
el  20035,33,152, 6199,4001, 13,4,12
* side tungsten - 0.003" gaps
el  20048,33,153, 4261,6248

```

el 20049,33,153, 4356,6252, 3,5,4
 el 20052,33,153, 4376,6312, 58,5,4
 el 20110,33,153, 4671,6544, 2,5,4
 el 20112,33,153, 4686,6552, 6,5,4
 el 20118,33,153, 4721,7317, 3,5,4
 * .07576" gap - steel wool
 el 20121,33,156, 6274,606, 4,11,2
 el 20125,33,156, 6597,614, 66,11,2
 el 20191,33,156, 7362,746, 3,7,2
 * .03788" gap - steel wool, top and bottom
 el 20194,33,154, 4261,6248
 el 20195,33,154, 4279,6249, 3,1,1
 el 20198,33,154, 4327,6265, 10,1,1
 el 20208,33,154, 7325,4731
 el 20209,33,154, 7326,4758, 3,1,1
 el 20212,33,154, 7345,4778, 4,1,1
 el 20216,33,154, 7371,4803, 6,1,1
 * top tungsten - 0.0 gap
 el 20222,33,155, 5157,7377, 12,1,1
 el 20234,33,155, 5190,7546, 4,1,1
 el 20238,33,155, 5211,7550, 3,1,1
 el 20241,33,155, 7533,5309, 12,1,1
 el 20253,33,155, 7650,5321, 6,1,1
 el 20259,33,155, 7656,5304
 * gap steel wool
 el 20260,33,157 7552,5213
 el 20261,33,157, 7560,5244, 13,8,5
 * contact-outer shell and bottom plate, low press cont.
 ***weld at el 20401
 el 20401,33,109, 3148,101
 el 20402,33,161, 3160,111 7,12,10
 * contact-bottom cavity shell and outer shell, low press cont.
 ***weld at el 20409
 el 20409,33,1090, 4012,171
 el 20410,33,161, 4024,259, 12,12,10
 el 20422,33,161, 4340,379, 4,2,10
 el 20426,33,160, 4346,409 ;.303" lip
 el 20427,33,160, 4336,606 ;.303" lip
 * contact-bottom cavity shell and bottom plate, low press cont.
 el 20428,33,162, 3136,4001
 el 20429,33,162, 3222,4002, 11,1,1
 * contact-lid and outer shell at top .007"
 el 20440,33,163, 3360,2495
 el 20441,33,163, 3368,2757, 3,8,10
 el 20444,33,163, 3400,2787, 4,8,10
 *
 el 20448,33,160, 750,4808, 2,1,30 ;.303" lip
 * contact-cavity and outer shells gap=.007"
 el 20450,33,163, 4838,751
 el 20451,33,163, 4840,2295, 4,2,10
 el 20455,33,163, 4862,2335, 4,8,10


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el 20459,33,163, 4902,2375, 12,8,10
***weld at el 20471
el 20471,33,1090, 4998,2495
* contact lid and cavity top 0.0 gap
el 20472,33,164, 4991,3353, 8,1,1
* contact cavity wall and plug - lower vertical I/F .010"
el 20480,33,165, 5012,4707
el 20481,33,165, 5024,4717, 3,12,5
el 20484,33,165, 5072,4737, 4,12,5
* contact cavity wall and plug - horizontal plane 0.0 gap
el 20488,33,166, 4752,5169, 5,1,1
el 20493,33,166, 4774,5195, 3,1,1
el 20496,33,166, 4798,5215, 4,1,1
* contact cavity wall and plug - upper vertical I/F .030"
el 20500,33,167 5218,4801
el 20501,33,167, 5223,4855, 4,5,8
el 20505,33,167, 5248,4895, 13,5,8
* contact lid and plug - .019"@top,.0303"@side
el 20518,33,167, 5308,3353
el 20519,33,167, 5394,3361, 2,5,8
el 20521,33,167, 5404,3332
el 20522,33,168, 5366,3233, 19,1,1
el 20541,33,168, 5401,3329, 4,1,1
* gap between cask and impact limiter
* lower segment 0.0 gp
el 20825,33,170, 3001,8197, 17,1,1
el 20842,33,170, 3138,8214, 11,1,1
el 20853,33,170, 101,8224
el 20854,33,170, 102,9289
el 20855,33,170, 103,9288
el 20856,33,170, 104,9287
el 20857,33,170, 105,9286
el 20858,33,170, 106,9285
el 20859,33,170, 107,9284
el 20860,33,170, 108,9283
el 20861,33,170, 109,9282
el 20862,33,170, 110,9281
el 20863,33,170, 181,9281
el 20864,33,170, 182,9569, 3,1,1
* pr171=0.121" air gap
el 20867,33,171, 215,9812
el 20868,33,171, 218,9805
el 20869,33,171, 222,9799
el 20870,33,171, 227,9794
el 20871,33,171, 233,9790
el 20872,33,171, 240,9787
el 20873,33,171, 248,9785
el 20874,33,171, 440,10772, 16,11,1
el 20890,33,171, 1503,11029, 7,11,1
el 20897,33,171, 1580,11521, 3,11,5
* upper segment

```

el	20900,33,171,	2174,18111,	4,11,5
el	20904,33,171,	2218,17736,	6,11,1
el	20910,33,171,	2284,17742	
el	20911,33,171,	2526,17530,	20,11,1
el	20931,33,171,	2746,16694	
el	20932,33,171,	2861,16686	
el	20933,33,171,	2864,16679	
el	20934,33,171,	2868,16673	
el	20935,33,171,	2873,16668	
el	20936,33,171,	2879,16664	
el	20937,33,171,	2886,16661	
* 0.0 gap			
el	20938,33,170,	3309,15481,	19,1,1
el	20957,33,170,	3349,15500,	4,1,1
el	20961,33,170,	3418,15504,	7,1,1
el	20968,33,170,	2817,15510	
el	20969,33,170,	2818,16234,	9,1,1
el	20978,33,170,	2855,16242	
el	20979,33,170,	2856,16628,	3,1,1
* 304SS impact limiter shell			
* bottom			
el	21001,33,107,	8225,8226,27,1,1	
el	21028,33,107,	8929,8945,5,16,16	
el	21033,33,107,	8673,8689,15,16,16	
el	21048,33,107,	8673,8674,15,1,1	
el	21063,33,107,	9609,9610,10,1,1	
el	21073,33,107,	9893,9894,7,1,1	
el	21080,33,107,	10077,10078,7,1,1	
el	21087,33,107,	10261,10262,16,1,1	
el	21103,33,107,	10788,10789,7,1,1	
el	21110,33,107,	11036,11037,15,1,1	
el	21125,33,107,	11051,11067,15,16,16	
el	21140,33,107,	11307,11323,6,16,16	
el	21146,33,107,	11419,11435,7,16,16	
el	21153,33,108,	8197,8198,27,1,1	
el	21180,33,108,	9281,9282,9,1,1	
el	21189,33,107,	9568,9569,3,1,1	
el	21190,33,107,	9820,9812	
el	21191,33,107,	9812,9805	
el	21192,33,107,	9805,9799	
el	21193,33,107,	9799,9794	
el	21194,33,107,	9794,9790	
el	21195,33,107,	9790,9787	
el	21196,33,107,	9787,9785	
el	21197,33,107,	10771,10772,16,1,1	
el	21213,33,107,	11028,11029,7,1,1	
el	21220,33,107,	11516,11517,15,1,1	
* top			
el	21301,33,107,	15451,15452,29,1,1	
el	21330,33,107,	15721,15737,15,16,16	
el	21345,33,107,	15961,15962,15,1,1	

el 21360,33,107, 16454,16455,7,1,1
 el 21367,33,107, 16623,16624,3,1,1
 el 21370,33,107, 16887,16888,7,1,1
 el 21377,33,107, 17015,17016,7,1,1
 el 21384,33,107, 17023,17024,21,1,1
 el 21405,33,107, 17551,17552,7,1,1
 el 21412,33,107, 17743,17744,15,1,1
 el 21427,33,107, 17743,17759,15,16,16
 el 21443,33,107, 17999,18015,7,16,16
 el 21450,33,107, 18111,18112,15,1,1
 el 21565,33,107, 17735,17736,7,1,1
 el 21572,33,107, 17529,17530,21,1,1
 el 21573,33,107, 16630,16661
 el 21574,33,107, 16661,16664
 el 21575,33,107, 16664,16668
 el 21576,33,107, 16668,16673
 el 21577,33,107, 16673,16679
 el 21578,33,107, 16679,16686
 el 21579,33,107, 16686,16694
 el 21580,33,108, 15481,15482,29,1,1
 el 21609,33,108, 16233,16234,9,1,1
 el 21618,33,108, 16627,16628,3,1,1

*

* outer surface convective elements - 32's

* surface 1

el 22001,32,110, 8225,8226,27,1,1

* surface 2

el 22028,32,111, 8929,8945,5,16,16

el 22033,32,111, 8673,8689,15,16,16

* surface 3

el 22048,32,112, 8673,8674,15,1,1

el 22063,32,112, 9609,9610,10,1,1

el 22073,32,112, 9893,9894,7,1,1

* surface 4

el 22080,32,113, 10077,10078,7,1,1

el 22087,32,113, 10261,10262,16,1,1

el 22106,32,113, 10788,10789,7,1,1

el 22113,32,113, 11036,11037,15,1,1

* surface 5

el 22128,32,114, 11051,11067,15,16,16

el 22143,32,114, 11307,11323,6,16,16

el 22149,32,114, 11419,11435,7,16,16

* surface 6 side

el 22156,32,115, 1602,1613,52,11,11

* surface 7

el 22208,32,116, 17743,17759,15,16,16

el 22223,32,116, 17999,18015,7,16,16

* surface 8

el 22230,32,117, 17743,17744,15,1,1

el 22245,32,117, 17551,17552,7,1,1

el 22252,32,117, 17023,17024,21,1,1

```

* surface 9
el 22273,32,118, 15961,15962,15,1,1
el 22288,32,118, 16454,16455,7,1,1
el 22295,32,118, 16623,16624,3,1,1
el 22298,32,118, 16887,16888,7,1,1
el 22305,32,118, 17015,17016,7,1,1
* surface 10
el 22312,32,119, 15721,15737,15,16,16
* surface 11
el 22327,32,120, 15451,15452,29,1,1
* cavity decay heat boundary elements
el 23001,32,121, 4227,4228,9,1,1
el 23010,32,121, 4236,4372
el 23011,32,121, 4372,4377,57,5,5
el 23069,32,121, 4657,4667
el 23070,32,121, 4667,4672
el 23071,32,121, 4672,4682
el 23072,32,121, 4682,4687,5,5,5
el 23077,32,121, 5001,5002,11,1,1
me 0.001
* Element Properties - axisymmetric
* stif34 - pr,pr#,mat#,thk,q,h,t(bath)
pr 101,1,0.0,0.0,0.0,0.0,0.0 ; 304ss outer shell. NM 101, thermal
Properties located in 1.
See PR record, attached.

pr 102,2,0.0,0.0,0.0,0.0,0.0 ; 304ss bottom plate and lid
pr 103,3,0.0,0.0,0.0,0.0,0.0 ; 304ss cavity shell
pr 104,4,0.0,0.0,0.0,0.0,0.0 ; 304ss plug shell
pr 105,5,0.0,0.0,0.0,0.0,0.0 ; tungsten
pr 106,6,0.0,0.0,0.0,0.0,0.0 ; foam-15 pcf lower IL
pr 1060,66,0.0,0.0,0.0,0.0,0.0 ; foam-21 pcf upper IL
* stif33 input - pr,pr#pr,mat#,area,q,conv flag, h
pr 107,7,.105,0.0,0.0,0, ; impact limiter 12 gage shell
pr 108,7,.188,0.0,0.0,0, ; impact limiter .188" base plate
pr 109,8,.625,0.0,0.0,0, ; 5/8" weld
pr 1090,8,.50,0.0,0.0,0, ; 1/2" weld
pr 1,-201,-202,.29 ; 304ss PR record for 1, points to Properties
records, 201 and 202. Minus (-) in
front identified that the properties
are a function of Temperature.

pr 2,-201,-202,.29 ; 304ss
pr 3,-201,-202,.29 ; 304ss
pr 4,-201,-202,.29 ; 304ss
pr 5,-203,-204,.654 ; tungsten
pr 6,.00227,.353,.0087 ; foam - 15 lb/ft3
pr 66,.00261,.353,.0122 ; foam - 21 lb/ft3
pr 7,-201,-202,.29 ; a304 ss overpack shell
pr 8,-201,-202,.29 ; a304 weld material
* stif33 input - elpr,matpr,area,heat flux,conv flag, h
pr 151,11,0.32, 0.0,1,0.231 ; 0.0 y gap tungsten-304 I/F
pr 152,12,0.36, 0.0,, ; .038" x gap with stl wool tungsten I/F

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pr 153,18,0.30, 0.0,, ; 0.003" x gap tungsten I/F
pr 154,11,0.31, 0.0,1,0.231 ; 0.0 y gap, shimmed, I/F
pr 155,11,0.29, 0.0,1,0.231 ; 0.0 y gap tungsten-304 I/F
pr 156,12,0.30, 0.0,, ; .76" x gap with stl wool tungsten I/F
pr 157,12,0.34, 0.0,, ; top tungsten w/ stl wool
pr 160,11,.15, 0.0,1,0.231 ; .30" lip cavity to outer shells
pr 161,11,0.31, 0.0,1,0.231 ; 0.0 x gap 304 to 304 I/F's
pr 162,11,0.30, 0.0,1,0.231 ; 0.0 y gap 304 to 304 I/F's
pr 163,13,0.25, 0.0,, ; 0.007" x gap lid+cavity-outer
pr 164,11,0.39, 0.0,1,0.231 ; 0.0 y gap lid to cavity surface @ bolt
pr 165,14,0.18, 0.0,, ; 0.010" x-gap plug-cavity wall lower vertical
pr 166,11,0.21, 0.0,1,0.231 ; 0.0 y gap horz plane cavity-plug
pr 167,15,0.26, 0.0,, ; 0.030" x gap plug-cavity wall upper vertical
pr 168,16,0.25, 0.0,, ; 0.019" y gap conv+rad plug-lid
pr 170,11,0.31, 0.0,1,0.231 ; 0.0 y gap cask-over pack i/f
pr 171,17,0.32, 0.0,, ; cask-over pack 0.121" x gap
* Thermal material properties - prop#,kx,c,m,e,ky,kz
pr 11,0.0,0.0,0.0,,, ; convect.i/p see pr
151,161,162,164,166,169,170
pr 12,.068,.24,.029 ; stl wool -
k=.1*k(304),c=c(air),den=.1*d(304)
pr 13,-216,-220,-221 ; enclosed air pr 163 s=.012"
pr 14,-217,-220,-221 ; enclosed air pr 165 s=.016"
pr 15,-218,-220,-221 ; enclosed air pr 153, and 167 s=.050"
pr 16,-219,-220,-221 ; enclosed air pr 168 s=.031"
pr 17,-222,-220,-221 ; air gap 0.2" at over pack i/f
pr 18,-223,-220,-221 ; air gap 0.005" at side tungsten i/f
pr 201, .6851, 4.544e-4,-4.126e-8 ; poly.coef.304ss cond. Polynomial
pr 202, .1120, 3.504e-5,-1.080e-8 ; poly.coef.304ss.sp.ht. Coefficients.

```

REFER TO THE CONDUCTIVITY AND SPECIFIC HEAT EQUATIONS PROVIDED IN CHAPTER 3, Paragraph 3.2.1.1, FOR A COMPARISON OF THE COEFFICIENTS SHOWN ABOVE, AND THOSE PRESENTED IN THE EQUATIONS.

```

pr 203, 3.673, 4.028e-4,-4.167e-7 ; tung.cond-test data
pr 204, 3.631e-2, 8.017e-6,-1.807e-9 ; tung.sp.ht.-test data
pr 205, 9.326e-3, 6.712e-6, 2.299e-8 ; h surf.1, e=.52
pr 206, 9.326e-3, 6.712e-6, 2.299e-8 ; h surf.2, e=.52
pr 207, 9.326e-3, 6.712e-6, 2.299e-8 ; h surf.3, e=.52
pr 208, 1.094e-2, 9.294e-6, 2.185e-8 ; h surf.4, e=.52
pr 209, 9.326e-3, 6.712e-6, 2.299e-8 ; h surf.5, e=.52
pr 210, 8.395e-3, 9.959e-6, 5.634e-9 ; h surf.6, e=.20
pr 211, 9.326e-3, 6.712e-6, 2.299e-8 ; h surf.7, e=.52
pr 212, 1.094e-2, 9.294e-6, 2.185e-8 ; h surf.8, e=.52
pr 213, 9.326e-3, 6.712e-6, 2.299e-8 ; h surf.9, e=.52
pr 214, 9.916e-3, 7.736e-6, 2.252e-8 ; h surf.10, e=.52
pr 215, 9.326e-3, 6.712e-6, 2.299e-8 ; h surf.11, e=.52
pr 216, 1.130e-3, 2.041e-6, -3.541e-13 ; k enclosed air pr 163-.007"
pr 217, 1.138e-3, 2.022e-6, 1.691e-10 ; k enclosed air pr 165-.010"
pr 218, 1.196e-3, 1.900e-6, 1.298e-9 ; k enclosed air pr 167-.030"
pr 219, 1.164e-3, 1.967e-6, 6.773e-10 ; k enclosed air pr 168-.019"

```

```

pr 220, 2.402e-1, -1.401e-6, 3.995e-8, -1.570e-11 ; Cp enclosed air
pr 221, 4.684e-5, -7.150e-8, 5.869e-11, -1.834e-14 ; density enclosed air
pr 222, 1.458e-3, 1.346e-6, 6.437e-9 ; k enclosed air overpack pr171-
.121"
pr 223, 1.118e-3, 2.065e-6, -2.262e-10 ; k enclosed air tungsten pr153-
.003"
* 32's pr,pr#,h,thk,Temp,q,e
* solar heat
pr 110,-205, 0.0,100, 0.4267,0.0 ; conv. surf.1 - 200c/cm2
pr 111,-206, 0.0,100, 0.8533,0.0 ; conv. surf.2 - 400c/cm2
pr 112,-207, 0.0,100, 0.8533,0.0 ; conv. surf.3 - 400c/cm2
pr 113,-208, 0.0,100, 0.8533,0.0 ; conv. surf.4 - 400c/cm2
pr 114,-209, 0.0,100, 0.4267,0.0 ; conv. surf.5 - 200c/cm2
pr 115,-210, 0.0,100, 0.8533,0.0 ; conv. surf.6 - 400c/cm2
pr 116,-211, 0.0,100, 0.4267,0.0 ; conv. surf.7 - 200c/cm2
pr 117,-212, 0.0,100, 0.8533,0.0 ; conv. surf.8 - 400c/cm2
pr 118,-213, 0.0,100, 0.8533,0.0 ; conv. surf.9 - 400c/cm2
pr 119,-214, 0.0,100, 0.8533,0.0 ; conv. surf.10- 400c/cm2
pr 120,-215, 0.0,100, 0.4267,0.0 ; conv. surf.11- 200c/cm2
pr 121,0.0, 0.0,70, 2.875 ; decay heat - 400 W
sc 20,1,1,10,0, 1,0,0.1,1.0,70, 1.0,1,, ; SS with decay heat
end

```

WARNING

Generate 2D Region by Isoparametric Mapping (G10)

G10 generates regions of 3- or 4-node elements and nodes by mapping with quadratic, isoparametric functions. Both flat and curved surfaces can be generated, with curved surfaces and curved boundaries mapped by parabolic functions. Mesh density is controlled by the location of mid-side nodes. By placing the mid-side node closer to a corner, the mesh density is increased in the corner region. This generator is flagged by a record containing only the descriptor G10 .

The coordinates of the control points (corners and mid-sides of the generated region) may entered directly, or by defining them on CND records and specifying the CND node ID numbers.

Control Data Record for Generator 10

ITEM	DESCRIPTION	SYMBOL
1	Number of nodes along side 1	N1
2	Number of nodes along side 2	N2
3	Number of first node (1)	NND1
4	Number of first element (2)	NEL1
5	Element type (3)	NET
6	Associated property set	MAT
7	Flag for local coordinates (4)	LCS
8	Flag for control points (5)	ICTLPT

Notes

- 1) If NND1=-1, node numbering continued from highest node number. The highest node and element numbers are listed on file MAX_NODE.
- 2) If NEL1=-1, element numbering continued from the highest element number. If NEL1=0, no elements are generated.
- 3) If NET, MAT, LCS and ICTLPT are omitted, values from last call to G10 used.
- 4) If control nodes are entered in local coordinates, set LCS=1
- 5) If the corners and mid-sides of the generated region are defined on Control Point Records, set ICTLPT=1 . Otherwise set ICTLPT=0 .

First Corner Node Data Record

If ICTLPT=0:

ITEM	DESCRIPTION	SYMBOL
1	X-coordinate of first node	X1
2	Y-coordinate of first node	Y1
3	Z-coordinate of first node	Z1
4	X-coordinate of second node	X2
5	Y-coordinate of second node	Y2
6	Z-coordinate of second node	Z2

If ICTLPT=1:

ITEM	DESCRIPTION	SYMBOL
1	ID number of first corner point	NCP(1)
2	ID number of second corner point	NCP(2)
3	ID number of third corner point	NCP(3)
4	ID number of forth corner point	NCP(4)

Second Corner Node Data Record

This record is omitted if the corners and mid-sides of the generated region are specified by defining the points with ID numbers.

ITEM	DESCRIPTION	SYMBOL
1	X-coordinate of third node	X3
2	Y-coordinate of third node	Y3
3	Z-coordinate of third node	Z3
4	X-coordinate of forth node	X4
5	Y-coordinate of forth node	Y4
6	Z-coordinate of forth node	Z4

Mid-Side Node Data Record

This data record defines a mid-side node, and is required for each mid-side node. Mid-side nodes are only required for curved boundaries.

If ICLTPT=0:

ITEM	DESCRIPTION	SYMBOL
1	Number of mid side node (1)	NND
2	X-coordinate of mid-side node	X
3	Y-coordinate of mid-side node	Y
4	Z-coordinate of mid-side node	Z

If ICLTPT=1:

ITEM	DESCRIPTION	SYMBOL
1	Number of mid side node (1)	NND
2	ID number of mid-side point	NCP

Notes

1) The four corner nodes are numbered 1-4. The mid-side nodes are numbered 5-8 as follows:

Corner Node Nos.	Mid-Side Node No.
1,2	5
2,3	6
3,4	7
4,1	8

Termination Record for Mid-Side Nodes

This data record terminates mid-side data. The record contains only -1, and is required even if no mid-side nodes are entered.

<u>ITEM</u>	<u>DESCRIPTION</u>	<u>SYMBOL</u>
	-1	

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Element Property Set Record (PR)

All element data is entered on Element Property records. This section defines the format of Element Property records, the specific data entries are defined in the Element Property Manual for the various element types.

The connection between elements and property records is the element property number. This number is entered on the element definition record (or specified to the model generator) and defines the first property record required by the element.

ITEM	DESCRIPTION	SYMBOL
1	Descriptor (PR)	
1	Property set number (1)	NM
2	First field of property set	PR_1
3	Second field of property set	PR_2
...
8	Eighth field of property set	PR_8

Notes:

- 1) Maximum value, NM=99999

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Thermal Material Properties (THE_PROP)

This record defines constant thermal properties, or pointers to temperature-dependent property sets. For temperature-dependent properties, enter the negative of number the temperature-dependent property set in place of the constant value. Data for temperature-dependent property sets is defined below.

ITEM	DESCRIPTION	SYMBOL
	Designator (PR)	
	Property set number	NM
1	X-conductivity / temp-depend property set (1)	Kx
2	Specific heat / temp-depend property set (1)	C
3	Lb-mass density / temp-depend property set (1)	m
4	Emissivity	e
5	Thermal conductivity in global y-direction (2)	Ky
6	Thermal conductivity in global z-direction (3)	Kz
7	Coordinate system for conduction properties (4)	MCS

Notes

- 1) For temperature-dependent properties, set value to NEGATIVE of temperature-dependent property set number.
- 2) Default $K_y = K_x$
- 3) Default $K_z = K_x$
- 4) For orthotropic conduction, MCS is the number of the coordinate system that defines the directions of K_x , K_y and K_z . For MCS=0 in 2D problems, K_x and K_y are oriented in the local x and y directions. For 3D problems, with MCS=0, K_x , K_y and K_z are oriented in the global x, y, and z directions.

Temperature-Dependent Thermal Properties

Temperature dependent properties are represented by a polynomial function of temperature:

$$f(t) = a_0 + a_1*t + a_2*t^2 + a_3*t^3 + \dots$$

The coefficients a_0 , a_1 , a_2 , ..., are entered on this property set record. From 1 to 8 coefficients may be entered. Trailing null coefficients may be omitted, but intermediate null coefficients must be entered.

Temperature-dependent properties may be specified for the following element properties:

STIF31: K,C,H,m
STIF32: H
STIF33: K,C,m
STIF34: K,C,H,m

STIF35: K,C,m
STIF36: K,C,H,m
STIF37: K,C,m
STIF38: K,C,m
STIF39: K,C,m

where, K:conduction, C:capacitence, m:lb-mass, H:convection

The initial temperature specified on the Solution Control record is required to determine initial property values. Temperature-dependent materials are assumed to be isotropic.

ITEM	DESCRIPTION	SYMBOL
	Designator (PR)	
	Property set number	NM
1	First coefficient	a0
2	Second coefficient	a1
...		...
	Eighth coefficient	a7

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**3.5.6 Description of LIBRA Files and Post-Processors:
AOS Safety Analysis Report**

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**Description of Libra Files and Post-Processors:
AOS Safety Analysis Report**

Prepared for: GE-Hitachi Nuclear Energy
PO No. 431004505
May 3, 2007

Prepared by: Structural Mechanics Analysis, Inc.
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1.0 Introduction

The Alpha-Omega Services (AOS) Safety Analysis Report (SAR) applies to four radioactive materials Type B cask configurations. These four cask configurations are designated by their relative size as AOS-025, AOS-050, AOS-100, and AOS-165. Configuration AOS-025 is approximately 25% the size of configuration AOS-100, configuration AOS-050 approximately 50%, and configuration AOS-165 approximately 165% in comparison to the AOS-100 model. The following provides a description of the Libra post-processors used to perform the structural and thermal analyses to support the preparation of the SAR for the four AOS cask models.

Notwithstanding the scaled nature of the four configurations, the thermal and stress analyses for the four models are not scalable. Rather, an independent set of analyses is required for each model. While the analyses are not scalable, the finite element models used in the analyses are largely scaled, although there are significant differences between models, particularly between model AOS-165 and the others.

Almost all of the thermal and stress analyses in the SAR are based on application of the Structural Mechanical Analysis, Inc. (SMA) Libra finite element program. The Libra program has been used by GE-Hitachi Nuclear Energy Americas, LLC ("GEH") for a number of years, and was used in the licensing of the Model 2000 Type-B transport packaging. SMA has proprietorship of the Libra program, as a result, SMA was able to develop sophisticated post-processing tools integrated with the Libra program, that facilitated the AOS analyses.

The majority of the SAR analyses permit use of axisymmetric, finite element models, since for the majority of load cases the cask, loading, and boundary conditions are axisymmetric. As a result, four axisymmetric models were developed corresponding to the four cask configurations, and these models are the cornerstones of all the finite element analyses in the SAR. For load cases such as drop and transport, where assumptions of axisymmetric loading and boundary conditions are not applicable, 3D finite element models are used. These 3D models are generated from the axisymmetric models by rotation of the model. In this way, there is a well-defined relationship between elements in the axisymmetric and 3D models, and this relationship allows combining stress resultants from the two models.

The two U.S. Nuclear Regulatory Commission (NRC) documents that govern the analyses included in the SAR are Regulatory Guides 7.6 and 7.8. Reg. Guide 7.6 defines the allowable stresses for nuclear shipping casks, while Reg. Guide 7.8 defines the required loading conditions and load combinations. Further, Reg. Guide 7.6 specifies allowable stresses in terms of membrane and bending stresses, or more generally stress resultants. Stress resultants are not a direct output of finite element analyses. For the detailed models used in the AOS analyses, forming stress resultants involves identifying and integrating element stresses across a number selected cask cross-sections. This is an arduous and time consuming task. In addition, NRC Reg. Guide 7.8, which defines the load combinations that must be met, presents additional difficult tasks for analyses based on the finite element method.

1.0 Introduction - Cont'd

Two major post-processing programs were developed to facilitate evaluation of stress resultants and stress combinations required by NRC Reg. Guides 7.6 and 7.8. The first, PmPb, forms the stress resultants required by Reg. Guide 7.6, while the second, CmbLds, forms the load combinations required by Reg. Guide 7.8. The methodology and application of these programs are described in detail in this report. The solution process for all of the four cask configurations involves first finding stresses corresponding to a set of basic load conditions, and then finding the stress combinations. For thermal loading conditions, one or more thermal solutions must be found before solving for stresses. After determining load case stresses, stress resultants are formed by application of the PmPb post-processing program. The PmPb program generates files containing stress resultants for the basic loading conditions. After all of the loading conditions have been run, and corresponding files of stress resultants generated by PmPb, The CmbLds program is executed. The CmbLds program reads the files generated by PmPb, forms the required combinations, and compares the combined stresses to the allowables in Reg. Guide 7.6. This entire process is automated by a Windows Command program, Run_AOS. A section of the Run_AOS batch program is shown in Appendix F.

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2.0 PmPb Post Processor Program

The PmPb program forms the stress resultants referenced by Reg. Guide 7.6. The PmPb is a suite of three programs: PmPbData, PmPb, and PmPb3D. Each of these three programs is described below. All three programs use the input file PmPb.in, which lists the elements at each model cross-section where stress resultants are evaluated. A sample PmPb.in file is shown in Appendix A.

The cross-sections on which PmPb operates are shown in Figures 1 and 2. Figure 1 shows the cross-sections for model 165, and Figure 2 shows the cross-section for models 025, 050, and 100. Model 165 has 25 stress cross-sections, while models 025, 050, and 100 have 22 stress cross-sections. The larger number of cross-sections for model 165 is due to the split outer shell. The elements comprising the cross-sections shown in Figures 1 and 2 are defined on the respective input data file PmPb.dat. The 165 cask axisymmetric, and three dimensional finite element models are shown in Figures 3 and 4, respectively.

2.1 AOS Input Load Case designations

AOS Libra input data files all have designations starting with LCnnn, where nnn is a three digit load case number; and ending with suffix mmm, where mmm is a three digit model number. For example, the input file for thermal load case 101, model 025 is, LC101.025. Additional file description is entered following the load case number, with a hyphen preceding the entry. For example LC101-2500-UPDATE.025 is the designation for input file for thermal load case 101, 2500 watts, updated.

AOS load case numbers define the type of loading involved in the load case. Load cases numbered 101-199 are thermal loadings. Load cases 201-299 are pressure or other axisymmetric normal loadings. Load cases 301-399 are accident condition loadings. The load case types are used by the CmbLds program to determine allowable stress for load combinations.

2.2 PmPbData Program

PmPbData program determines the geometry data for the PmPb program, and stores this data on the file PmPb.dat. This geometry function is separated from the PmPb program for efficiency, as it needs to be performed only once for each model. PmPbData must be executed immediately following an execution of the Libra program, as it uses Libra output. The program reads Libra model geometry data from binary file Tape9, and generates the geometric data required to form membrane and moment stress resultants for each stress cross-section. This data is written to the file PmPb.dat, and is utilized by both PmPb and PmPb3D.

2.3 PmPb Program

The PmPb program generates files of membrane and bending stress resultants for axisymmetric loading conditions. The program utilizes the geometry data on the file PmPb.dat, the cross-section elements defined on PmPb.in, and Libra stress data on the binary file Tape8. PmPb generates output files labeled LOAD_CASE.nnn, where nnn is the load case number. For each LCnnn file there is a corresponding LOAD_CASE.nnn file. A typical output file generated by PmPb is shown in Appendix B. Output files list maximum principal stress, and membrane and bending stress for each cross-section. The PmPb program must be executed immediately following execution of a Libra stress run.

2.4 PmPb3D Program

The PmPb3D program generates files containing membrane and moment stress resultants for 3D loading conditions. The program utilizes the geometry data on the file PmPb.dat, cross-section element data on the file PmPb.in, and Libra stress output on the binary file Tape8. All AOS 3D models are generated from axisymmetric models. As a result, each element along a meridian corresponds to a element in the corresponding axisymmetric model. PmPb3D finds the stress resultants for each element along a meridian, and outputs maximum values on the LOAD_CASE file. Stress combinations involving axisymmetric and 3D load cases conservatively combine maximum meridian 3D values with axisymmetric values. The output of PmPb3D is the same as PmPb, and a typical file shown in Appendix B.

2.5 GroupAllow Program

The GroupAllow program finds maximum temperatures at cross-sections where stress resultants are evaluated, and interpolates temperature-dependent, allowable stress data to find the allowable cross-section stress corresponding to these maximum temperatures. This program is executed only for thermal load cases, and is executed after a Libra thermal solution. The GroupAllow program generates files ALLOWABLES.nnn, where nnn is load case number, and the file is subsequently used by the CmbLds program. A typical GroupAllow output file is shown in Appendix C.

3.0 CmbLds Program

As described in Section 2.3, The PmPb program generates stress resultant files LOAD_CASE.nnn, where nnn is the load case number. The CmbLds program forms load combinations using these files, and also determines the allowable stresses against which the combined stresses are compared. A typical CmbLds.in file is shown in Appendix D.

The load case number nnn in the file name LOAD_CASE.nnn defines the type of loading, as described in Section 2.1. LOAD_CASE.nnn files list both membrane and bending stress for each stress cross-section. The ALLOWABES.nnn files, described in Section 2.5, specify allowable stresses for thermal loadings. Based on all this information, the CmbLds program determines the maximum combined stress, the minimum allowable stress, and the minimum margin of safety at all stress cross-sections. The maximum stresses and minimum allowables are output on the file CmbLds.out. A typical output section generated by CmbLds is shown in Appendix E. The table in Appendix E lists the combined stress, allowable stress, and minimum margins of safety for each cross-section. The overall minimum margin of safety is listed at the end of the table.

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4.0 AOS Files

The AOS input and output data files, PMPB verification files, and Libra Program files are contained on a single CD. The folders on this disk are listed below, and the following sections describe the contents of these folders.

aos-25	Input data files for AOS cask Model 025
aos-50	Input data files for AOS cask Model 050
aos-100	Input data files for AOS cask Model 100
aos-165	Input data files for AOS cask Model 165
aos-165-2500	Input data files for AOS cask Model 165, 2500 watts
PMPB_Verification	Verification report for post-processors
Source	Post-processors source code
aos-25-out	Output files for AOS cask Model 025
aos-50-out	Output files for AOS cask Model 050
aos-100-out	Output files for AOS cask Model 100
aos-165-out	Output files for AOS cask Model 165
aos-165-2500-out	Output files for AOS cask Model 165, 2500 watts
drop-25	Files for AOS cask Model 025 30' drop analyses
drop-50	Files for AOS cask Model 050 30' drop analyses
drop-100	Files for AOS cask Model 100 30' drop analyses
drop-165	Files for AOS cask Model 165 30' drop analyses

4.1 Input Data Files

The five input data folders, aos-25 ... aos-165-2500, contain all files required to run the Libra stress and thermal analyses for the five-cask models. After establishing the Libra program (see Section 4.5), there is a two step process for executing Libra analyses and post-processing programs for a cask model: 1) copy the entire contents of an input data folder onto the Libra.app, or Libra.app.sub-folder, directory; 2) execute the batch program RUN_AOS.

All input data is in English units. For thermal problems temperatures are in degrees F, energy in Btu, and length in inches. For structural problems loads are in lb, moduli in lb/in², and length in inches.

Libra executions may take several hours. Output from the Libra runs and post-processors consist of a series of text files labeled Load_Case.nnn, where nnn represents the load case number, and a file labeled Cmb_Loads.out. The Load_Case.nnn files contain the Pm and Pb stress measures at the monitored cask cross-sections for the individual load cases. The Cmb_Loads.out file contains the load combination results, including margins of safety for all combined load cases.

4.2 PMPB Verification Files

The PMPB_Verification folder contains both a report and a verification problem for PMPB and Cmb_Loads post-processors. The verification problem is a simple flat-top cylindrical shell under pressure and thermal loads. The stress resultants as two shell cross-sections are determined analytically, and by the PMPB and Cmb_Loads post processors. The two sets of results are shown to compare well.

A folder containing a set of verification problems for the Libra program, with emphasis on the AOS problem types, is established with installation of the Libra program (see Section 4.5). The Source folder contains the Fortran source codes for the six post processing programs used in the AOS Libra analyses.

4.3 Output Data Files

The AOS-25-out ... AOS-165-2500-out folders contain selected output from the individual Libra load case analyses (see Section 2.1). Each folder contains the LOAD_CASE file (see Section 2.4), The ALLOWABLES file (see Section 2.5), and the Libra output file (TAPE6) for each input data file. The extensions on LOAD_CASE, ALLOWABLES, and TAPE6 files are the same as the input file extension.

4.4 Files for 30' Drop Analyses

The four drop analysis folders, drop-25 ... drop-165, contain input and selected output files for the 30' head-on, side and cg/corner drop analyses. Each folder contains files for a single model, and for the three drop analyses. The output files are plot files for force-energy curves, model displacement, and model stress. The file names have -force, -disp, or -stress to indicate content. File names containing -cold are plots for -40° F thermal conditions, all other files are for 75° F.

The same Libra input data file can be used for all three drop orientations, with non-applicable orientation data commented out by an asterisk in column 1. All of the plot files are BMP format files, and may be viewed by means of the MS Paint program. The displacement and stress files are for displacement fields close to, but not necessarily at maximum values.

The drop-165 folder also contains the Libra input data file slap-down.t5 for slap-down analysis. This file is specifically for AOS model 165 cask, but is easily adapted to other cask models by changing the model structure dimensions and contact stiffness values. Contact stiffness values are taken from the 30' side-drop analyses.

5.0 Libra Installation

Libra installation files are contained in the Libra64 folder. The Libra Program is installed by executing the SETUP program on the Libra64 folder. The SETUP program will request names for Libra Program and Application directories. Libra program files reside on the Program directory, and problems are executed from the Application directory or sub-directories. Default folder names are Libra64 for the program directory, and Libra.app for the application directory. The SETUP program will also prompt for installation of the 64-bit version of Libra. The 64-bit version should be installed only if the host operating system is 64 bits.

On Vista operating systems it may be necessary to set permission for running Script files before executing the Libra SETUP program. The following steps establish permission:

go to Control Panel
click on User Accounts
click on Turn user control on or off
uncheck user account control

After the Libra SETUP program is completed, the Libra program can be executed from the Start menu, or from the Command line in the Libra application folder. The AOS files are organized to run from the Libra Command line. To access the Libra Command-line, left click on the Libra Desktop icon. To then execute a Libra input file, at the Command prompt enter,

Libra input_file output_file

If output_file is omitted, the default file name is TAPE6. After a Libra execution, the model can be viewed by entering HPL0T at the command prompt, and stresses viewed by entering STRSPP. Both HPL0T and STRSPP are menu driven.

To execute a set of AOS analyses on the distribution disk, say \aos-25, read the entire contents of \aos-25 onto the application directory (or sub-directory), then enter run_aos at the Command prompt. This executes the batch program run_aos, which executes all of the files and post-processors for AOS Model 025. Output will be contained on a set of files labeled Load_Case.nnn, and on the file Cmb_Loads.out (see Sections 2.3 and 3.0).

Libra installation establishes a folder labeled Verification. This folder contains a number of verification problems for Libra elements and solution procedures. The thermal problems, and several of the structural problems are directly applicable to AOS analyses. In total, the verification problems in this folder encompass all of the Libra elements and solution procedures applied in the AOS analyses. The verification files described in Section 4.2 address the post-processors used in the AOS analyses, and are an adjunct to these Libra verification problems.

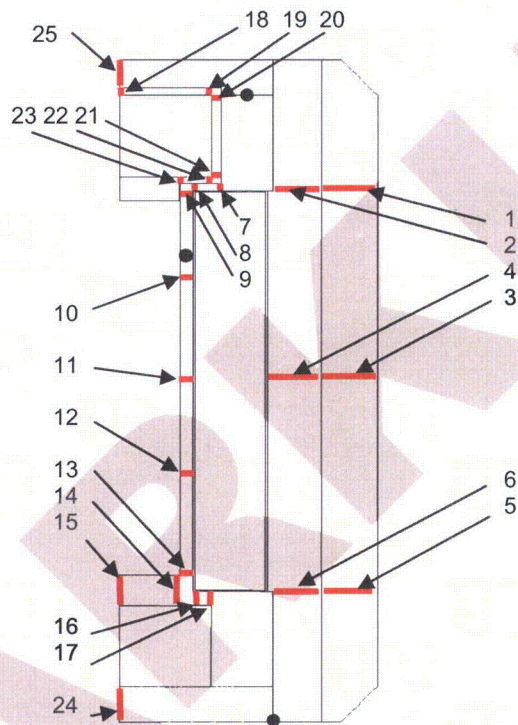


Figure 1. Model 165 PmPb Cross-Sections

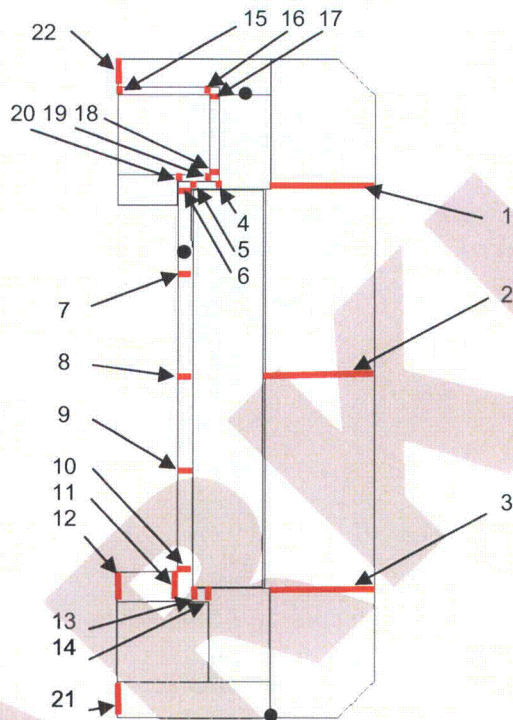


Figure 2. Models 025, 050 and 100 PmPb Cross-Sections

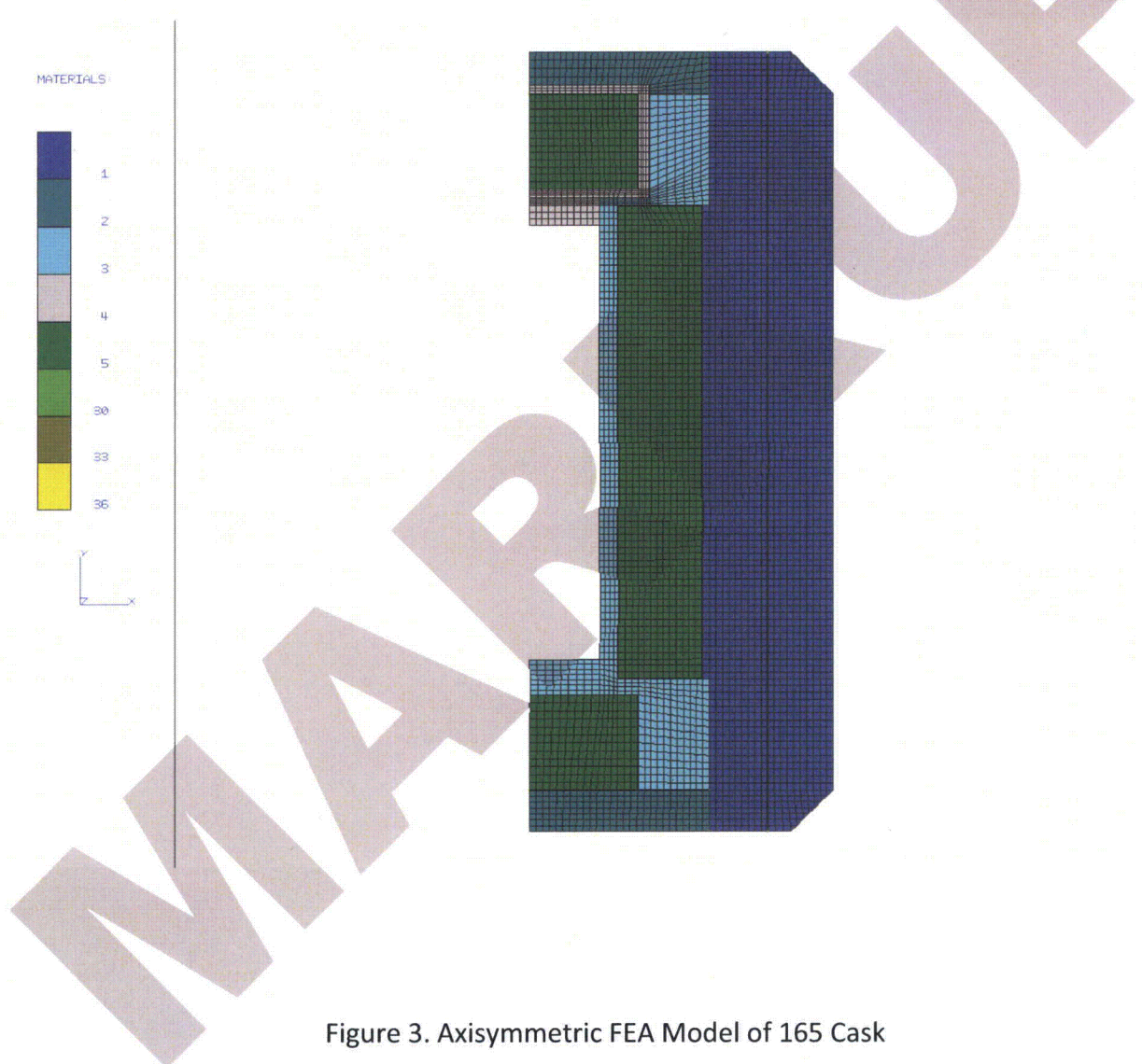


Figure 3. Axisymmetric FEA Model of 165 Cask

MATERIALS

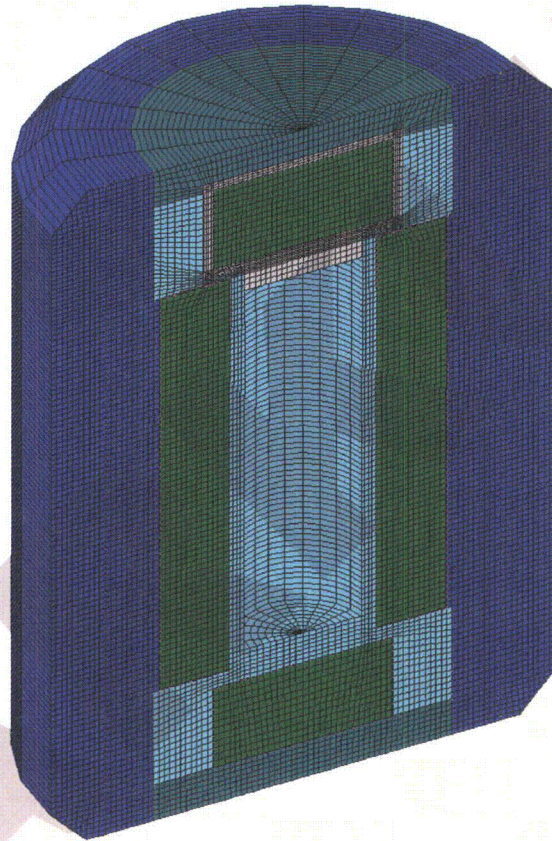
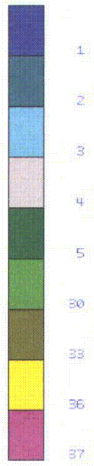


Figure 4. Three Dimensional FEA Model of 165 Cask

Appendix A. Typical PmPb.in File

The following is a typical PmPb.in file listing elements at each stress cross-section. For ease of viewing, cross-section entries are not confined to one line, and blank lines separate entries. In the actual file all section entries are on one line, and there are no blank lines.

1957, 1958, 1959, 1960, 1961, 1962, 1963, 1964, 1965, 2146, 2147, 2148, 2149, 2150,
2151, 2152, 2153, 2154, 2155

552, 904, 905, 906, 907, 908, 909, 910, 911, 912, 1587, 1588, 1589, 1590, 1591, 1592,
1593, 1594, 1595, 1596

348, 349, 350, 351, 352, 353, 354, 355, 356, 507, 508, 509, 510, 511, 512, 513, 514, 515,
516

4587, 4591, 4595, 4599

4572, 4575, 4578, 4581

552, 4553, 4554, 4555

4476, 4477, 4478, 4479

4408, 4409, 4410, 4411

4344, 4345, 4346, 4347

4280, 4281, 4282, 4283

4141, 4150, 4159, 4168, 4177, 4186, 4195

4133, 4142, 4151, 4160, 4169, 4178, 4187

4212, 4215, 4218, 4221

4214, 4217, 4220, 4223

5218, 5236, 5254

5235, 5253, 5271

5214, 5215, 5216, 5217

5166, 5167, 5168, 5169

5140, 5143, 5146, 5149

5122, 5126, 5130, 5134

3001, 3017, 3033, 3049, 3065, 3081, 3097

3190, 3208, 3226, 3244

Appendix B. PmPb output file, LOAD_CASE.101

The following is the PmPb output file for load case LC101.025. The file lists maximum principal stresses, and calculated membrane and bending stress at each section analyzed. Stresses are listed in both English and metric units.

Load Case_101 - 100F Ambient, Max Decay Heat

Stress (psi/MPa)

Location	Sigma_1	Sigma_2	Sigma_3	Pm	Pb
1	1.2232E+01 8.4340E-02	-2.5191E+01 -1.7369E-01	-1.8387E+00 -1.2677E-02	3.7423E+01 2.5803E-01	5.8177E+01 4.0111E-01
2	1.6225E+01 1.1187E-01	-3.2962E+01 -2.2727E-01	-6.5255E+00 -4.4992E-02	4.9187E+01 3.3913E-01	1.0016E+02 6.9059E-01
3	1.0870E+01 7.4943E-02	-2.3382E+01 -1.6122E-01	-1.1174E+00 -7.7043E-03	3.4252E+01 2.3616E-01	5.3526E+01 3.6905E-01
4	6.2382E+01 4.3011E-01	-2.3843E+02 -1.6439E+00	-4.1530E+01 -2.8634E-01	3.0081E+02 2.0740E+00	5.9563E+02 4.1067E+00
5	6.1432E+01 4.2356E-01	-2.6905E+02 -1.8550E+00	-1.2242E+02 -8.4406E-01	3.3048E+02 2.2786E+00	5.2038E+02 3.5879E+00
6	6.4534E+00 4.4494E-02	-1.3381E+02 -9.2256E-01	-1.5795E+02 -1.0890E+00	1.4026E+02 9.6705E-01	1.6725E+02 1.1532E+00
7	-1.9752E+00 -1.3619E-02	-4.9672E+01 -3.4248E-01	2.5928E+00 1.7877E-02	4.7697E+01 3.2886E-01	4.3899E+01 3.0267E-01
8	-2.0037E+00 -1.3815E-02	-4.9648E+01 -3.4231E-01	1.9949E-03 1.3755E-05	4.7644E+01 3.2850E-01	4.3457E+01 2.9962E-01
9	-1.9811E+00 -1.3659E-02	-4.9582E+01 -3.4185E-01	-5.2273E-01 -3.6041E-03	4.7600E+01 3.2819E-01	4.1764E+01 2.8795E-01
10	-7.5888E+00 -5.2323E-02	-6.6970E+01 -4.6174E-01	1.0700E+01 7.3772E-02	5.9381E+01 4.0942E-01	1.2009E+02 8.2802E-01
11	-1.6114E+01 -1.1110E-01	-1.0104E+02 -6.9668E-01	-5.3150E+01 -3.6645E-01	8.4930E+01 5.8557E-01	7.0193E+00 4.8396E-02
12	4.9440E+00 3.4087E-02	-1.1870E+02 -8.1839E-01	-1.1938E+02 -8.2311E-01	1.2364E+02 8.5248E-01	7.5796E+00 5.2260E-02

13	-1.3346E+01	-1.7829E+02	-2.9776E+01	1.6495E+02	8.7679E+01
	-9.2016E-02	-1.2293E+00	-2.0530E-01	1.1373E+00	6.0452E-01
14	-1.2832E+01	-1.5680E+02	3.6799E+00	1.4396E+02	9.5911E+01
	-8.8473E-02	-1.0811E+00	2.5372E-02	9.9259E-01	6.6128E-01
15	3.4752E+02	-3.2306E+02	-3.0278E+01	6.7058E+02	1.1250E+03
	2.3960E+00	-2.2274E+00	-2.0876E-01	4.6235E+00	7.7568E+00
16	1.2110E+02	-2.3963E+02	-7.8259E+01	3.6074E+02	5.8708E+02
	8.3498E-01	-1.6522E+00	-5.3958E-01	2.4872E+00	4.0478E+00
17	5.3313E+01	-1.6483E+02	7.7898E+00	2.1815E+02	3.7767E+02
	3.6758E-01	-1.1365E+00	5.3709E-02	1.5041E+00	2.6039E+00
18	1.3652E+01	-8.6978E+01	1.2149E+02	1.0063E+02	1.5144E+02
	9.4130E-02	-5.9969E-01	8.3767E-01	6.9382E-01	1.0442E+00
19	3.7352E+01	-1.4759E+02	9.9594E+01	1.8495E+02	3.1090E+02
	2.5754E-01	-1.0176E+00	6.8668E-01	1.2752E+00	2.1436E+00
20	2.5189E+01	-1.9576E+02	9.1481E+00	2.2095E+02	4.1088E+02
	1.7367E-01	-1.3497E+00	6.3074E-02	1.5234E+00	2.8329E+00
21	6.6491E+00	-2.2294E+00	-1.0467E+00	8.8785E+00	6.0550E+00
	4.5844E-02	-1.5371E-02	-7.2168E-03	6.1215E-02	4.1748E-02
22	2.7655E+00	-1.5235E+01	-3.0961E+00	1.8000E+01	4.4221E+01
	1.9068E-02	-1.0504E-01	-2.1347E-02	1.2411E-01	3.0489E-01

MA

Appendix C. GroupAllow Program Output File

The following is the GroupAllow program output file for load case LC101.025. This file lists maximum and average temperatures at each stress section, and the allowable membrane, yield, and ultimate stress at these sections.

Allowable Stress for Load Case 101

LOC	Tmax (deg_F)	Tave (deg_F)	Sm (ksi)	Sy (ksi)	Su (ksi)
1	138.91	138.74	20.00	30.00	70.00
2	138.94	138.59	20.00	30.00	70.00
3	138.62	138.37	20.00	30.00	70.00
4	139.15	139.13	20.00	30.00	70.00
5	139.61	139.54	20.00	30.00	70.00
6	139.79	139.72	20.00	30.00	70.00
7	140.04	139.89	20.00	30.00	70.00
8	139.99	139.85	20.00	30.00	70.00
9	139.92	139.77	20.00	30.00	70.00
10	139.78	139.64	20.00	30.00	70.00
11	139.92	139.66	20.00	30.00	70.00
12	140.39	140.09	20.00	30.00	70.00
13	139.33	139.20	20.00	30.00	70.00
14	139.04	138.97	20.00	30.00	70.00
15	139.08	139.03	20.00	30.00	70.00
16	139.19	139.14	20.00	30.00	70.00
17	139.22	139.19	20.00	30.00	70.00
18	139.37	139.34	20.00	30.00	70.00
19	139.50	139.44	20.00	30.00	70.00
20	140.26	140.14	20.00	30.00	70.00
21	138.43	138.36	20.00	30.00	70.00
22	138.82	138.76	20.00	30.00	70.00

Appendix D. Typical CmbLds.in File

The following is a typical PmPb.in file. The first entry is the number of stress cross-sections. The next set of entries is the load case numbers, and this set is terminated with a -1. The second and last set of entries are the load combination numbers, and the combination load cases. Text following entries is descriptive, and not used by the program

```
22
101 ; 100F Ambient, Max Decay Heat
102 ; 100F Ambient, Max Decay Heat, Max Insolation
103 ; -20F Ambient, Zero Decay Heat, Zero Insolation
104 ; -40F Ambient, Zero Decay Heat, Zero Insolation
105 ; -40F Ambient, Max Decay Heat
111 ; Fire @ 30 Min, 1475F Ambient, Max Decay Heat
112 ; Fire @60 Min, 100F, Max Decay Heat, Max Insolation
113 ; Fire @90 Min, 100F, Max Decay heat, Max Insolation
114 ; Fire @120 Min, 100F, Max Decay Heat, Max Insolation
115 ; Fire @150 Min, 100F, Max Decay Heat, Max Insolation
116 ; Fire @180 Min, 100F, Max Decay Heat, Max Insolation
201 ; Maximum Internal Pressure, 30 psi
202 ; Minimum External Pressure, 3.5 psia
203 ; Maximum Increased Pressure, 20 psia
204 ; Additional Increased External Pressure, 290 psi
211 ; Fabrication Stress
215 ; Compression Load
216 ; Rod Drop
221 ; Forward 5g Vibration Inertia Load
222 ; Lateral 5g Vibration Inertia Load
223 ; Vertical 10g Vibration Inertia Load
231 ; 4 ft head-on drop
232 ; 30 ft head-on drop, normal conditions
301 ; 30 ft Head-on drop
302 ; 30 ft Side drop + slap-down
303 ; CG/Corner Drop
304 ; 30 ft Head-on drop, low temp
305 ; 30 ft Side drop + slap-down, low temp
306 ; CG/Corner Drop, low temp
311 ; 3 ft drop onto rod
-1
101, 101, 201, 211 ; hot environment
102, 104, 201, 211 ; cold environment
103, 103, 201, 211 ; increased ex pres
104, 101, 201, 202, 211 ; min ex pres
105, 105, 201, 202, 211 ; cold environment
106, 101, 201, 203, 211 ; max pres, hot environment
107, 105, 201, 203, 211 ; max pres, cold environment
215, 215, 101, 201, 211 ; compression load
216, 216, 101, 201, 211 ; rod drop
217, 216, 104, 201, 211 ; rod drop cold environment
221, 221, 101, 201, 211 ; fwd vibration
222, 222, 101, 201, 211 ; lateral vibration
```


223, 223,101,201,211 ; vertical vibration
231, 231,102,201,211 ; 4 ft head-on drop, normal conditions
232, 232,102,201,211 ; 30 ft head-on drop, normal conditions
301, 301,102,201,211 ; head-on drop
302, 302,102,201,211 ; side drop
303, 303,102,201,211 ; cg/corner drop
304, 304,105,202,211 ; head-on drop, cold environment
305, 305,105,202,211 ; side drop, cold environment
306, 306,105,202,211 ; cg/corner drop, cold environment
310, 204,101,211 ; add ext pres (290 psi)
311, 311,101,201,211 ; 3 ft drop onto rod
312, 311,104,201,211 ; 3 ftdrop onto rod, cold environment
350, 111,201,211 ; fire @ 30 min
351, 112,201,211 ; fire @ 60 min
352, 113,201,211 ; fire @ 90 min
353, 114,201,211 ; fire @ 120 min
354, 115,201,211 ; fire @ 150 min
355, 116,201,211 ; fire @ 180 min

-1

MARKUP

Appendix E. Typical Output from CmbLds Program

The following is a typical output file from the CmbLds program. The load combination is listed at the top of the table. The file lists maximum membrane and bending stress, and minimum allowables at each section analyzed. Stresses are listed in both English and metric units. Minimum MS and associated values are listed at the end of the table.

Normal Load Combination 101

 Load Cases: 101 201 211
 100F Ambient, Max Decay Heat
 Maximum Internal Pressure - 30 Psia
 Fabrication Stress

Loc	Pm		Pb		Q		Pm+Pb		Pm+Pb+Q		Sm	Su	MS
	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa			
1	0.75	1.10	0.04	1.85	1.89	20.00	70.00	>10					
	5.16	7.60	0.26	12.75	13.01	137.90	482.63						
2	0.14	0.20	0.05	0.34	0.38	20.00	70.00	>10					
	0.96	1.35	0.34	2.31	2.65	137.90	482.63						
3	0.08	0.08	0.03	0.16	0.20	20.00	70.00	>10					
	0.58	0.54	0.24	1.12	1.36	137.90	482.63						
4	1.16	1.78	0.30	2.94	3.24	20.00	70.00	9.20					
	8.00	12.28	2.07	20.28	22.35	137.90	482.63						
5	1.18	1.00	0.33	2.18	2.51	20.00	70.00	>10					
	8.17	6.88	2.28	15.05	17.32	137.90	482.63						
6	0.78	1.17	0.14	1.95	2.09	20.00	70.00	>10					
	5.40	8.05	0.97	13.44	14.41	137.90	482.63						
7	0.34	0.07	0.05	0.40	0.45	20.00	70.00	>10					
	2.34	0.45	0.33	2.79	3.12	137.90	482.63						
8	0.32	0.04	0.05	0.36	0.41	20.00	70.00	>10					
	2.21	0.27	0.33	2.48	2.81	137.90	482.63						
9	0.36	0.07	0.05	0.43	0.48	20.00	70.00	>10					
	2.48	0.48	0.33	2.97	3.29	137.90	482.63						
10	1.23	0.15	0.06	1.38	1.44	20.00	70.00	>10					
	8.49	1.03	0.41	9.52	9.93	137.90	482.63						

11	0.93 6.44	1.23 8.51	0.08 0.59	2.17 14.95	2.25 15.53	20.00 137.90	70.00 482.63	>10
12	1.01 6.95	1.49 10.27	0.12 0.85	2.50 17.23	2.62 18.08	20.00 137.90	70.00 482.63	>10
13	1.19 8.21	1.05 7.23	0.16 1.14	2.24 15.44	2.40 16.58	20.00 137.90	70.00 482.63	>10
14	1.21 8.36	1.54 10.61	0.14 0.99	2.75 18.97	2.89 19.96	20.00 137.90	70.00 482.63	9.91
15	1.70 11.69	1.94 13.38	0.67 4.62	3.64 25.07	4.31 29.70	20.00 137.90	70.00 482.63	7.25
16	1.70 11.72	2.69 18.55	0.36 2.49	4.39 30.27	4.75 32.75	20.00 137.90	70.00 482.63	5.83
17	1.12 7.71	1.79 12.31	0.22 1.50	2.90 20.02	3.12 21.52	20.00 137.90	70.00 482.63	9.33
18	0.87 5.99	1.40 9.65	0.10 0.69	2.27 15.64	2.37 16.33	20.00 137.90	70.00 482.63	>10
19	1.46 10.09	2.17 14.96	0.18 1.28	3.63 25.05	3.82 26.33	20.00 137.90	70.00 482.63	7.26
20	1.82 12.58	2.90 19.99	0.22 1.52	4.72 32.57	4.95 34.09	20.00 137.90	70.00 482.63	5.35
21	0.32 2.24	0.44 3.00	0.01 0.06	0.76 5.24	0.77 5.30	20.00 137.90	70.00 482.63	>10
22	0.46 3.20	0.47 3.23	0.02 0.12	0.93 6.43	0.95 6.55	20.00 137.90	70.00 482.63	>10

Min MS: 5.350, Location: 20, Combination: Pm+Pb

Appendix F. Typical Section of Batch Program to Execute AOS Load Cases

The AOS input data files and post-processor executions are organized and run by a Command batch program. A separate batch program is required for each of the four model configurations. A section of a typical batch program is shown below. Note that the program PmPbData is run before the first execution of PmPb. The GroupAllow program is only run after a Libra thermal analysis. The PmPb (or PmPb3D) program is run after each Libra stress analysis. Calls to the Libra program include the input file name, output file name, and a flag set to 1 to prevent libra pausing after execution.

```
rem load case 101
call libra lc101-t-update.025  tape6 1
call libra lc101-update.025  tape6 1
groupallow lc101-update.025
pmpbdata
pmpb
```

```
rem load case 102
call libra lc102-t-update.025  tape6 1
call libra lc102-update.025  tape6 1
groupallow lc102-update.025
pmpb
```

```
rem load case 103
call libra lc103-t-update.025  tape6 1
call libra lc103-update.025  tape6 1
groupallow lc103-update.025
pmpb
```

```
rem load case 104
call libra lc104-t-update.025  tape6 1
call libra lc104-update.025  tape6 1
groupallow lc104-update.025
pmpb
```

```
rem load case 105
call libra lc105-t-update.025  tape6 1
call libra lc105-update.025  tape6 1
groupallow lc105-update.025
pmpb
```

```
rem load case 106
call libra lc106-t-update.025  tape6 1
call libra lc106-update.025  tape6 1
groupallow lc106-update.025
pmpb
```

MARKUP

This appendix provides information related to the following materials:

- Contact Resistance
- Decay Heat
- Stainless Steel (SS304)
- Tungsten Alloy
- General Plastics LAST-A-FOAM
- Air Properties
- Port Seal
- Lid Seal

A list of References is also included.

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Contact Resistance

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Contact Resistance

- Surfaces with 0.0 clearance.
- All contact surfaces are assumed low a resistance (approximately 30 psi) and have a value of:

$$1/h_c = 0.03 \frac{\text{hr-ft}^2\text{°F}}{\text{Btu}}$$

$$h_c = 0.231 \text{ Btu/hr-in}^2\text{°F}$$

The exception is the shrinkfit surface at the outside shell, where the contact pressure is approximately 2 ksi.

$$1/h_c = 0.003 \frac{\text{hr-ft}^2\text{°F}}{\text{Btu}}$$

$$h_c = 2.315 \text{ Btu/hr-in}^2\text{°F}$$

MARKYUP

Excerpt, *Heat Transfer Data Book*, Nancy D. Fitzroy, Ed., 1970, Section G502.5, Page 7

Heat Transfer
Division

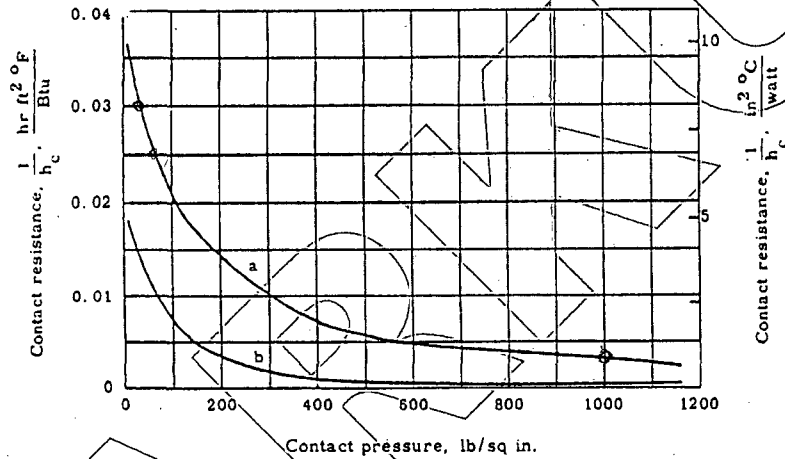
CONDUCTION IN SOLIDS - STEADY STATE
IMPERFECT METAL-TO-METAL SURFACE CONTACT

Section G502.5
Page 7
November 1970*

STEEL, BARE SURFACES AT HIGH CONTACT PRESSURES (0 to 1200 psi) - Solid blocks in air at reduced pressure
($p < 0.1 \text{ atm}$)

For steel with bare surfaces in air, see pages 5-6.
For steel with sandwich material in air, see page 8.
For steel in other gases, see page 9.
For steel with dissimilar metal in air, see page 20; at reduced pressure ($p < 0.1 \text{ atm}$), see page 21.
For other metals in air, see pages 10-11, 17; at reduced pressure ($p < 0.1 \text{ atm}$), see pages 12-13, 18-19.
For laminated steels in air, see page 23.

Curve	Material ⁴	Finish	Roughness Rms ($\mu \text{ in.}$) Block		Fluid in Gap	Temp ($^{\circ}\text{F}$)	Condition	Ref. No.
			1	2				
a	Stainless Steel 304	Ground	42-60	43-48	Air	75	Clean, 10^{-4} mm Hg abs	45
b	Stainless Steel 304	Ground	15-15	10-10	Air	84	Clean, 10^{-4} mm Hg abs	45



⁴⁻⁵ See page 24

The decay heat of the cask contents is introduced in the model by two-node convective boundary elements along the cask cavity wall. In the model, it is assumed that the load is uniformly distributed over the entire cavity surface.

Convective boundary elements define the convective and radiative properties at the interface between the impact limiter outer surface and the regulatory environments. Another convective surface is located on the side of the cask's outer shell, between the upper and lower impact limiter structures. In addition to convective and radiative properties, these boundary two-node elements have the capability to include required solar heat flux loads.

Figure 3-2 illustrates all components and interfaces of the thermal model.

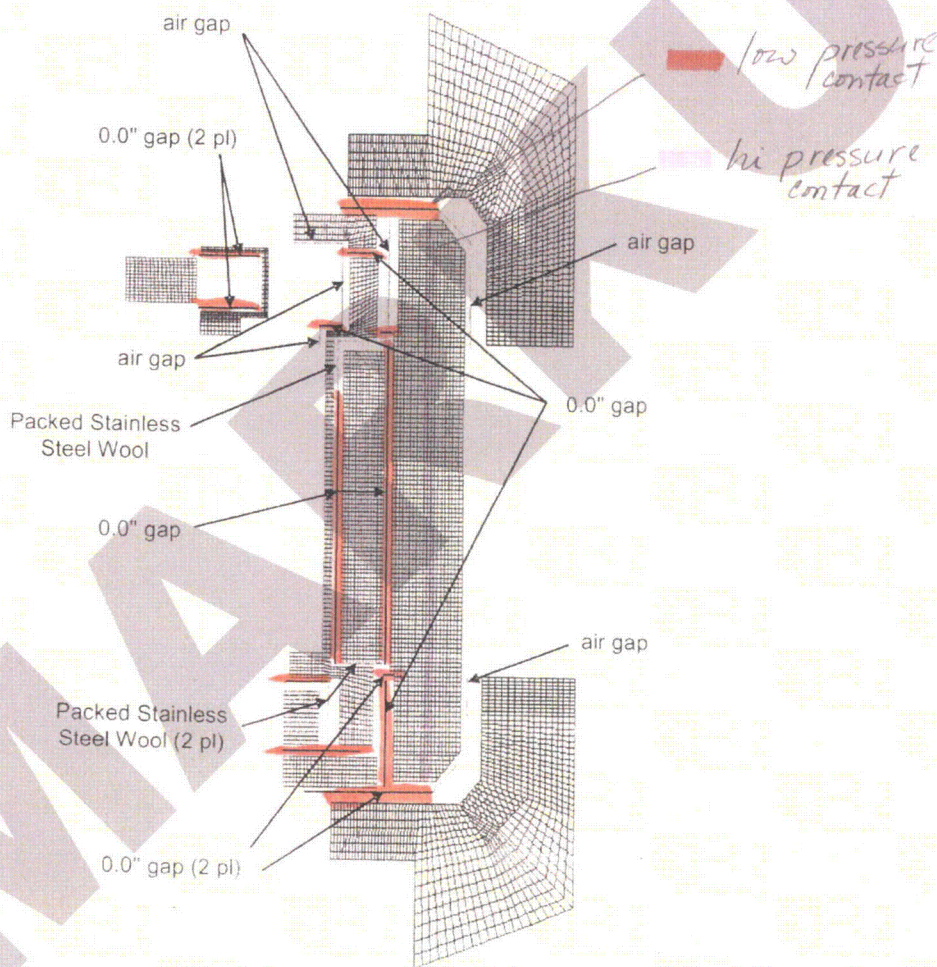


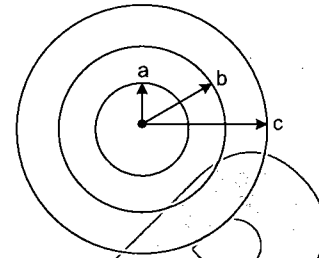
Figure 3-2. Expanded View of Thermal Model Defining Component Interfaces

Shrinkfit

1/13/06

Reference – Shigley, Joseph Edward, *Mechanical Engineering Design*, McGraw Hill Companies, 3rd Ed., 1977.

$$P = \frac{E\delta}{b} \left[\frac{(c^2 - b^2)(b^2 - a^2)}{2b^2(c^2 - a^2)} \right]$$



where:

$$a = 13.2 \text{ and } 13.7$$

$$b = 18.1$$

$$c = 23.1$$

$$E = 28.3 \times 10^6$$

$$\delta = 0.02$$

$$P_1 = \left(\frac{28.3 \times 10^6 \times 0.02}{18.1} \right) \left[\frac{(23.1^2 - 18.1^2)(18.1^2 - 13.2^2)}{(2 \times 18.1^2)(23.1^2 - 13.2^2)} \right]$$

$$= (0.031271 \times 10^6) \left[\frac{(206)(153.37)}{235466.41} \right]$$

$$= 4,196 \text{ psi}$$

$$P_2 = 31271 \left[\frac{(206)(18.1^2 - 13.7^2)}{(2 \times 18.1^2)(23.1^2 - 13.7^2)} \right]$$

$$= 31271 \left[\frac{(206)(139.92)}{226654} \right]$$

$$= 3,977 \text{ psi}$$

for $\delta = 0.01$ in.

$P \sim 2,000$ psi

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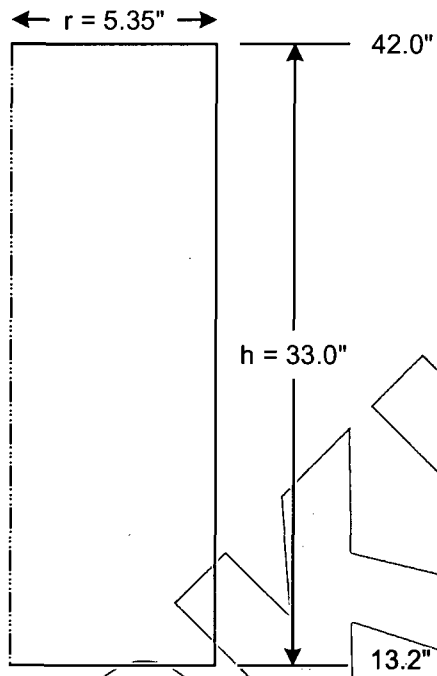
MARKYUP

Decay Heat

MARKUP

Decay Heat

Cask Radius and Height – Model AOS-165



$$\begin{aligned} A &= 2\pi (5.36)^2 + 2\pi (5.36) (33.0) \\ &= 1,291.88 \text{ in}^2 \end{aligned}$$

Heat Flux at Inside Cask Surface

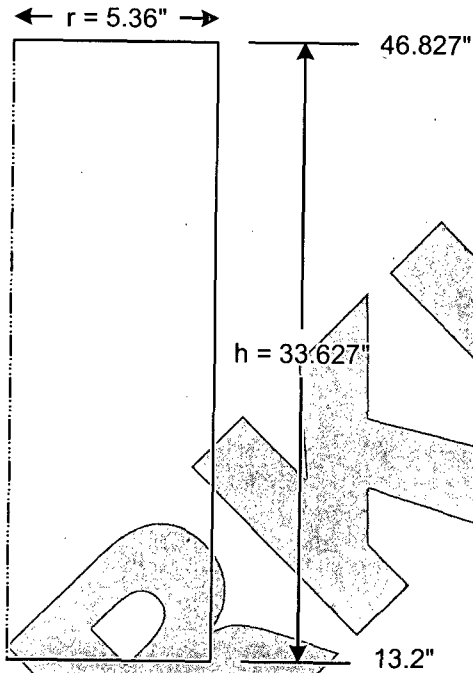
$$q = 23,666.3 / 1,291.88 = 18.319 \text{ Btu/hr-in}^2$$

Decay Heat Load

$$450,000 \text{ Curies} = 6,936 \text{ W} = 23,666.3 \text{ Btu/hr}$$

$$(64.88 \text{ c} = 1 \text{ W})$$

Cask Surface Area – Model AOS-165



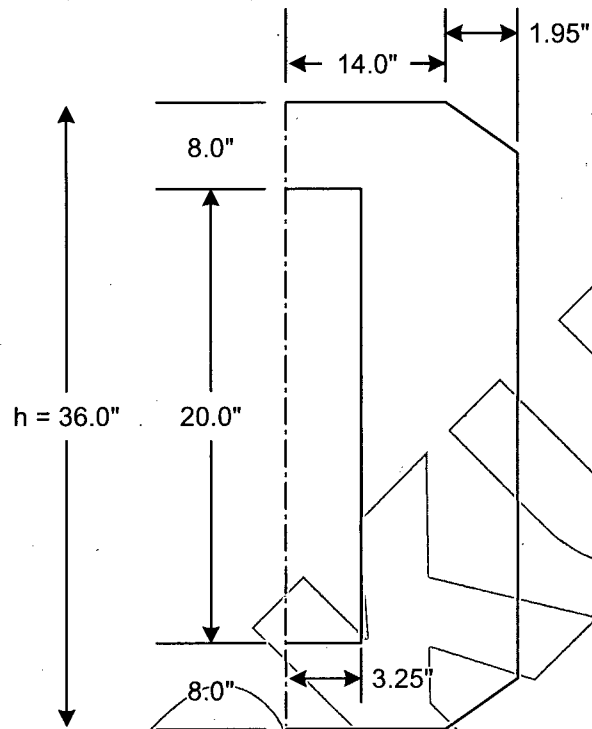
$$A = 2\pi (5.36)^2 + 2\pi (5.36) (33.627) = 1,313.0 \text{ in}^2$$

Heat Flux @ Inside Cask Surface

$$q = 23,666.3 / 1,313.0 = 18.02 \text{ Btu/hr-in}^2$$

Model AOS-100 Cask

Outside Cask Body and Cask Height – Model AOS-100



Decay Heat = 400W

$$400W = 3.4121 \cdot 400 = 1,365 \text{ Btu/hr}$$

Cavity Surface Area

$$2\pi (3.25^2 + ((3.25) (20))) = 474.77 \text{ in}^2$$

Heat Flux

$$1,365 / 474.77 \text{ in}^2 = 2.88 \text{ Btu/hr-in}^2$$

Model AOS-050 Cask

Decay Heat = 100W

$$100W = 3.4121 * 100 = 341.21 \text{ Btu/hr}$$

Cavity Area

$$2\pi (1.62424^2 + 1.62424 * (14.0 - 4.0))$$
$$= 118.63 \text{ in}^2$$

Heat Flux

$$341.21 / 118.63 = 2.876 \text{ Btu/hr-in}^2$$

Model AOS-025 Cask

Decay Heat = 10W

Heat Flux

$$(3.4121 * 10) / (2\pi) (0.812^2 + ((0.812) (7.0 - 2.0)))$$
$$= 1.151 \text{ Btu/hr-in}^2$$

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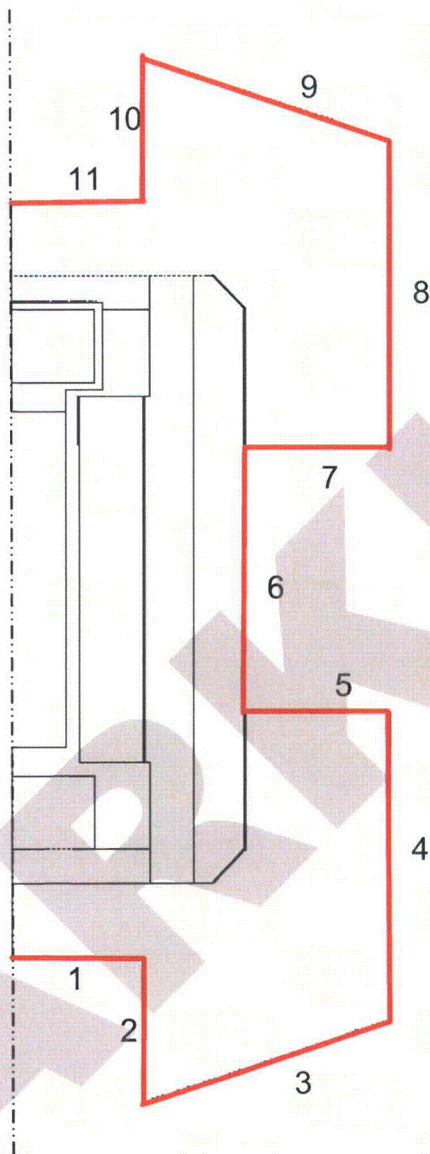
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Insolation

Treat surfaces as follows:

Cask Assembly External Surface Identification



$1 \text{ cal/cm}^2 = 0.0256 \text{ Btu/in}^2$

Horizontal Surface	Total Insolation (cal/cm ²)	(Btu/in ²)	Heat Rate BTU/hr-in ²
1, 11	200	5.12	0.4267
2, 10	400	10.24	0.8533
3, 9	400	10.24	0.8533
4, 8	400	10.24	0.8533
5, 7	200	5.12	0.4267
6	400	10.24	0.8533

Stainless Steel (SS304)

MARKUP

2.3 MECHANICAL PROPERTIES OF MATERIALS

The transport package is fabricated from pig lead per Federal Specification QQ-L-171e and 304 stainless steel per ASTM A240. The mechanical properties used in the structural analysis are listed in Tables 2.3.1 and 2.3.2.

TABLE 2.3.1. MECHANICAL PROPERTIES OF LEAD[2.11.7]

Temp. (°F)	E:106(psi)	μ	$\alpha:10^{-6}(1/°F)$	ρ (Lbm/in.3) [2.11.8]	σ_y (psi) [2.11.9]
-50	-	0.43	13.94	0.4097	810
-40	2.58		-		795
75	2.41		16.0		620
100	2.38		16.025		580
150	2.30		16.12		550
200	2.21		16.26		505
250	2.14		16.46		495
300	2.04	0.43	16.7	0.4097	390

TABLE 2.3.2. MECHANICAL PROPERTIES OF STAINLESS STEEL[2.11.10]

Temp. (°F)	E:106(psi)	μ	$\alpha:10^{-6}(1/°F)$	ρ (Lbm/in.3) [2.11.11]	$\sigma_y:10^3$ (psi)
-100	29.4	0.30	7.35	0.29	-
70	28.3		-		-
100	-		8.03		30.0
200	27.7		8.20		25.0
300	27.1		8.37		22.5
400	26.6	0.30	8.54	0.29	20.7

TABLE 2.3.3. MECHANICAL PROPERTIES OF BOLTS

Bolt Size/ASTM Standard	Stress Area (in.2)	Min. Tensile Strength (ksi)	Yield Strength (ksi)
1.25-7 UNC-2A Socket Head/[2.11.12]	0.969	145	130
ASTM A540, GR B-22 Class 3 7/8-9 UNC-2A Shoulder Screw/	0.462	145	130
ASTM A540, GR B-22 Class 3 1-8 UNC-2A Hexagonal Head/[2.11.13]	0.606	110	85
ASTM A193-B6			

2.11 REFERENCES

1. Code of Federal Regulations, Title 10, Part 71, 1983.
2. U.S. NRC Regulatory Guide 7.6, "Design Criteria for the Structural Analysis of Shipping Cask Containment Vessels".
3. U.S. NRC Regulatory Guide 7.8, "Load Combinations for the Structural Analysis of Shipping Casks", Table 10.
4. W. R. Holman and R. T. Langland, "Recommendations for Protecting Against Failure by Brittle Fracture in Ferritic Steel Shipping Containers Up to Four Inches Thick", Lawrence Livermore Laboratory; Livermore, California; August, 1981; NUREG/CR-1815.
5. ASME, Boiler and Pressure Vessel Code, Section III, Division I, Appendix 1, 1980, Figure I-9.2.
6. Bruhn, E. F., "Analysis and Design of Flight Vehicle Structures", Tri-State Offset Company, Cincinnati, 1965.
7. W. Hoffman, "Lead and Lead Alloys", English Translation of the Second Revised German Edition, Springer-Verlag, New York-Heidelberg-Berlin, 1970.
8. Heat Transfer Data Book, D. A. Kaminski, Ed., General Electric Company, NY, 1981, Sct. G515/29, p. 5.
9. Tietz, E. Thomas, "Determination of the Mechanical Properties of a High Purity Lead and a 0.05% Copper-Lead Alloy", Stanford Research Institute; Menlo Park, California; April, 1958; WADC Technical Report 57-695, ASTIA Document No. 151165.
10. ASME, Boiler and Pressure Vessel Code, Section III, Division 1, Appendix 1, 1980.
11. The International Nickel Company, Inc.; Mechanical and Physical Properties of Austenitic Chromium-Nickel Stainless Steels at Ambient Temperature, 3rd Edition, New York, 1963.

3.2.2 Stainless Steel (304 Type)

TABLE 3.2.2.1. THERMOPHYSICAL PROPERTIES [3.7.4]

Temp.	k (Btu/hr-ft-°F)	α (ft ² /hr)
70	8.6	0.151
100	8.7	0.152
200	9.3	0.156
300	9.8	0.160
400	10.4	0.165
500	10.9	0.170
600	11.3	0.174
700	11.8	0.179
800	12.2	0.184
900	12.7	0.189
1,000	13.2	0.194
1,100	13.6	0.198
1,200	14.0	0.203
1,300	14.5	0.208
1,400	14.9	0.212
1,500	15.3	0.216

Conductivity, K (Btu/hr-in.-°F)

$$K(T) = 7.0287 \times 10^{-1} + 3.8987 \times 10^{-4} T$$

1,500°F
70°F

Thermal Diffusivity, α (in.²/hr)

$$\alpha(T) = 21.110 + 6.7346 \times 10^{-3} T$$

1,500°F
70°F

Density, ρ (lb/in.³)

$$\rho(T) = 0.29$$

1,000°F
70°F

Specific Heat, C_p (Btu/lb-°F)

$$C_p(T) = K(T) / \alpha(T) (\rho)$$

$$C_p(T) = K(T) / (6.1219 + 1.953 \times 10^{-3} T)$$

1,000°F
70°F

3.7 REFERENCES

1. Touloukian, Y. S., Thermophysical Properties of Matter, Purdue University, 1970, Vol. 1, p. 191.
2. Ibid, Vol. 4, p. 115.
3. Heat Transfer Data Book, D. A. Kaminski, Ed.; General Electric Company, New York, 1981, Sct. G515.29, p. 5.
4. ASME, Boiler and Pressure Vessel Code, Section III, Division I, Appendix 1, 1980.
5. Kreith, F., Principles of Heat Transfer, International Textbook Company, Pennsylvania, 2nd Ed., 1969, Table A-3.
6. Ibid, Table A-1.
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8. Ibid, p. 355.
9. Ibid, p. 376.
10. Kreith, F., Principles of Heat Transfer, International Textbook Company, Pennsylvania, 2nd Ed., 1969, Table 5-2.
11. Heat Transfer Data Book, D. A. Kaminski, Ed.; General Electric Company, New York, 1981, Sct, G515.5, p. 13.
12. Gebhart, B., Heat Transfer, McGraw-Hill Book Company, New York, 2nd Ed., 1971, p. 371.
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14. Regulatory Guide 7.8, Load Combinations for Structural Analysis of Shipping Casks, U.S. Nuclear Regulatory Commission; May, 1977; Table 1.
15. D. R. Smith and R. H. Jones, "GE Model 1500 Shipping Package Heat Test for Thermal Benchmarking", GE Vallecitos Nuclear Center, NEDO-24899; April, 1981.

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MARKYUP

Tungsten Alloy

MARKUP

Date: 8 November 2006

To: Alpha-Omega Services, Inc.
GE Energy

Elevated Temperature Material Characterization

-- Summary of Findings --

Abstract

Summarized herein are the results of specific thermal property tests performed with SD180 as requested by the customer. Elevated temperature tensile testing of this alloy identified a gradual decrease in both offset yield strength and UTS with increasing temperature whereas the elongation at failure rose sharply and then leveled off. Thermal conductivity testing was inconclusive, as thermal testing firms now utilize laser flash diffusivity measurement, which has been shown to provide unreliable results for this material.

Background

ATI Firth Sterling tungsten heavy alloy (WHA) grade SD180 was selected for use in a new large scale design of gamma shield. This alloy has a nominal composition of 95W-3.57Ni-1.43Fe and a nominal density of 18.0 g/cc. The intensity of the gamma flux will result in significant heating of the shield, such that elevated temperature material properties are of significant interest. As a result, this application requires that the shielding material possess a multiplicity of attributes:

- adequate strength and ductility
- good γ radiation attenuation
- sufficient thermal conductivity

The customer specified the tests and the temperatures at which measurements should be made. Temperatures of interest were ambient, 200F, 400F, 600F, and 800F. Further, so as to match the application, testing was to be performed in air. As ATI Firth Sterling is presently equipped only for room temperature material characterization, elevated temperature testing was contracted out to two selected testing firms.

Experimental

Elevated Temperature Tensile Testing

Tensile Testing Metallurgical Lab (Cleveland, OH) was selected to perform the required elevated temperature tests. Tensile testing was conducted using ASTM E8 1" gauge length

specimens pulled at a constant speed of 0.05 in/min. The notch sensitivity of WHA precluded the use of scribe lines or grooves for positioning of a high temperature extensometer. Therefore, crosshead motion was used to generate the displacement measurements in this low compliance, lead screw testing machine. For comparison purposes, a pair of room temperature tensile tests was also performed at ATI Firth Sterling using the same test parameters but with a servohydraulic machine and extensometer. Two specimens were pulled for each test temperature. Averaged results are shown in Table 1.

Table 1. Summary of tensile testing results for SD 180 lot 1808.

Test Temperature	UTS (ksi)	0.2% YS (ksi)	EL (%)
RT (ATIFS)	114.0	93.9	5.0
RT (TTML)	109.7	94.3	3.5
200F (TTML)	112.4	70.8	15.5
400F (TTML)	105.2	60.2	21.8
600F (TTML)	98.2	51.9	21.9
800F (TTML)	95.4	47.8	21.6

The data pairs for each temperature exhibited good agreement, suggesting test results were free from anomalies.

Thermal Property Measurement

Anter Laboratories (Pittsburgh, PA) was selected for measurement of thermal diffusivity and specific heat at the various temperatures of interest. Anter specified that a single disk sample of 0.500" nominal diameter and 0.140" nominal thickness with parallel surfaces and known density be supplied. A SD180 sample from lot 1748 giving a measured ASTM B311 density of 18.11 g/cc was prepared and supplied by ATIFS. Measurements were conducted per ASTM E1461-01. Results are presented in Table 2.

Table 2. Summary of thermal property evaluation of SD 180 lot 1748.

Test Temperature		Diffusivity (cm ² /sec)	Specific Heat (J/(kg-K))	Conductivity (W/m-K)
Nom. (F)	Actual (C)			
RT	25	0.2742	154.7	76.8
200	97	0.2700	159.2	77.8
400	206	0.2624	163.4	77.6
600	316	0.2553	170.3	78.8
800	427	0.2451	173.9	77.2

The thermal conductivity remained relatively constant over the entire test temperature range, whereas specific heat showed a gradual increase and thermal diffusivity a slow decrease. The room temperature density was applied to all conductivity calculations, as the very low CTE of WHA (less than $5.0 \times 10^{-6} \text{ K}^{-1}$) would result in a change of calculated value of only 0.5 W/m-K or less even at the highest test temperature. This was a factor of 4 less than the reported uncertainty of the test procedure.

Discussion of Results

In reviewing the tensile data set generated, the most pronounced effect was that of moving above the ductile to brittle test temperature (DBTT) for WHA, which in most metallurgical conditions is in the vicinity of room temperature. This accounts for the significant increase in alloy ductility, as measured by %EL. Accompanying this increase in ductility was a gradual decrease in both the ultimate and offset yield strengths, which is to be expected in light of induced thermal effects on various dislocation mechanisms that determine deformation response under load. These effects can be seen clearly when the data of Table 1 are plotted and displayed in Figure 1.

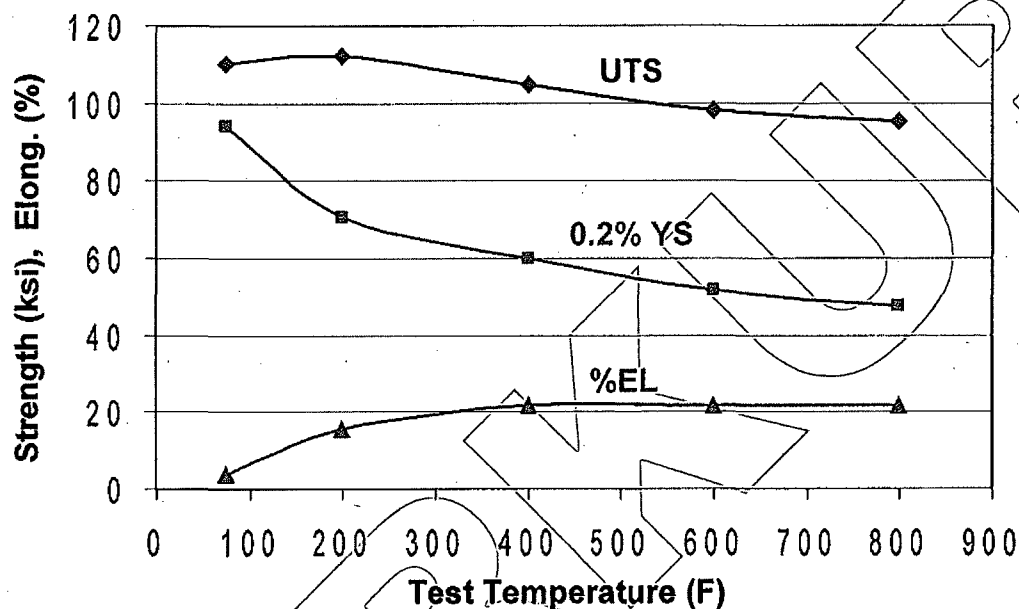


Figure 1. Graphical display of tensile property variation with test temperature.

While the strength of the gamma shield would decrease slightly with heating, the durability of the shield would tend to increase, depending on the magnitude of temperature rise attained.

The data set obtained from thermal property evaluation exhibited consistent trends. However, the resultant calculated values for thermal conductivity, which averaged 78 W/m-K, were well below the accepted industry values for this composition class of WHA. The literature for about two decades has reported values in the range of 110-130 W/m-K. This range is much more in-keeping with an alloy having 95 wt.% of a metal that has a conductivity of ~160 W/m-K and is present as a virtually pure phase in the two phase WHA microstructure. The reason for the low measured values is presently unknown. The results obtained appear to underestimate the accepted thermal conductivity by about 35%. Dialogue with Anter revealed no apparent test execution problems. The data set obtained from Anter Laboratories did show that for the temperature range of interest, the thermal conductivity of the WHA, though of systematically low magnitude, did not vary significantly. It was decided that a second independent test be conducted in an effort to understand these results relative to industry accepted values.

Supplemental Testing

In view of the question posed from thermal conductivity testing of the SD180 alloy, a second test sample was prepared for submission to a different laboratory for analysis. While

Anter is nationally recognized for both thermal analysis and the manufacture of thermal analyzers, it was desirable to have a completely independent measurement made. Raul Pomares forwarded the firm of M & P Lab, in that they performed thermal measurements for GE Energy in the past. However, when their thermal analysis contact M. B. Bolduc was contacted, it was learned that they do not perform any thermal conductivity measurements. Harrop likewise, while performing other thermal measurements, does not perform conductivity measurement. Netzsch was therefore chosen as the second source for SD180 thermal conductivity measurement. Netzsch indicated that they also use the laser flash method per ASTM E1461 and calculate the thermal conductivity from measured diffusivity. After about a 6 week lead time, the room temperature test was completed and is shown in Table 3. Netzsch used a density of 18.0 g/cc for the calculation, whereas our measurement yielded 18.06 g/cc.

Table 3. Second conductivity evaluation of grade SD 180.

Test Temperature		Diffusivity (mm ² /sec)	Specific Heat (J/(g·K))	Conductivity (W/m·K)
Nom. (F)	Actual (C)			
RT	25	16.6	0.153	45.9

This new value for thermal conductivity was even further away from the expected value based on composition and density. This measurement underestimated the accepted average conductivity by at least 60%. After obtaining this margin of error, testing was halted, as any elevated temperature values would likewise be of no value.

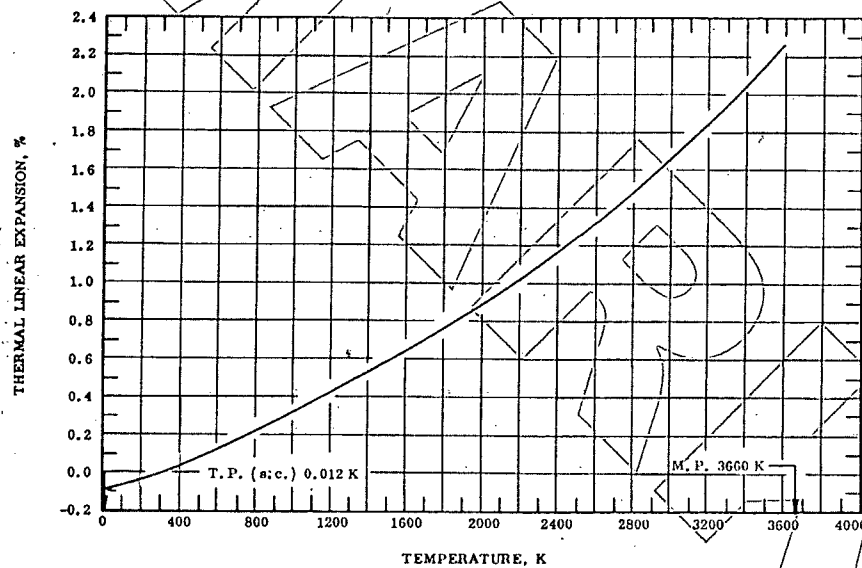
Conclusions

The selected elevated temperature characterization of SD180 provided a more comprehensive prediction of alloy performance in the target application. The identified property trends were in keeping with fundamental elevated temperature response of metallic materials. Excellent ductility was retained over the entire range of test temperature.

Thermal conductivity measurements however were inconclusive. Two independent tests – both using nationally recognized testing firms that not only routinely perform toll thermal testing but also actually manufacture the equipment – failed to provide results that were even in approximate agreement or close to the accepted values used for decades within the refractory metals industry. These low values should therefore be disregarded, as they cannot be independently repeated. As the entirety of this testing was conducted off site, the reasons for this extreme variation in measurements are presently unknown. Both testing houses guarantee conformance to ASTM E1461. Whatever the case, those skilled in performing laser flash tests have not demonstrated that this technique, now used almost universally for thermal conductivity measurements, is appropriate for tungsten heavy alloy. To the contrary, conductivity measurements obtained to date suggest the flash diffusivity approach is unreliable for this material. The higher industry accepted values of 110-130 W/m·K were no doubt made by techniques that predated laser flash diffusivity and measured conductivity directly using larger size samples. No presently available source for repeating earlier test methods is known.

S. G. Caldwell
 Technical Director – Tungsten Alloys

FIGURE AND TABLE NO. 58R. RECOMMENDED VALUES FOR THERMAL LINEAR EXPANSION OF TUNGSTEN W

RECOMMENDED VALUES
[Temperature, T, K; Linear Expansion, $\Delta L/L_0$, %; α , K^{-1}]

T	$\Delta L/L_0$	$\alpha \times 10^6$
5	-0.086	0.0006
25	-0.086	0.21
50	-0.085	0.89
100	-0.076	2.6
200	-0.040	4.1
293	0.000	4.5
400	0.048	4.5
500	0.093	4.6
600	0.140	4.7
700	0.188	4.8
800	0.237	5.0
900	0.287	5.0
1000	0.339	5.2
1200	0.444	5.3
1400	0.551	5.4
1600	0.661	5.6
1800	0.774	5.8
2000	0.893	6.1
2200	1.020	6.6
2400	1.157	7.1
2600	1.307	7.8
2800	1.469	8.3
3000	1.646	9.2
3200	1.837	10.0
3400	2.042	10.8
3600	2.263	11.6

REMARKS

The tabulated values are considered accurate to within $\pm 3\%$ over the entire temperature range. These values can be represented approximately by the following equations:

$$\Delta L/L_0 = 4.266 \times 10^{-4} (T - 293) + 8.479 \times 10^{-8} (T - 293)^2 - 1.974 \times 10^{-11} (T - 293)^3 \quad (293 < T < 1395)$$

$$\Delta L/L_0 = 0.548 + 5.416 \times 10^{-4} (T - 1395) + 1.952 \times 10^{-8} (T - 1395)^2 + 4.422 \times 10^{-11} (T - 1395)^3 \quad (1395 < T < 2495)$$

$$\Delta L/L_0 = 1.226 + 7.451 \times 10^{-4} (T - 2495) + 1.654 \times 10^{-7} (T - 2495)^2 + 7.568 \times 10^{-12} (T - 2495)^3 \quad (2495 < T < 3600)$$

Excerpt, *Formulas for Stress, Strain, and Structural Matrices*, by Walter D. Pilkey, 1st Ed. Table 4-1 (Partial), "Moduli of Elasticity, Poisson's Ratios, and Thermal Coefficients of Expansion," Page 176

TABLE 4-1 (continued) MODULI OF ELASTICITY, POISSON'S RATIOS, AND THERMAL COEFFICIENTS OF EXPANSION

Material	Modulus of Elasticity, E		Poisson's Ratio, ν	Thermal Coefficient of Expansion, α	
	$\times 10^6$ psi ^a	GPa		$\times 10^{-6}/^\circ\text{C}^b$	$\times 10^{-6}/^\circ\text{F}^b$
Teflon—TFE	0.038–0.065	0.26–0.45	—	55	99
TiC	67	462	—	4	7.2
Titanium—6 Al-4V	16.5	115	0.34	4.9	8.8
Titanium—pure	15.1	104	0.34	4.8	8.6
Titanium—silicate	9.8	68	0.17	0.0 (± 0.017)	0.0 (± 0.03)
Tungsten	50	345	0.28	2.4–2.6	4.3–4.7
Tungsten-Carbide Cermet	61.6–94.3	425–650	—	2.5–3.0	4.5–5.4
Vanadium	18–20	124–138	—	4.6	8.3
Vinyl Chloride—rigid	0.3–0.5	2–3.5	0.28–0.34	28–56	50–100
Wood—structural	1–2	7–14	—	1–3	2–5
Zircaloy-2	11	76	0.37–0.41	2.9	5.2
Zirconium	13.7–14.0	95–96.5	0.37–0.41	3.1	5.6

^aFor psi, multiply tabulated values by 10^6 . For example, if the entry is 40, this corresponds to 40×10^6 psi. An entry of 0.2–0.4 means that the values of E range from 0.2×10^6 psi to 0.4×10^6 psi.

^bFor α , multiply tabulated value by 10^{-6} . For example, for "Aluminum—Alloy 2024-T4", the α values are $12.9 \times 10^{-6}/^\circ\text{F}$ and $23.2 \times 10^{-6}/^\circ\text{C}$.

^c E_1, ν_1 properties in fiber direction.

^d E_2, ν_2 properties in 90° to fiber direction.

MARK

4 September 2008

Troy Hedger / Raul J. Pomares
 Alpha-Omega Services, Inc.
 9156 Rose Street
 Bellflower, CA 90706

Dear Troy / Raul:

I have prepared the following comments in response to your request to address the differences between our previously reported data (under Alpha-Omega Services P.O. #AOS-03590) and the cited specific heat values listed in NUREG/CR-6150.

In briefly revisiting previously submitted project reports, the initial thermal analysis data presented as part of our 7 September 2006 report contained a *Transmittal of Test Results* document from Anter Laboratories, a leading thermal analysis equipment manufacturer and provider of toll thermal analysis services. Testing of our tungsten heavy alloy grade SD180 material used in work defined by the referenced AOS purchase order was conducted by laser flash measurement, as described by ASTM E1461-01 using NIST traceable standards in a NADCAP certified laboratory. This testing house was extremely well qualified to make accurate measurements of specific heat.

Data were obtained at 5 temperatures of interest. The following values were reported by Anter for the 18.1 g/cc density tungsten heavy alloy (nominal composition 95W-3.57Ni-1.43Fe):

Nominal Temperature (F)	Specific Heat (J/[kg-K])
RT	154.7
200	159.2
400	163.4
600	170.3
800	173.9

Then, at a later date, additional thermal analysis of a SD180 sample was performed by Netzsch, who is also both a manufacturer of thermal analysis equipment as well as a toll service provider. As our 11 December 2006 report detailed, Netzsch obtained the following result using the same laser flash ASTM E1461 technique:

Nominal Temperature (F)	Specific Heat (J/[g-K])
RT	0.153

When the reported unit of measure is converted from a gram to kilogram basis, this supplemental testing by a second independent testing house yielded excellent agreement in specific heat – a value of 153 compared to the earlier 154.7 (J/[kg-K]). These values were thus in agreement within ~1.1% - an excellent match for single test data comparison.

In examining Section 15 of NUREG/CR-6150, it is not surprising to find disagreement in specific heat values to those we reported – it is rather to be expected. Tables 15-1 and 15-2 both list data for pure, elemental tungsten (W) – not tungsten heavy alloy. The SD180 alloy additionally contains Fe and Ni, and possesses a lower theoretical alloy density than pure W.

The relevance of previously reported specific heat values for the SD180 used in the aforementioned project over those contained in the cited NUREG document can therefore be summarized as follows:

1. NUREG/CR-6150 does not even relate to the tungsten heavy alloy used in the cask project.
2. NUREG/CR-6150 contains calculated values only, whereas our reported values were from actual material testing conducted by equipment manufacturers to an ASTM standard.
3. The thermodynamic data used for computation of NUREG/CR-6150 data are not given in Section 15. Even for the case of pure W, the calculated density reported in NUREG/CR-6150 Section 15.3 is 19.600 g/cc, which is greater than the tungsten industry accepted value of 19.3 g/cc for W as well as the value of 19.30 g/cc specified in the National Institute of Standards Physical Reference Data listing. It would appear that at least that input datum used in thermal calculations is in slight error even for the case of pure W. Calculated data are only as good as the input data and model.
4. Specific heat values we reported previously accounted for the actual measured density of the SD180 tungsten heavy alloy, as was determined using ASTM B311. As both chemical makeup and density varied from that of pure W, it is only natural that the thermal properties would differ from pure W as well.
5. The values we reported from Anter and Netzsch tests are consistent in trend with data for pure W in Table 15-1 of NUREG/CR-6150. For example, room temperature specific heat for pure W is listed as ~138 J/(kg-K), whereas testing of SD180 gave ~155 J/(kg-K) – an increase of ~12%. The tungsten heavy alloy contained 5 wt.% of transition metals having significantly higher specific heats than W (~460 J/(kg-K) for Ni, ~440 J/(kg-K) for Fe). It is therefore only expected that the room temperature specific heat for the SD180 heavy alloy would be higher than that of pure W.

There is therefore no reason whatsoever to question the specific heats reported by ATI Firth Sterling for SD180 based on NUREG/CR-6150. At best, the cited Section 15 data are not applicable for the reasons described above. Please contact me if further information is needed.

Yours truly,

Steven G. Caldwell

Steven G. Caldwell, Ph.D.
R&D Director
ATI Firth Sterling
1297 County Line Road
Madison, AL 35756

15. TUNGSTEN

15.1 Specific Heat (TUNGCP)

Specific heat is calculated by subroutine **TUNGCP** as a function of temperature. The temperature dependent specific heat¹⁵⁻¹ values are shown in Table 15-1. Linear interpolation is provided for temperature calls which fall between tabular values. Calls to **TUNGCP** that are outside of the table range will be returned with either the first or last table value.

Table 15-1. Specific heat of tungsten as a function of temperature.

Temperature (K)	Specific Heat (J/kg • K)
295	138.2
373	141.2
573	148.6
773	155.6
1,023	163.9
1,273	171.6
1,523	178.8
1,773	185.3
2,023	191.3
2,273	196.7
2,523	201.6
2,723	205.1
3,073	210.2

15.2 Thermal Conductivity (TUNGK)

Thermal conductivity is calculated by subroutine **TUNGK** as a function of temperature. The temperature dependent thermal conductivity¹⁵⁻¹ values are shown in Table 15-2. Linear interpolation is provided for temperature calls which fall between tabular values. Calls to **TUNGK** that are outside the table range will be returned with either the first or last table value.

Table 15-2. Thermal conductivity of tungsten as a function of temperature.

Temperature (K)	Thermal Conductivity (W/m • K)
573	124.7
673	122.9
773	121.2
873	119.4
1,073	161.1
1,773	114.5
1,373	111.5
1,573	108.6
2,573	96.73
2,973	93.16
3,173	91.63

15.3 Density Correlations (TUNGRO)

A constant value density¹⁵⁻¹ is returned by subroutine **TUNGRO**. The density value returned is 19600 (kg/m³).

15.4 Reference

- 15-1 M. Firnhaber, K. Trambauer, S. Hagen, P. Hofmann, *Specification of the International Standard Problem ISP-31: CORA 13 Experiment on Severe Fuel Damage*, Gesellschaft für Reaktorsicherheit (GRS) mbH, August 1991.

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MARKYUP

General Plastics LAST-A-FOAM

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**DESIGN GUIDE FOR USE OF
LAST-A-FOAM® FR-3700
FOR
CRASH & FIRE PROTECTION
OF
RADIOACTIVE MATERIAL
SHIPPING CONTAINERS**

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Design Guide for use of LAST-A-FOAM FR-3700 for Crash and Fire Protection of Radioactive Material Shipping Containers

Product Data

LAST-A-FOAM® FR-3700 is a HCFC-free, rigid, closed-cell, flame-retardant polyurethane foam available in densities ranging from 4 to 40 pounds per cubic foot. It exhibits a high strength-to-weight ratio due to its cellular structure and crosslinked resin. Also, because of its closed-cell structure, LAST-A-FOAM® FR-3700 has great resistance to water absorption, and will not swell, crack, or split on exposure to water. LAST-A-FOAM® is stable, inert, and is resistant to most chemicals and solvents. It is easily worked with common tools, and performs well as a primary or replacement material in a variety of applications.

Basic Properties

Table 1: Basic Physical Properties

Property	English/Metric	Test Method
Closed Cell Content	96.7%	ASTM D-2856 Procedure B
Water Absorption	< 85% by weight	ASTM D-2842
Glass Transition	279°F / 137°C	MDSC
Hardness, Shore-D	1.7812(D) + 0.37	ASTM D-2240
Tumbling Friability - loss %	41.314x2.7183 ^{-0.1873(D)}	ASTM C-421 (20 min. @ 60 rpm)

Table 2: Basic Chemical Properties

Property	English/Metric	Test Method
Chemical Composition	Carbon (C)	50-70%
	Oxygen (O)	14-34%
	Nitrogen (N)	4-12%
	Hydrogen (H)	4-10%
	Phosphorous (P)	0-2%
	Silicon (Si)	< 1%
	Chloride (Cl)	< 1800 ppm
	Other	< 1%
Leachable Chlorides	< 1 ppm	GP-TM9510

Table 3: Thermal Properties

Property	English	Metric	Test Method	
Thermal Conductivity	BTU/hr-ft ² -°F/inch	W/m-K	ASTM C177 @75°F (24°C)	
	FR-3704	0.200		0.029
	FR-3706	0.205		0.030
	FR-3708	0.209		0.030
	FR-3710	0.213		0.031
	FR-3718	0.324		0.047
	FR-3720	0.349		0.050
	FR-3725	0.414		0.060
Specific Heat @25°C	0.353 BTU/lb-°F	1.477 J/g°C	ASTM E-1269	
Heat of Combustion	11,706 BTU/lb	27.17 MJ/Kg	ASTM D-240	
Coefficient of Linear Thermal Expansion From -50°F to 200°F	3.5 x 10 ⁻⁵ in/in/°F	6.2 x 10 ⁻⁵ K ⁻¹	ASTM C-518	
	to 5.0 x 10 ⁻⁵ in/in/°F	to 9.0 x 10 ⁻⁵ K ⁻¹		

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The Federal Aviation Regulation (FAR) 25.853(a) App. F(a)(1)(I) flame test is commonly used to assess the relative burning characteristics of foam plastic materials under controlled laboratory conditions. The results of these tests performed on LAST-A-FOAM® are shown in Table 4.

Table 4: Typical FAR 25.853 flame test results

LAST-A-FOAM® Grade	FAR 25.835 12-second Ignition		FAR 25.835 60-second Ignition	
	Extinguish Time, Seconds	Burn Distance, inches (mm)	Extinguish Time, Seconds	Burn Distance, inches (mm)
FR-3704	0.5	5.7 (144.8)	0.7	5.6 (142.2)
FR-3706	3.0	5.2 (132.0)	0.8	5.4 (137.2)
FR-3710	2.5	3.8 (96.5)	-0-	4.6 (116.8)
FR-3718	6.1	2.7 (68.6)	-0-	4.5 (114.3)
FR-3720	5.5	2.9 (73.7)	-0-	4.7 (119.4)

The results of these test are not to be considered or used as fire hazard classifications, and are not intended or implied to reflect hazards presented by this or any other material in actual fire conditions.

In the above tests, a 0.5 inch x 3.0 inch x 12 inch (12.7 mm x 76.2 mm x 305 mm) long foam sample is mounted in a vertical position. The lower end is exposed to a 1.5 inch (38.1 mm) Bunsen burner flame for the described time. The time to flame extinguishment after removal of the flame and burned length of the sample are recorded.

Chemical Resistance

LAST-A-FOAM® products exhibit very good-to-excellent resistance to a wide range of chemicals and solvents. Common petroleum products such as oil or gasoline have a negligible affect on LAST-A-FOAM®. Exposure to liquid acids and bases, either in dilute or highly-concentrated forms, does not significantly deteriorate foam properties at normal room temperatures. Some chlorinated solvents will cause LAST-A-FOAM® to temporarily swell or soften on exposure, which can be useful in some production situations. If you need specific advice regarding chemical resistance, please contact us.

Bonding, Filling, and Sealing LAST-A-FOAM

LAST-A-FOAM® can be bonded, filled, sealed and painted with a wide variety of commercially available finishing products. Our customers report greatest success with automotive and wood finishing materials, but the range of usable products is not limited to those types.

General Plastics Manufacturing Company has prepared a "Guide to Bonding, Filling, and Sealing LAST-A-FOAM® Products", available on request, to help with making appropriate finishing material selections. You should follow manufacturer's safety instructions when using any bonding, filling, or finishing product with LAST-A-FOAM®, and observe their recommended precautions.



Design Guide for use of LAST-A-FOAM FR-3700 for Crash and Fire Protection of Radioactive Material Shipping Containers

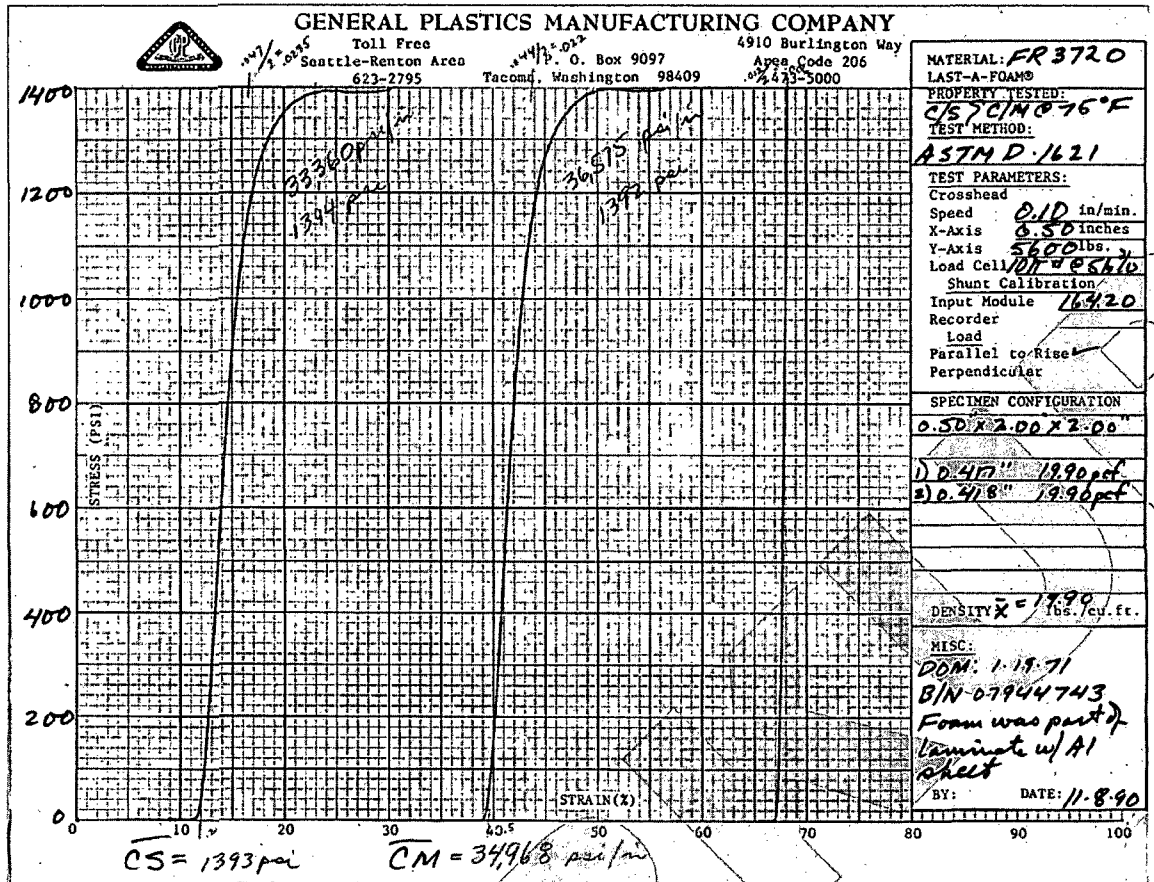


Figure 3: Long-Term Compressive Strength

Effect of Radiation

Cubic specimens (2.5 inch)-LAST-A-FOAM® FR-3710 were submitted to the University of Michigan Phoenix Memorial Laboratory. The Specimens were irradiated in a Cobalt-60 Irradiator to a maximum cumulative dose of 2×10^8 rads (gamma). This dosage is representative of approximately 40 years of life in a field of 500 rads per hour. Discoloration was observed to increase with dosage but was not correlated with any change of physical properties. The compressive strength of the specimens was unaffected by the radiation as evidenced by the data shown in Table 5 and Table 6. (Test date: 1994)

Table 5: Average of five specimens at each dosage (results for individual tests available upon request)

Exposure	DENSITY lbs/ft ³	Stress(psi) @ % Crush							
		10%	20%	30%	40%	50%	60%	65%	70%
Control	10.78	352	359	382	426	508	686	851	1,121
2 X 10 ⁷ rads	10.68	341	348	373	417	499	678	848	1,137
4.2 X 10 ⁷ rads	10.58	328	336	360	405	488	666	835	1,122
7 X 10 ⁷ rads	10.64	333	341	366	408	491	666	831	1,106
2 X 10 ⁸ rads	10.76	347	356	380	422	507	682	844	1,112

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Water Immersion

Using the same cubic samples from the radiation testing, LAST-A-FOAM® FR-3710 was shown to remain resistant to significant water absorption. The samples were placed in water at temperature of 125°F (52°C) and a pressure of 17.7 psig (122 kPa). As shown by the results presented in Table 6, water absorption occurs slowly, even considering the affects of radiation exposure. Resistance to water absorption is consistent with the close cell content of LAST-A-FOAM® FR-3700 of greater than 95%.

Table 6: Water Absorption as a function of time and Radiation Exposure

Time and Radiation Exposure	Density, lbs/ft ³	Before Submersion	After Submersion	Weight Gain, grams	% Gain By Volume, *
1 Day Immersion					
Non Irradiated	10.61	44.19	47.29	3.10	1.21
2.0 X 10 ⁷ rads	10.72	44.72	48.47	3.75	1.46
4.2 X 10 ⁷ rads	10.96	45.66	48.88	3.22	1.26
7.0 X 10 ⁷ rads	10.64	44.66	48.67	4.01	1.57
				Average-->	1.37
10 Day Immersion					
Non Irradiated	10.80	44.73	50.12	5.39	2.11
2.0 X 10 ⁷ rads	10.61	44.51	51.93	7.42	2.90
4.2 X 10 ⁷ rads	10.62	44.62	52.85	8.23	3.21
7.0 X 10 ⁷ rads	10.65	44.29	53.78	9.49	3.71
				Average-->	2.98
100 Day Immersion					
Non Irradiated	10.87	45.35	61.74	16.39	6.40
2.0 X 10 ⁷ rads	10.59	44.3	66.30	22.00	8.59
4.2 X 10 ⁷ rads	10.89	45.35	67.70	22.35	8.73
7.0 X 10 ⁷ rads	10.62	44.44	69.26	24.82	9.69
				Average-->	8.35
156 Day Immersion					
Non Irradiated	10.67	44.22	65.12	20.90	8.16
2.0 X 10 ⁷ rads	10.52	43.89	69.70	25.81	10.08
4.2 X 10 ⁷ rads	10.73	44.66	72.06	27.40	10.70
7.0 X 10 ⁷ rads	10.73	44.58	74.59	30.01	11.72
				Average-->	10.17

Design Guide for use of LAST-A-FOAM FR-3700 for Crash and Fire Protection of Radioactive Material Shipping Containers

Mechanical Properties

The data below are nominal values and appropriate tolerances should be considered when incorporating foam materials into static structural applications. Datasheet with values calculated may be found by following the link: [LAST-A-FOAM® FR-3700 Datasheets](#).

CAUTION: When using metric units, you must convert the input variable, D (density), to English units ($1 \text{ lb}_m/\text{ft}^3 = 16.02 \text{ kg}/\text{m}^3$).

Property	Line of Best Fit Where 'D' is the foam density in lb_m/ft^3 ($1 \text{ lb}_m/\text{ft}^3 = 16.02 \text{ kg}/\text{m}^3$)		Test Method	
	English (psi)	Metric (MPa)		
Compressive Strength				
Parallel to Rise				
@75°F	= 8.745 (D) ^{1.6154}	=0.0603 (D) ^{1.6154}	ASTM D-1621	
@250°F	= 4.537 (D) ^{1.6050}	=0.0313 (D) ^{1.6154}		
Perpendicular to Rise				
@75°F	= 3.456 (D) ^{1.9178}	=0.0238 (D) ^{1.6154}	ASTM D-1621	
@250°F	= 2.966 (D) ^{1.7146}	=0.0205 (D) ^{1.6154}		
Compressive Modulus				
Parallel to Rise	@75°F	= 276.2 (D) ^{1.5413}	=1.9043 (D) ^{1.6154}	ASTM D-1621
	@250°F	= 144.0 (D) ^{1.6396}	=0.9928 (D) ^{1.6154}	
Perpendicular to Rise	@75°F	= 74.66 (D) ^{1.9995}	=0.5148 (D) ^{1.6154}	ASTM D-1621
	@250°F	= 93.03 (D) ^{1.7174}	=0.6414 (D) ^{1.6154}	
Tensile Strength				
Parallel to Rise	= 29.68 (D) ^{1.1496}	=0.2046 (D) ^{1.6154}	ASTM D-1623 Type "A" Specimens	
Perpendicular to Rise	= 14.74 (D) ^{1.3852}	=0.1016 (D) ^{1.6154}		
Tensile Modulus				
Parallel to Rise	= 922.4 (D) ^{1.1817}	=6.3597 (D) ^{1.6154}	ASTM D-1623 Type "B" Specimens	
Perpendicular to Rise	= 286.5 (D) ^{1.5324}	=1.9753 (D) ^{1.6154}		
Shear Strength				
Parallel to Rise	= 7.530 (D) ^{1.5433}	=0.0519 (D) ^{1.6154}	ASTM C-273 Compression Shear	
Perpendicular to Rise	= 11.60 (D) ^{1.3754}	=0.0800 (D) ^{1.6154}		
Shear Modulus				
Parallel to Rise	= 40.53 (D) ^{1.8555}	=0.2794 (D) ^{1.6154}	ASTM C-273 Compression Shear	
Perpendicular to Rise	= 133.0 (D) ^{1.4209}	=0.9170 (D) ^{1.6154}		
Flexural Strength				
Parallel to Rise	= 8.287 (D) ^{1.6660}	=0.0571 (D) ^{1.6154}	ASTM D-790 Method 1-A	
Perpendicular to Rise	= 21.17 (D) ^{1.3614}	=0.1456 (D) ^{1.6154}		
Flexural Modulus				
Parallel to Rise	= 151.2 (D) ^{1.8084}	=1.0425 (D) ^{1.6154}	ASTM D-790 Method 1-A	
Perpendicular to Rise	= 545.8 (D) ^{1.3628}	=3.7631 (D) ^{1.6154}		



Design Guide for use of LAST-A-FOAM FR-3700 for Crash and Fire Protection of Radioactive Material Shipping Containers

Table 7: Static Nominal Crush Strength, Parallel to Direction of Rise (see Table 8 for Perpendicular to Rise)

For 4 to 10 lb _m /ft ³									
Temp	Correlation Factors	Crush Strength, psi, Parallel to Direction of Rise							
		10%	20%	30%	40%	50%	60%	65%	70%
-20°F	C _T	1.29	1.36	1.32	1.29	1.26	1.28	1.29	1.37
75°F	Y _{int}	7.3058	6.7276	6.4961	6.9137	5.6711	5.3279	5.9871	6.2085
	S	1.6590	1.7021	1.7350	1.7255	1.8877	2.0431	2.0870	2.1868
100°F	C _T	0.87	0.88	0.89	0.89	0.90	0.91	0.91	0.96
140°F	C _T	0.73	0.75	0.76	0.77	0.78	0.78	0.79	0.84
180°F	C _T	0.65	0.66	0.67	0.68	0.69	0.68	0.68	0.71
220°F	C _T	0.61	0.60	0.60	0.61	0.61	0.59	0.59	0.61
260°F	C _T	0.45	0.44	0.46	0.47	0.48	0.49	0.49	0.52
For 11 to 40 lb _m /ft ³									
Temp	Correlation Factor	Crush Strength, psi, Parallel to Direction of Rise							
		10%	20%	30%	40%	50%	60%	65%	70%
-20°F	C _T	1.35	1.33	1.32	1.31	1.31	1.30	1.28	1.26
75°F	Y _{int}	4.3422	3.8755	3.5241	3.0307	3.0402	3.4889	5.8935	5.6055
	S	1.8809	1.9321	1.9872	2.0755	2.1451	2.2143	2.1041	2.2368
100°F	C _T	0.86	0.87	0.88	0.88	0.89	0.90	0.90	0.97
140°F	C _T	0.72	0.74	0.75	0.75	0.75	0.76	0.76	0.81
180°F	C _T	0.62	0.63	0.65	0.65	0.65	0.65	0.64	0.68
220°F	C _T	0.56	0.56	0.57	0.57	0.56	0.54	0.54	0.57
260°F	C _T	0.40	0.40	0.41	0.42	0.41	0.43	0.43	0.47

The room temperature (75°F) foam crush strength is calculated at each %-Crush and is a function of density; $\sigma = Y_{int}(\rho)^S$, where Y_{int} and S are defined above, ρ is the nominal foam density in lb/ft³, and σ is the resulting crush stress in psi at the indicated strain. The foam crush strength at temperatures other than 75°F is calculated at each %-Crush and is a function of the strength at 75°F; $\sigma = \sigma_{75°F} C_T$. General Plastics Mfg. Co. is re-investigating the correlations factors at temperatures above and below 75°F. Please contact us for more specific and detailed data, as needed.

Design Guide for use of LAST-A-FOAM FR-3700 for Crash and Fire Protection of Radioactive Material Shipping Containers

Table 8: Static Nominal Crush Strength, Perpendicular to Direction of Rise (see Table 7 for Parallel to Rise)

For 4 to 10 lb _m /ft ³									
Temp	Correlation Factors (see below)	Crush Strength, psi, Perpendicular to Direction of Rise							
		10%	20%	30%	40%	50%	60%	65%	70%
-20°F	C _T	1.32	1.35	1.34	1.32	1.32	1.33	1.34	1.36
75°F	Y _{int}	6.3841	6.5943	6.1154	5.7722	5.3041	5.3181	5.7864	5.7701
	S	1.7182	1.6946	1.7403	1.8023	1.9054	2.0392	2.1002	2.2255
100°F	C _T	0.85	0.87	0.88	0.89	0.90	0.91	0.91	0.92
140°F	C _T	0.75	0.77	0.78	0.79	0.79	0.79	0.79	0.80
180°F	C _T	0.63	0.66	0.68	0.69	0.69	0.70	0.69	0.70
220°F	C _T	0.59	0.59	0.60	0.61	0.60	0.60	0.59	0.60
260°F	C _T	0.45	0.45	0.47	0.48	0.48	0.48	0.48	0.48
For 11 to 40 lb _m /ft ³									
Temp	Correlation Factors (see below)	Crush Strength, psi, Perpendicular to Direction of Rise							
		10%	20%	30%	40%	50%	60%	65%	70%
-20°F	C _T	1.34	1.33	1.32	1.33	1.30	1.28	1.24	1.17
75°F	Y _{int}	4.1342	3.5581	3.2664	2.8352	2.8988	3.3972	6.5439	5.6464
	S	1.8957	1.9593	2.0109	2.0955	2.1602	2.2242	2.0660	2.2321
100°F	C _T	0.84	0.85	0.86	0.88	0.87	0.88	0.88	0.90
140°F	C _T	0.72	0.73	0.74	0.76	0.75	0.76	0.76	0.79
180°F	C _T	0.62	0.63	0.64	0.65	0.65	0.65	0.65	0.67
220°F	C _T	0.53	0.53	0.54	0.55	0.54	0.54	0.54	0.56
260°F	C _T	0.39	0.39	0.40	0.41	0.41	0.40	0.40	0.42

The room temperature (75°F) foam crush strength is calculated at each %-Crush and is a function of density; $\sigma = Y_{int} (\rho)^S$, where Y_{int} and S are defined above, ρ is the nominal foam density in lb/ft³, and σ is the resulting crush stress in psi at the indicated strain. The foam crush strength at temperatures other than 75°F is calculated at each %-Crush and is a function of the strength at 75°F; $\sigma = \sigma_{75°F} C_T$. General Plastics Mfg. Co. is re-investigating the correlations factors at temperatures above and below 75°F. Please contact us for more specific and detailed data, as needed.



Dynamic Crush Strength

The crush strength of LAST-A-FOAM®, like many materials, is modestly sensitive to strain rate. The static to dynamic adjustment shown in Table 9 is based on a significant testing program and included strain rates in the range of 30 sec⁻¹ to 100 sec⁻¹. It is expected that the adjustment will provide good predictions of dynamic impact strength of FR-3700 for most Packaging design conditions. This information is intended to be a guide for designers of impact mitigating devices. The constitutive material models may be useful in targeting a foam density or rage for a particular application. However, each design should be thoroughly analyzed or tested to understand the implications of the complete design.

Table 9: Static to Dynamic Crush Strength Adjustment

Strain	10%	20%	30%	40%	50%	60%	65%	70%
Y _{int}	1.2971	1.4397	1.5181	1.3887	1.4419	1.4275	1.3871	1.4660
S	1.0330	1.0069	0.9941	1.0028	0.9912	0.9831	0.9910	0.9586

The dynamic crush strength is calculated at each %-strain and a function of the static crush strength at the same %-strain;

$$\sigma_{\text{Dynamic}} = y_{\text{int}} (\sigma_{\text{Static}})^S$$

CAUTION: Use only units of PSI for input σ_{Static} value.



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MARKUP

Air Properties

Air Properties

Properties from Incropera, Frank P., David P. DeWitt, *Fundamentals of Heat and Mass Transfer*, New York: John Wiley & Sons, Incorporated, 4th Ed., 1996.

Used modeling air gaps. Illustrations that follow show the Air gap locations (excerpt from Revision A of this report) and size of gap within the cask (dimensions included, Model AOS-165 provided as an example).

$$Gr = \frac{gS^3}{T\mu^2} \Delta T \quad \leftarrow \text{This part is calculated for different temperatures.}$$

Results shows for large range of ΔT ,

$$Gr < 2000 \quad \therefore N_u = 1$$

$$\therefore h_c = k/s \quad k_c = h_c S$$

Radiation assuming $T_1 \sim T_2$ (temperature across gap)

$$h_r = J * F * 4T^3$$

$$F = 0.351 \quad (\text{refer to Paragraph 3.3.1.2, "Enclosed Air Space Property Sets," within this report})$$

$$K_R = h_r S$$

Excerpt, *Fundamentals of Heat and Mass Transfer*, Table A.4,
 "Thermophysical Properties of Gases at Atmospheric Pressure," Page 839

Appendix A ■ Thermophysical Properties of Matter

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TABLE A.4 Thermophysical Properties
 of Gases at Atmospheric Pressure^a

T (K)	ρ (kg/m ³)	c_p (kJ/kg · K)	$\mu \cdot 10^7$ (N · s/m ²)	$\nu \cdot 10^6$ (m ² /s)	$k \cdot 10^3$ (W/m · K)	$\alpha \cdot 10^6$ (m ² /s)	Pr
Air							
100	3.5562	1.032	71.1	2.00	9.34	2.54	0.786
150	2.3364	1.012	103.4	4.426	13.8	5.84	0.758
200	1.7458	1.007	132.5	7.590	18.1	10.3	0.737
250	1.3947	1.006	159.6	11.44	22.3	15.9	0.720
300	1.1614	1.007	184.6	15.89	26.3	22.5	0.707
350	0.9950	1.009	208.2	20.92	30.0	29.9	0.700
400	0.8711	1.014	230.1	26.41	33.8	38.3	0.690
450	0.7740	1.021	250.7	32.39	37.3	47.2	0.686
500	0.6964	1.030	270.1	38.79	40.7	56.7	0.684
550	0.6329	1.040	288.4	45.57	43.9	66.7	0.683
600	0.5804	1.051	305.8	52.69	46.9	76.9	0.685
650	0.5356	1.063	322.5	60.21	49.7	87.3	0.690
700	0.4975	1.075	338.8	68.10	52.4	98.0	0.695
750	0.4643	1.087	354.6	76.37	54.9	109	0.702
800	0.4354	1.099	369.8	84.93	57.3	120	0.709
850	0.4097	1.110	384.3	93.80	59.6	131	0.716
900	0.3868	1.121	398.1	102.9	62.0	143	0.720
950	0.3666	1.131	411.3	112.2	64.3	155	0.723
1000	0.3482	1.141	424.4	121.9	66.7	168	0.726
1100	0.3166	1.159	449.0	141.8	71.5	195	0.728
1200	0.2902	1.175	473.0	162.9	76.3	224	0.728
1300	0.2679	1.189	496.0	185.1	82	238	0.719
1400	0.2488	1.207	530	213	91	303	0.703
1500	0.2322	1.230	557	240	100	350	0.685
1600	0.2177	1.248	584	268	106	390	0.688
1700	0.2049	1.267	611	298	113	435	0.685
1800	0.1935	1.286	637	329	120	482	0.683
1900	0.1833	1.307	663	362	128	534	0.677
2000	0.1741	1.337	689	396	137	589	0.672
2100	0.1658	1.372	715	431	147	646	0.667
2200	0.1582	1.417	740	468	160	714	0.655
2300	0.1513	1.478	766	506	175	783	0.647
2400	0.1448	1.558	792	547	196	869	0.630
2500	0.1389	1.665	818	589	222	960	0.613
3000	0.1135	2.726	955	841	486	1570	0.536
Ammonia (NH₃)							
300	0.6894	2.158	101.5	14.7	24.7	16.6	0.887
320	0.6448	2.170	109	16.9	27.2	19.4	0.870
340	0.6059	2.192	116.5	19.2	29.3	22.1	0.872
360	0.5716	2.221	124	21.7	31.6	24.9	0.872
380	0.5410	2.254	131	24.2	34.0	27.9	0.869

The decay heat of the cask contents is introduced in the model by two-node convective boundary elements along the cask cavity wall. In the model, it is assumed that the load is uniformly distributed over the entire cavity surface.

Convective boundary elements define the convective and radiative properties at the interface between the impact limiter outer surface and the regulatory environments. Another convective surface is located on the side of the cask's outer shell, between the upper and lower impact limiter structures. In addition to convective and radiative properties, these boundary two-node elements have the capability to include required solar heat flux loads.

Figure 3-2 illustrates all components and interfaces of the thermal model.

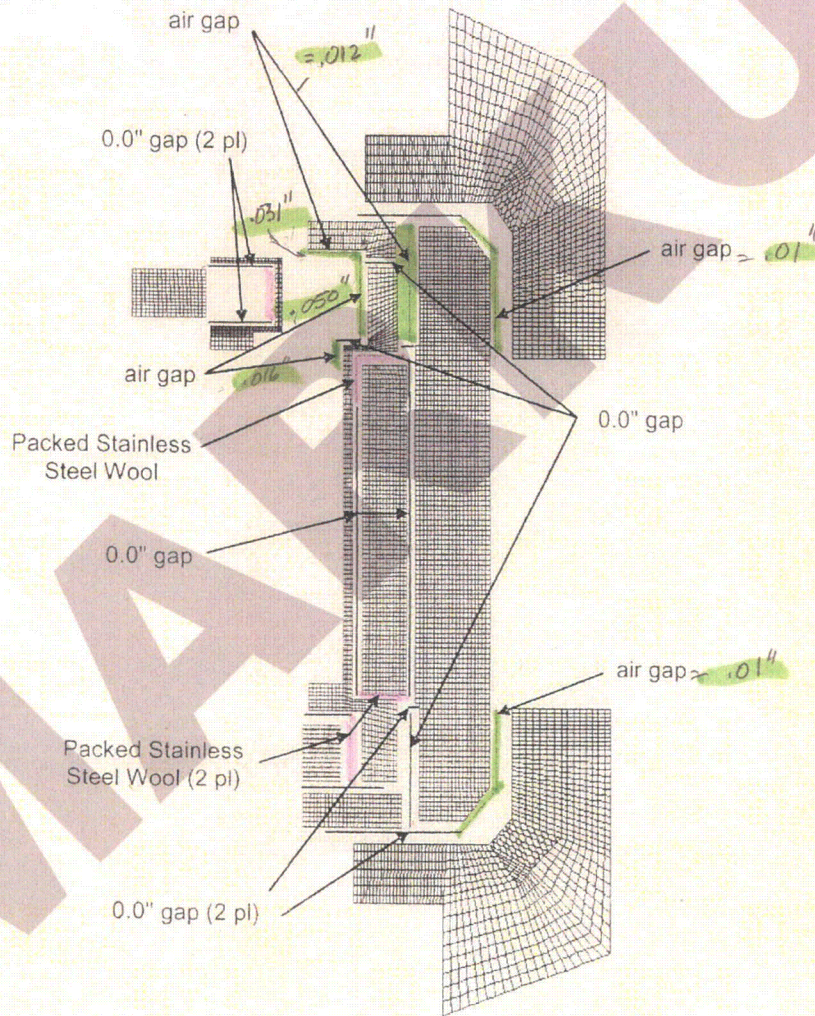
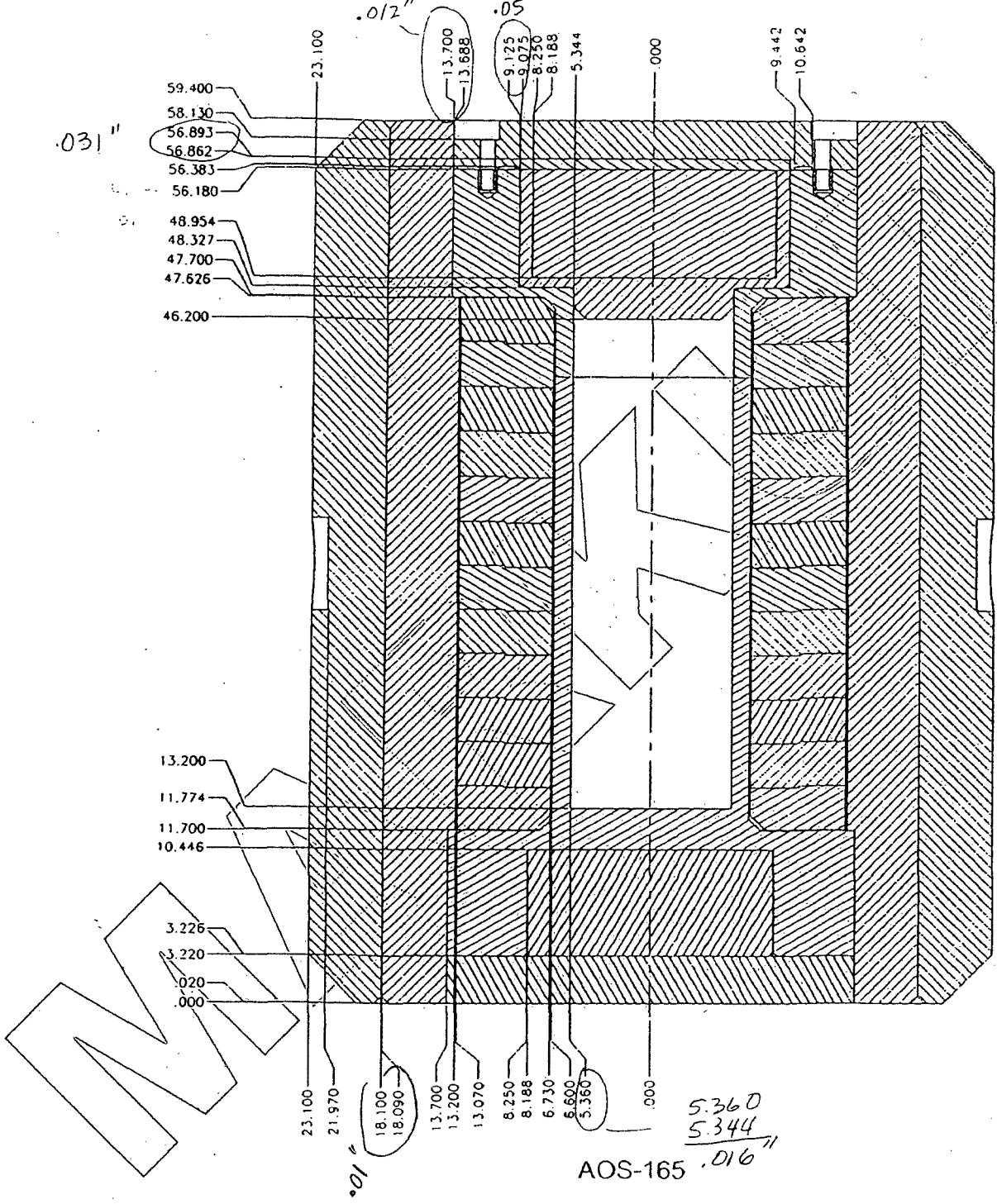
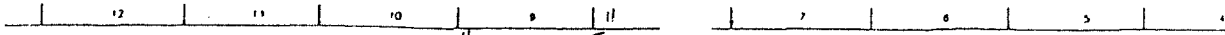


Figure 3-2. Expanded View of Thermal Model Defining Component Interfaces

Size of Gap within Cask - Model AOS-165



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Port Seal



MATERIAL REPORT

REPORT NUMBER: KK2206
DATE: 06/19/96

TITLE: Evaluation of Parker Compound S1224-70 to ASTM D2000
7GE705 A19 B37 EA14 EO16 E036 F19 G11

PURPOSE: To determine if S1224-70 meets the callout.

CONCLUSION: Compound S1224-70 meets the ASTM D2000 callout.

Recommended temperature limits: -65⁰F to 450⁰F

Recommended For

Dry heat
Some petroleum oils
Moderate water resistance
Fire resistant hydraulic fluids (HFD-R and HFD-S)
Ozone, aging, and weather resistance
Low temperature

Not Recommended For

Ketones
Acids
Silicone oils
Auto and aircraft brake fluid



Compound Data Sheet
Parker O-Ring Division United States

REPORT DATA

Report Number: KK2206

	ASTM D2000 7GE705 A19 B37 EA14 EO16 E036 F19 G11 Pass / Fail Limits	S1224-70 Slab Results
<u>Basic Physical Properties</u>		
Hardness	70 +/- 5	69
Tensile Strength, psi min	725	1204
Elongation, % min	150	265
<u>ASTM D573 Heat Aging, 70 HRS @ 225°C</u>		
Hardness Change, pts max	+10	+6
Tensile Change, % max	-25	-14
Elongation Change, % max	-30	-26
<u>Compression Set ASTM D395, 22 HRS @ 347°F, plies</u>		
% of Original Deflection, max	30	23
<u>Fluid Immersion, ASTM #1 Oil, 70 HRS @ 150°C</u>		
Hardness Change, pts	0 to -15	-9
Tensile Change, % max	-20	+10
Elongation Change, % max	-20	+3
Volume Change, %	0 to +15	+4
<u>Fluid Immersion, ASTM #3 Oil, 70 HRS @ 302°F</u>		
Hardness Change, pts max	-40	-19
Volume Change, % max	+60	+35
<u>Fluid Immersion ASTM D471 Water 70 HRS @ 212°F</u>		
Hardness Change, pts. max.	+/-5	0
Volume Change, % max.	+/-5	0
<u>Tear Resistance, ASTM D624, Die B</u>		
kN/M, min	9	14
<u>Low Temperature Brittleness Test ASTM D2137, Method A</u>		
3 min. @ -55°C	Pass	Pass

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Lid Seal

HELICOFLEX®

Spring Energized Seals

PERFORMANCE DATA

Jacket Material	HELIUM SEALING							BUBBLE SEALING				Max Temp °F	Dimensions in Inches
	Cross Section	e ₂	e _c	Y ₂ lbs/inch	Y ₁ lbs/inch	Pu68°F PSI	PuØ392°F PSI	Y ₂ lbs/inch	Y ₁ lbs/inch	Pu68°F PSI	PuØ392°F PSI		
Aluminum	0.063	0.024	0.028	857	114	7250	N/A	514	114	5075	N/A	302	R
	0.075	0.028	0.033	914	114	7540	N/A	571	114	5800	N/A	302	
	0.087	0.028	0.035	942	114	7685	N/A	600	114	5800	N/A	356	
	0.098	0.028	0.035	999	114	7975	725	657	114	6090	725	428	
	0.118	0.031	0.039	1056	143	7975	1450	742	114	6525	1450	482	
	0.138	0.031	0.039	1085	143	7975	2030	799	114	6815	2030	482	
	0.157	0.035	0.043	1142	143	8700	2465	857	114	7250	2465	536	
	0.177	0.035	0.047	1199	143	8700	2900	914	114	7540	2900	536	
	0.197	0.035	0.055	1256	171	9135	3190	971	143	7975	3190	572	
	0.217	0.035	0.063	1313	171	9425	3480	1028	143	8265	3480	608	
	0.236	0.039	0.071	1399	200	9715	3625	1113	171	8700	3625	644	
	0.276	0.039	0.087	1542	228	10150	4060	1171	200	9425	4060	644	
	0.315	0.039	0.102	1656	286	10440	4640	1285	228	9860	4495	680	
							PuØ482°F				PuØ482°F		
Silver	0.063	0.020	0.024	1142	171	9425	N/A	857	171	5800	N/A	464	
	0.075	0.024	0.028	1256	171	9425	N/A	857	171	5800	N/A	464	
	0.087	0.024	0.031	1313	200	10150	N/A	914	171	5800	580	536	
	0.098	0.028	0.035	1370	257	10875	1160	971	228	6525	725	536	
	0.118	0.031	0.039	1485	286	12325	2030	1028	257	7250	1305	572	
	0.138	0.031	0.039	1599	286	13775	3190	1085	257	7975	1885	572	
	0.157	0.031	0.043	1713	314	15225	3915	1142	286	8700	2320	662	
	0.177	0.031	0.043	1827	343	16675	4495	1256	286	10150	2755	698	
	0.197	0.031	0.051	1941	343	18125	5220	1313	286	11600	3190	698	
	0.217	0.031	0.055	2056	371	19575	5800	1428	343	13050	3625	752	
	0.236	0.035	0.067	2284	400	21750	6815	1542	343	15950	4350	842	
	0.276	0.035	0.079	2512	457	23200	7830	1713	371	18125	5220	842	
	0.315	0.035	0.094	2798	514	24650	8700	1999	400	20300	6090	932	
							PuØ572°F				PuØ572°F		
Copper, Soft Iron, Mild Steels and Annealed Nickel	0.063	0.020	0.024	1485	228	7250	1450	1085	171	5075	725	662	
	0.075	0.024	0.028	1599	286	7250	1595	1142	228	5075	870	662	
	0.087	0.024	0.031	1713	343	7975	1885	1256	286	5075	1160	680	
	0.098	0.028	0.035	1827	400	8700	2465	1313	343	5800	1450	716	
	0.118	0.028	0.039	1999	457	9425	2900	1428	400	5800	1740	716	
	0.138	0.028	0.039	2227	457	10150	3335	1542	400	6525	2175	752	
	0.157	0.031	0.043	2455	514	10150	3915	1656	457	6525	2465	788	
	0.177	0.031	0.043	2684	571	11600	4350	1827	457	6525	2755	842	
	0.197	0.031	0.051	2912	628	12325	4785	1884	514	7250	3045	842	
	0.217	0.031	0.055	3141	685	13050	5220	2056	571	7250	3335	896	
	0.236	0.035	0.067	3597	799	13775	5800	2284	571	7975	3770	968	
	0.276	0.035	0.079	4225	914	14500	6525	2627	628	8700	4205	968	
	0.315	0.035	0.094	4911	1085	15950	7105	3026	742	9425	4640	1022	
							PuØ662°F				PuØ662°F		
Nickel, Monel, Tantalum	0.063	0.016	0.020	1827	457	10150	1595	1142	343	5800	1015	716	
	0.075	0.020	0.024	1999	457	10440	2320	1256	343	6090	1305	716	
	0.087	0.020	0.028	2227	514	11020	3045	1313	400	6380	1740	788	
	0.098	0.024	0.031	2512	571	11890	3915	1542	400	6815	2320	842	
	0.118	0.024	0.035	2512	628	12615	4930	1713	457	7250	2900	896	
	0.138	0.024	0.035	2798	685	13485	5800	1941	514	7830	3335	932	
	0.157	0.028	0.039	3312	799	13920	6525	2170	571	8265	3915	1022	
	0.177	0.028	0.039	4111	857	15225	7540	2398	628	8700	4350	1112	
	0.197	0.028	0.043	4454	1028	15950	8265	2627	628	9425	4785	1202	
	0.217	0.028	0.051	4625	1142	16675	8990	2855	685	9715	5365	1202	
	0.236	0.031	0.063	N/A	N/A	N/A	N/A	3198	742	10440	5945	1202	
	0.276	0.031	0.071	N/A	N/A	N/A	N/A	3712	857	11310	6525	1202	
	0.315	0.031	0.083	N/A	N/A	N/A	N/A	4168	914	12035	7250	1202	
							PuØ752°F				PuØ752°F		
Stainless Steel, Inconel, Titanium	0.063	0.016	0.020	1999	571	13050	3625	1713	457	6815	870	788	
	0.075	0.020	0.024	2284	571	13195	3915	1827	457	7250	1160	788	
	0.087	0.020	0.028	2570	628	13340	4205	1999	514	7540	1595	896	
	0.098	0.024	0.031	2855	685	14065	4640	2170	571	8265	2175	932	
	0.118	0.024	0.035	3283	742	14500	5220	2427	628	8990	2900	932	
	0.138	0.024	0.035	3769	857	15080	5655	2684	742	9715	3625	1022	
	0.157	0.028	0.039	4283	971	15515	6090	2969	857	10440	4350	1112	
	0.177	0.028	0.039	4711	1256	15950	6525	3198	1028	11165	4930	1202	
	0.197	0.028	0.043	N/A	N/A	N/A	N/A	3426	1085	11890	5365	1292	
	0.217	0.028	0.051	N/A	N/A	N/A	N/A	3712	1142	12615	6090	1292	
	0.236	0.031	0.063	N/A	N/A	N/A	N/A	4111	1256	13630	6815	1292	
	0.276	0.031	0.071	N/A	N/A	N/A	N/A	4568	1485	14790	7540	1292	
	0.315	0.031	0.083	N/A	N/A	N/A	N/A	5139	1656	15660	8410	1292	

HELICOFLEX[®]

Spring Energized Seals

SEAL AND GROOVE DIMENSIONS

Jacket Material	SEAL			Pressure < 300psi		Pressure > 300psi		GROOVE		Groove Finish RMS	Dimension: in inches
	Free Height	Installation Compression e2	Seal Diameter Range	Diametrical Clearance X	Diametrical Clearance X	Groove Depth F	Groove Width (Min.) G	Groove Finish RMS			
Aluminum	0.063	0.024	0.500 to 4.000	0.024	0.012	0.039 +/- 0.003	0.111	32-125 Contact Applications Engineering for Recommendation			
	0.075	0.028	0.625 to 6.000	0.028	0.012	0.047 +/- 0.003	0.131				
	0.087	0.028	0.750 to 10.000	0.028	0.012	0.059 +/- 0.003	0.143				
	0.098	0.028	0.875 to 15.000	0.028	0.012	0.070 +/- 0.003	0.154				
	0.118	0.031	1.000 to 20.000	0.031	0.012	0.087 +/- 0.004	0.180				
	0.138	0.031	1.250 to 25.000	0.031	0.020	0.107 +/- 0.004	0.200				
	0.157	0.035	1.750 to 30.000	0.035	0.020	0.122 +/- 0.004	0.227				
	0.177	0.035	2.000 to 40.000	0.035	0.020	0.142 +/- 0.004	0.247				
	0.197	0.035	3.000 to 50.000	0.035	0.020	0.162 +/- 0.004	0.267				
	0.217	0.035	4.000 to 50.000 +	0.035	0.020	0.182 +/- 0.004	0.287				
	0.236	0.039	5.000 to 50.000 +	0.039	0.020	0.197 +/- 0.005	0.314				
0.276	0.039	6.000 to 50.000 +	0.039	0.028	0.237 +/- 0.005	0.354					
0.315	0.039	8.000 to 50.000 +	0.039	0.028	0.276 +/- 0.005	0.393					
Silver	0.063	0.020	0.500 to 4.000	0.020	0.012	0.043 +/- 0.002	0.103	63-125 Contact Applications Engineering for Recommendation			
	0.075	0.024	0.625 to 6.000	0.024	0.012	0.051 +/- 0.003	0.123				
	0.087	0.024	0.750 to 10.000	0.024	0.012	0.063 +/- 0.003	0.135				
	0.098	0.028	0.875 to 15.000	0.028	0.012	0.070 +/- 0.003	0.154				
	0.118	0.031	1.000 to 20.000	0.031	0.012	0.087 +/- 0.004	0.180				
	0.138	0.031	1.250 to 25.000	0.031	0.020	0.107 +/- 0.004	0.200				
	0.157	0.031	1.750 to 30.000	0.031	0.020	0.126 +/- 0.004	0.219				
	0.177	0.031	2.000 to 40.000	0.031	0.020	0.146 +/- 0.004	0.239				
	0.197	0.031	3.000 to 50.000	0.031	0.020	0.166 +/- 0.004	0.259				
	0.217	0.031	4.000 to 50.000 +	0.031	0.020	0.186 +/- 0.004	0.279				
	0.236	0.035	5.000 to 50.000 +	0.035	0.020	0.201 +/- 0.004	0.306				
0.276	0.035	6.000 to 50.000 +	0.035	0.028	0.241 +/- 0.004	0.346					
0.315	0.035	8.000 to 50.000 +	0.035	0.028	0.280 +/- 0.004	0.385					
Copper, Soft Iron, Mild Steels and Annealed Nickel	0.063	0.020	0.500 to 4.000	0.020	0.012	0.043 +/- 0.002	0.103	63-125 Contact Applications Engineering for Recommendation			
	0.075	0.024	0.625 to 6.000	0.024	0.012	0.051 +/- 0.003	0.123				
	0.087	0.024	0.750 to 10.000	0.024	0.012	0.063 +/- 0.003	0.135				
	0.098	0.028	0.875 to 15.000	0.028	0.012	0.070 +/- 0.003	0.154				
	0.118	0.028	1.000 to 20.000	0.028	0.012	0.090 +/- 0.003	0.174				
	0.138	0.028	1.250 to 25.000	0.028	0.020	0.110 +/- 0.003	0.194				
	0.157	0.031	1.750 to 30.000	0.031	0.020	0.126 +/- 0.004	0.219				
	0.177	0.031	2.000 to 40.000	0.031	0.020	0.146 +/- 0.004	0.239				
	0.197	0.031	3.000 to 50.000	0.031	0.020	0.166 +/- 0.004	0.259				
	0.217	0.031	4.000 to 50.000 +	0.031	0.020	0.186 +/- 0.004	0.279				
	0.236	0.035	5.000 to 50.000 +	0.035	0.020	0.201 +/- 0.004	0.306				
0.276	0.035	6.000 to 50.000 +	0.035	0.028	0.241 +/- 0.004	0.346					
0.315	0.035	8.000 to 50.000 +	0.035	0.028	0.280 +/- 0.004	0.385					
Nickel, Monel, Tantalum	0.063	0.016	0.500 to 4.000	0.016	0.012	0.047 +/- 0.002	0.095	32-63 Contact Applications Engineering for Recommendation			
	0.075	0.020	0.625 to 6.000	0.020	0.012	0.055 +/- 0.002	0.115				
	0.087	0.020	0.750 to 10.000	0.020	0.012	0.067 +/- 0.002	0.127				
	0.098	0.024	0.875 to 15.000	0.024	0.012	0.074 +/- 0.003	0.146				
	0.118	0.024	1.000 to 20.000	0.024	0.012	0.094 +/- 0.003	0.166				
	0.138	0.024	1.250 to 25.000	0.024	0.020	0.114 +/- 0.003	0.186				
	0.157	0.028	1.750 to 30.000	0.028	0.020	0.129 +/- 0.003	0.213				
	0.177	0.028	2.000 to 40.000	0.028	0.020	0.149 +/- 0.003	0.233				
	0.197	0.028	3.000 to 50.000	0.028	0.020	0.169 +/- 0.003	0.253				
	0.217	0.028	4.000 to 50.000 +	0.028	0.020	0.189 +/- 0.003	0.273				
	0.236	0.031	5.000 to 50.000 +	0.031	0.020	0.205 +/- 0.004	0.298				
0.276	0.031	6.000 to 50.000 +	0.031	0.028	0.245 +/- 0.004	0.338					
0.315	0.031	8.000 to 50.000 +	0.031	0.028	0.284 +/- 0.004	0.377					
Stainless Steel, Inconel, Titanium	0.063	0.016	0.500 to 4.000	0.016	0.012	0.047 +/- 0.002	0.095	32-63 Contact Applications Engineering for Recommendation			
	0.075	0.020	0.625 to 6.000	0.020	0.012	0.055 +/- 0.002	0.115				
	0.087	0.020	0.750 to 10.000	0.020	0.012	0.067 +/- 0.002	0.127				
	0.098	0.024	0.875 to 15.000	0.024	0.012	0.074 +/- 0.003	0.146				
	0.118	0.024	1.000 to 20.000	0.024	0.012	0.094 +/- 0.003	0.166				
	0.138	0.024	1.250 to 25.000	0.024	0.020	0.114 +/- 0.003	0.186				
	0.157	0.028	1.750 to 30.000	0.028	0.020	0.129 +/- 0.003	0.213				
	0.177	0.028	2.000 to 40.000	0.028	0.020	0.149 +/- 0.003	0.233				
	0.197	0.028	3.000 to 50.000	0.028	0.020	0.169 +/- 0.003	0.253				
	0.217	0.028	4.000 to 50.000 +	0.028	0.020	0.189 +/- 0.003	0.273				
	0.236	0.031	5.000 to 50.000 +	0.031	0.020	0.205 +/- 0.004	0.298				
0.276	0.031	6.000 to 50.000 +	0.031	0.028	0.245 +/- 0.004	0.338					
0.315	0.031	8.000 to 50.000 +	0.031	0.028	0.284 +/- 0.004	0.377					

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3.5.8 Data CDs

All thermal input/output files, as well as all Autodesk Inventor files, are attached on the Compact Discs (CDs), as listed below:

- **CDs 1, 2, and 3** – All analytical files, including the LIBRA FE program
- **CD 4** – Autodesk Inventor files

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3.5.9 Justification for Use of Uniformly Distributed Decay Heat throughout Cask Cavity

Typically, the content is placed in the cask cavity in a basket or rack device. This device provides shoring to the content, to ensure that its loading arrangement is maintained during transportation. Selection of the type of material for fabrication of this device is based upon the temperature environment within the cask cavity. A cavity temperature of less than 400°F will allow the use of aluminum. For temperatures of 400°F or greater, the choice is stainless steel material, although this material could be used in either case.

The cavity temperature within all AOS Transport System Models is less than 300°F under Normal conditions of transport; therefore, the use of either material in the fabrication of the shoring devices is acceptable.

In the AOS cask analyses, the decay heat is assumed to be uniformly distributed throughout the cask cavity. The effect of this assumption is examined here, by comparing cask stress and temperatures corresponding to three assumed distributions of decay heat over the surface of the cask cavity. The three assumed distributions represent usual, assumed decay heat distributions over the cask cavity cylinder, top, and bottom.

- **Case 1** – Decay heat uniformly distributed over the cask cavity cylindrical surface, top surface, and bottom surface (as in the AOS analyses).
- **Case 2** – Decay heat distributed over the cask cavity cylindrical surface, top surface, and bottom surface, such that the cylindrical surface receives twice the heat intensity as the top and bottom surfaces.
- **Case 3** – Decay heat distributed over only cask cavity cylindrical surface, with the top and bottom surfaces receiving no heat.

Cask temperatures and thermal stress were determined for each of the three distributions. The maximum component temperatures are presented in Table 3-100 through Table 3-102, and cask temperature distributions are illustrated in Figure 3-146 through Figure 3-148. Pm and Pb stress at the critical cask cross-sections are presented in Table 3-103 through Table 3-105, and plots of maximum principal stress in the cask dog-leg region are illustrated in Figure 3-149 through Figure 3-151.

A comparison of Table 3-100 through Table 3-102 shows little variation in maximum temperature for the three heat distributions. Figure 3-146 through Figure 3-148 show that Case 1, uniformly distributed decay heat, provides maximum temperature in the seal region. From Table 3-100 through Table 3-102, the maximum temperature difference is less than 6°F.

A comparison of Table 3-103 through Table 3-105 shows little variation in stress due to heat distribution. Maximum thermal bending stress occurs at Location 4, and the maximum stress difference due to heat distribution is 0.5 ksi. Figure 3-149 through Figure 3-151 also show only a small stress difference in the cask dog-leg region due to the heat distribution.

In the AOS cask analyses, thermal stress due to maximum decay heat represents only a small portion of total stress in all load combinations. As a result, the small stress change in the three cases shows that a change in assumed decay heat distribution would have negligible effect upon overall stress evaluations. In addition, maximum change in the corresponding temperatures for the three cases is less than 6°F, with the uniform decay heat distribution producing maximum temperature in the seal region.

Table 3-100. Case 1, Maximum Component Temperatures^a

Component	Node_1	Node_2	Node	Max_Temp
Outside Shell	101	2894	606	1.8090E+02
Bottom Plate	3001	3232	3120	1.8160E+02
Lid	3233	3424	3233	1.8210E+02
Shell Cavity	4001	4998	4227	1.9420E+02
Plug	5001	5404	5001	1.9820E+02
Tungsten	6001	7656	7377	1.8620E+02
LAST-A-FOAM	8001	10791	9501	1.8160E+02

Table 3-101. Case 2, Maximum Component Temperatures^b

Component	Node_1	Node_2	Node	Max_Temp
Outside Shell	101	2894	620	1.7830E+02
Bottom Plate	3001	3232	3120	1.7850E+02
Lid	3233	3424	3233	1.7680E+02
Shell Cavity	4001	4998	4482	1.8920E+02
Plug	5001	5404	5012	1.8000E+02
Tungsten	6001	7656	6392	1.8120E+02
LAST-A-FOAM	8001	10791	8197	1.7810E+02

Table 3-102. Case 3, Maximum Component Temperatures^c

Component	Node_1	Node_2	Node	Max_Temp
Outside Shell	101	2894	634	1.8120E+02
Bottom Plate	3001	3232	3120	1.8060E+02
Lid	3233	3424	3233	1.8000E+02
Shell Cavity	4001	4998	4497	1.9310E+02
Plug	5001	5404	5012	1.8350E+02
Tungsten	6001	7656	6432	1.8450E+02
LAST-A-FOAM	8001	10791	8197	1.8030E+02

- a. **Case 1** – Decay heat uniformly distributed over the cask cavity cylindrical surface, top surface, and bottom surface (as in the AOS analyses).
- b. **Case 2** – Decay heat distributed over the cask cavity cylindrical surface, top surface, and bottom surface, such that the cylindrical surface receives twice the heat intensity as the top and bottom surfaces.
- c. **Case 3** – Decay heat distributed over only cask cavity cylindrical surface, with the top and bottom surfaces receiving no heat.

Table 3-103. Case 1, Stress (psi/MPa)

Location	Sigma_1	Sigma_2	Sigma_3	Pm	Pb
-----	-----	-----	-----	--	--
1	1.0456E+02 7.2091E-01	-1.8983E+02 -1.3088E+00	-2.8034E+01 -1.9329E-01	2.9439E+02 2.0297E+00	4.2926E+02 2.9597E+00
2	1.3149E+02 9.0661E-01	-2.9406E+02 -2.0275E+00	-8.4539E+01 -5.8288E-01	4.2555E+02 2.9341E+00	8.7203E+02 6.0124E+00
3	1.0021E+02 6.9094E-01	-1.8730E+02 -1.2914E+00	-2.2414E+01 -1.5454E-01	2.8752E+02 1.9823E+00	4.2741E+02 2.9469E+00
4	6.3127E+02 4.3524E+00	-2.1814E+03 -1.5040E+01	-4.4076E+02 -3.0390E+00	2.8126E+03 1.9392E+01	5.5355E+03 3.8166E+01
5	6.2466E+02 4.3069E+00	-2.4329E+03 -1.6774E+01	-9.8919E+02 -6.8202E+00	3.0575E+03 2.1081E+01	4.8291E+03 3.3295E+01
6	9.6377E+01 6.6450E-01	-1.2090E+03 -8.3357E+00	-1.3048E+03 -8.9960E+00	1.3054E+03 9.0002E+00	1.5833E+03 1.0916E+01
7	-1.9217E+01 -1.3249E-01	-4.1327E+02 -2.8494E+00	2.4598E+01 1.6960E-01	3.9406E+02 2.7169E+00	4.2739E+02 2.9468E+00
8	-1.9485E+01 -1.3434E-01	-4.1288E+02 -2.8467E+00	-1.5849E-01 -1.0927E-03	3.9339E+02 2.7123E+00	4.2023E+02 2.8974E+00
9	-1.9384E+01 -1.3364E-01	-4.1271E+02 -2.8456E+00	-1.5390E+00 -1.0611E-02	3.9333E+02 2.7119E+00	4.1618E+02 2.8695E+00
10	-7.2193E+01 -4.9775E-01	-5.3770E+02 -3.7073E+00	6.2101E+01 4.2817E-01	4.6550E+02 3.2095E+00	9.5760E+02 6.6024E+00
11	-1.2200E+02 -8.4114E-01	-6.7410E+02 -4.6478E+00	-3.2254E+02 -2.2238E+00	5.5211E+02 3.8066E+00	1.2549E+02 8.6522E-01
12	2.5799E+00 1.7788E-02	-8.1753E+02 -5.6367E+00	-8.1351E+02 -5.6090E+00	8.2011E+02 5.6545E+00	1.7232E+02 1.1881E+00
13	-8.6733E+01 -5.9800E-01	-1.2094E+03 -8.3386E+00	-1.2100E+02 -8.3430E-01	1.1227E+03 7.7406E+00	8.1844E+02 5.6430E+00
14	-6.9338E+01 -4.7807E-01	-1.0534E+03 -7.2632E+00	5.7286E+01 3.9497E-01	9.8411E+02 6.7852E+00	6.6719E+02 4.6001E+00
15	2.1678E+02 1.4946E+00	-2.8099E+02 -1.9374E+00	-3.4633E+01 -2.3879E-01	4.9777E+02 3.4320E+00	8.3966E+02 5.7893E+00
16	6.5964E+01 4.5480E-01	-1.3093E+02 -9.0271E-01	-3.3301E+01 -2.2960E-01	1.9689E+02 1.3575E+00	3.3071E+02 2.2802E+00

17	3.0783E+01	-9.2873E+01	-1.1470E+01	1.2366E+02	2.1759E+02
	2.1224E-01	-6.4034E-01	-7.9082E-02	8.5258E-01	1.5002E+00
18	4.5328E+01	-9.9979E+01	5.5228E+02	1.4531E+02	6.1413E+01
	3.1252E-01	-6.8933E-01	3.8078E+00	1.0019E+00	4.2343E-01
19	-1.8918E+01	-2.1523E+02	6.9267E+02	1.9631E+02	2.1305E+02
	-1.3043E-01	-1.4840E+00	4.7758E+00	1.3535E+00	1.4689E+00
20	-3.7965E+01	-5.4220E+02	1.6813E+02	5.0423E+02	2.4979E+02
	-2.6176E-01	-3.7383E+00	1.1592E+00	3.4765E+00	1.7222E+00
21	3.1481E+00	-8.6388E+01	-8.2724E+01	8.9536E+01	1.2184E+02
	2.1705E-02	-5.9563E-01	-5.7036E-01	6.1733E-01	8.4008E-01
22	-2.8719E+01	-1.4109E+02	-1.3557E+02	1.1237E+02	1.3962E+02
	-1.9801E-01	-9.7277E-01	-9.3474E-01	7.7476E-01	9.6264E-01

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Table 3-104. Case 2, Stress (psi/MPa)

Location	Sigma_1	Sigma_2	Sigma_3	Pm	Pb
-----	-----	-----	-----	--	--
1	1.0626E+02 7.3263E-01	-1.8898E+02 -1.3029E+00	-1.7071E+01 -1.1770E-01	2.9524E+02 2.0356E+00	4.2317E+02 2.9176E+00
2	1.3586E+02 9.3669E-01	-3.0081E+02 -2.0740E+00	-9.1768E+01 -6.3272E-01	4.3667E+02 3.0107E+00	8.9696E+02 6.1843E+00
3	1.0306E+02 7.1056E-01	-1.8881E+02 -1.3018E+00	-1.6976E+01 -1.1704E-01	2.9187E+02 2.0124E+00	4.2935E+02 2.9603E+00
4	6.8554E+02 4.7267E+00	-2.0418E+03 -1.4077E+01	-4.0530E+02 -2.7944E+00	2.7273E+03 1.8804E+01	5.3361E+03 3.6791E+01
5	7.1795E+02 4.9501E+00	-2.3302E+03 -1.6066E+01	-7.5061E+02 -5.1752E+00	3.0481E+03 2.1016E+01	4.8219E+03 3.3246E+01
6	1.0763E+02 7.4210E-01	-1.1763E+03 -8.1103E+00	-9.7713E+02 -6.7371E+00	1.2839E+03 8.8524E+00	1.6656E+03 1.1484E+01
7	-2.0446E+01 -1.4097E-01	-4.0750E+02 -2.8096E+00	2.8551E+01 1.9685E-01	3.8706E+02 2.6687E+00	4.7858E+02 3.2997E+00
8	-2.0978E+01 -1.4464E-01	-4.0600E+02 -2.7992E+00	-4.8058E-01 -3.3135E-03	3.8502E+02 2.6546E+00	4.5443E+02 3.1332E+00
9	-2.0912E+01 -1.4418E-01	-4.0664E+02 -2.8037E+00	-9.9173E+00 6.8378E-02	3.8573E+02 2.6595E+00	4.6822E+02 3.2283E+00
10	-5.2623E+01 -3.6282E-01	-4.2684E+02 -2.9429E+00	-1.1668E+02 -8.0447E-01	3.7421E+02 2.5801E+00	5.2219E+02 3.6003E+00
11	-4.6965E+01 -3.2381E-01	-4.3616E+02 -3.0072E+00	-2.8320E+02 -1.9526E+00	3.8919E+02 2.6834E+00	1.9263E+01 1.3281E-01
12	1.4280E+00 9.8457E-03	-4.9718E+02 -3.4279E+00	-4.9572E+02 -3.4179E+00	4.9861E+02 3.4378E+00	7.6981E+00 5.3076E-02
13	-6.2872E+01 -4.3349E-01	-1.0239E+03 -7.0592E+00	-1.9446E+02 -1.3407E+00	9.6098E+02 6.6258E+00	8.5804E+02 5.9160E+00
14	-3.7412E+01 -2.5795E-01	-8.9557E+02 -6.1747E+00	-3.3335E+01 -2.2984E-01	8.5816E+02 5.9168E+00	6.0010E+02 4.1376E+00
15	2.1957E+02 1.5139E+00	-2.7300E+02 -1.8823E+00	-2.5945E+01 -1.7889E-01	4.9258E+02 3.3962E+00	8.3463E+02 5.7545E+00
16	6.4300E+01 4.4333E-01	-1.2668E+02 -8.7340E-01	-3.6108E+01 -2.4895E-01	1.9097E+02 1.3167E+00	3.1495E+02 2.1715E+00

17	2.8317E+01	-8.6767E+01	1.9932E+00	1.1508E+02	2.0063E+02
	1.9524E-01	-5.9824E-01	1.3742E-02	7.9347E-01	1.3833E+00
18	7.6299E+00	-4.6973E+01	1.0789E+02	5.4603E+01	6.5954E+01
	5.2606E-02	-3.2387E-01	7.4391E-01	3.7647E-01	4.5473E-01
19	1.4607E+01	-8.9408E+01	8.3077E+01	1.0401E+02	1.6972E+02
	1.0071E-01	-6.1645E-01	5.7280E-01	7.1716E-01	1.1702E+00
20	2.8480E+00	-1.0012E+02	-6.3027E+01	1.0297E+02	1.9318E+02
	1.9636E-02	-6.9030E-01	-4.3456E-01	7.0994E-01	1.3319E+00
21	5.8399E+00	-7.5225E+01	-6.8959E+01	8.1065E+01	1.2310E+02
	4.0265E-02	-5.1866E-01	-4.7546E-01	5.5892E-01	8.4872E-01
22	-2.2860E+01	-5.5165E+01	-4.5433E+01	3.2305E+01	5.0119E+01
	-1.5761E-01	-3.8035E-01	-3.1325E-01	2.2273E-01	3.4556E-01

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Table 3-105. Case 3, Stress (psi/MPa)

Location	Sigma_1	Sigma_2	Sigma_3	Pm	Pb
-----	-----	-----	-----	--	--
1	1.1332E+02 7.8130E-01	-2.0167E+02 -1.3904E+00	-1.7830E+01 -1.2294E-01	3.1499E+02 2.1717E+00	4.5244E+02 3.1195E+00
2	1.4456E+02 9.9670E-01	-3.1945E+02 -2.2025E+00	-9.9536E+01 -6.8628E-01	4.6401E+02 3.1992E+00	9.5345E+02 6.5738E+00
3	1.0883E+02 7.5036E-01	-1.9587E+02 -1.3504E+00	-1.1934E+01 -8.2283E-02	3.0470E+02 2.1008E+00	4.4224E+02 3.0492E+00
4	6.9648E+02 4.8021E+00	-2.1058E+03 -1.4519E+01	-4.1724E+02 -2.8768E+00	2.8022E+03 1.9321E+01	5.4835E+03 3.7807E+01
5	7.3302E+02 5.0540E+00	-2.4089E+03 -1.6609E+01	-7.8913E+02 -5.4409E+00	3.1419E+03 2.1663E+01	4.9727E+03 3.4285E+01
6	1.1040E+02 7.6121E-01	-1.2142E+03 -8.3716E+00	-1.0213E+03 -7.0419E+00	1.3246E+03 9.1328E+00	1.7067E+03 1.1767E+01
7	-2.1151E+01 -1.4583E-01	-4.2187E+02 -2.9087E+00	3.0050E+01 2.0719E-01	-4.0072E+02 2.7629E+00	5.1802E+02 3.5716E+00
8	-2.2697E+01 -1.5649E-01	-4.1929E+02 -2.8909E+00	-8.1965E-01 -5.6513E-03	3.9660E+02 2.7344E+00	4.9239E+02 3.3949E+00
9	-2.0069E+01 -1.3837E-01	-4.2351E+02 -2.9200E+00	2.3821E+01 1.6424E-01	4.0344E+02 2.7816E+00	5.2751E+02 3.6370E+00
10	1.0335E+02 7.1255E-01	-4.4853E+02 -3.0925E+00	-3.3947E+02 -2.3405E+00	5.5188E+02 3.8050E+00	1.1988E+00 8.2654E-03
11	1.0720E+02 7.3910E-01	-2.2665E+02 -1.5627E+00	-2.4470E+02 -1.6871E+00	3.3385E+02 2.3018E+00	1.8718E+02 1.2906E+00
12	1.2235E+01 8.4356E-02	-1.3838E+02 -9.5409E-01	-1.2779E+02 -8.8110E-01	1.5061E+02 1.0384E+00	2.1751E+02 1.4996E+00
13	3.8109E+00 2.6275E-02	-8.7929E+02 -6.0625E+00	-2.9444E+02 -2.0301E+00	8.8310E+02 6.0887E+00	9.4655E+02 6.5262E+00
14	1.4413E+01 9.9376E-02	-7.5512E+02 -5.2064E+00	-1.5131E+02 -1.0432E+00	7.6954E+02 5.3058E+00	5.5921E+02 3.8556E+00
15	2.3622E+02 1.6287E+00	-2.9365E+02 -2.0246E+00	-2.7933E+01 -1.9259E-01	5.2987E+02 3.6533E+00	8.9787E+02 6.1906E+00
16	6.9144E+01 4.7673E-01	-1.3625E+02 -9.3939E-01	-3.8755E+01 -2.6721E-01	2.0539E+02 1.4161E+00	3.3867E+02 2.3350E+00

17	3.0430E+01	-9.3259E+01	2.3069E+00	1.2369E+02	2.1560E+02
	2.0981E-01	-6.4300E-01	1.5906E-02	8.5281E-01	1.4865E+00
18	8.1408E+00	-5.0305E+01	1.1570E+02	5.8446E+01	7.0571E+01
	5.6129E-02	-3.4684E-01	7.9773E-01	4.0297E-01	4.8657E-01
19	1.5492E+01	-9.5652E+01	8.9411E+01	1.1114E+02	1.8136E+02
	1.0681E-01	-6.5950E-01	6.1647E-01	7.6631E-01	1.2505E+00
20	2.8083E+00	-1.0699E+02	-6.7307E+01	1.0980E+02	2.0545E+02
	1.9362E-02	-7.3769E-01	-4.6406E-01	7.5706E-01	1.4165E+00
21	1.1268E+01	-6.6794E+01	-5.5199E+01	7.8062E+01	1.3120E+02
	7.7691E-02	-4.6053E-01	-3.8058E-01	5.3822E-01	9.0459E-01
22	-2.4790E+01	-5.9183E+01	-4.8922E+01	3.4393E+01	5.6968E+01
	-1.7092E-01	-4.0805E-01	-3.3730E-01	2.3713E-01	3.9278E-01

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VECTOR 1
MIN 1.7357E+02
MAX 1.9820E+02

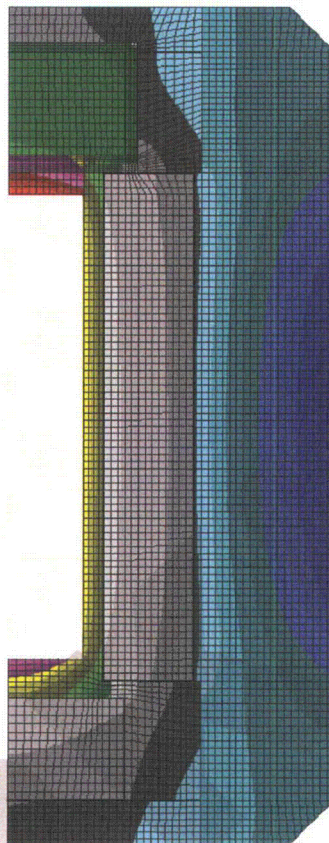


Figure 3-146. Case 1 – Temperature

VECTOR 1
MIN: 1.7109E+02
MAX: 1.8915E+02

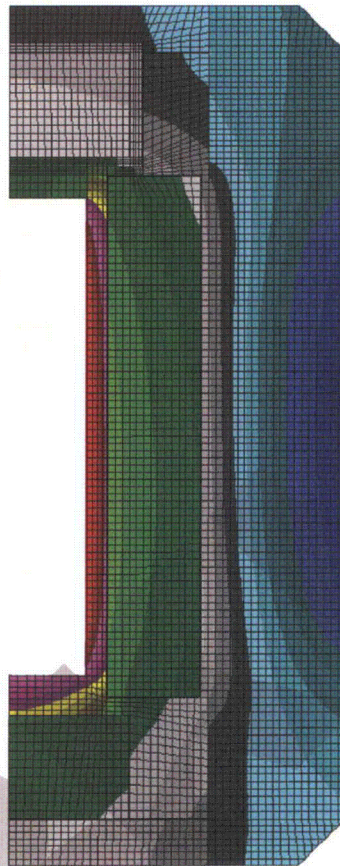


Figure 3-147. Case 2 – Temperature

VECTOR 1
MIN 1.7391E+02
MAX 1.9310E+02

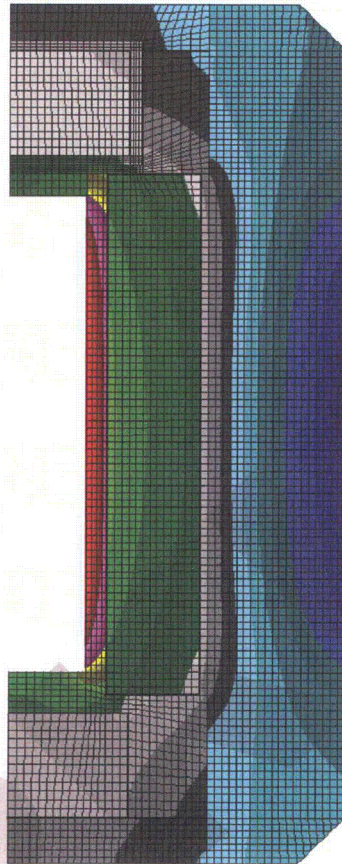
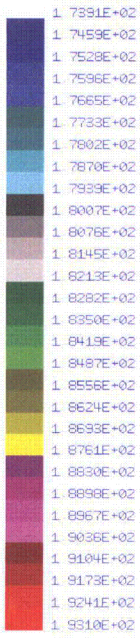


Figure 3-148. Case 3 – Temperature

ELEM TYPE 8
 COMPONENT 6
 VECTOR 1

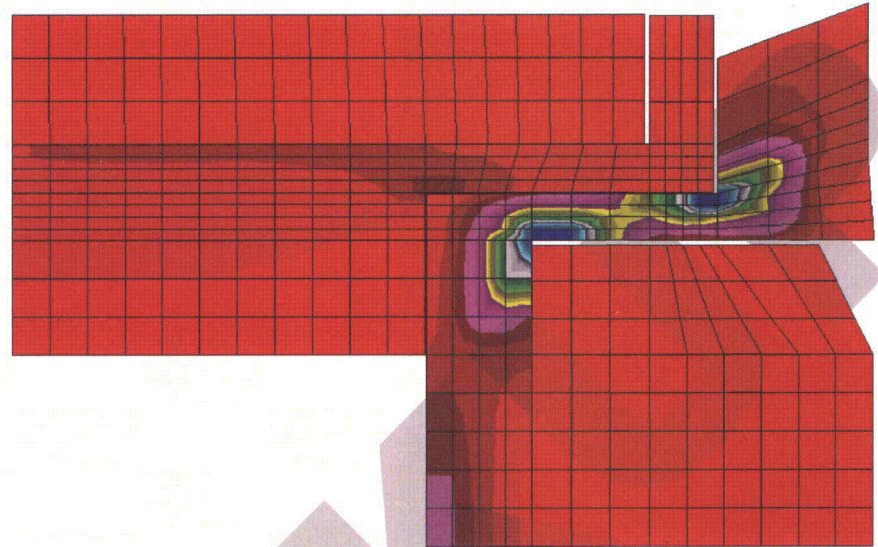
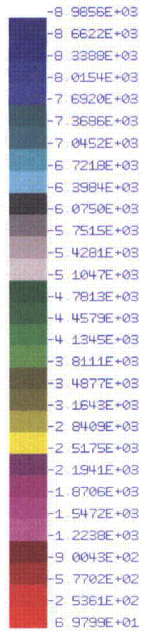


Figure 3-149. Case 1 – Maximum Principal Stress at Lid Corner

ELEM TYPE 8
COMPONENT 6
VECTOR 1

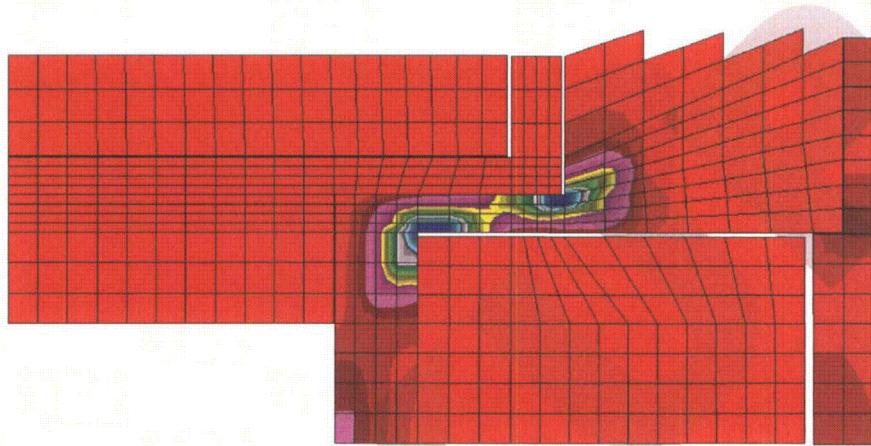
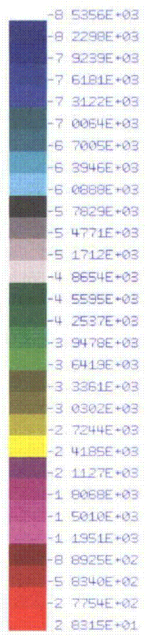


Figure 3-150. Case 2 – Maximum Principal Stress at Lid Corner

ELEM TYPE: 8
COMPONENT: 6
VECTOR: 1

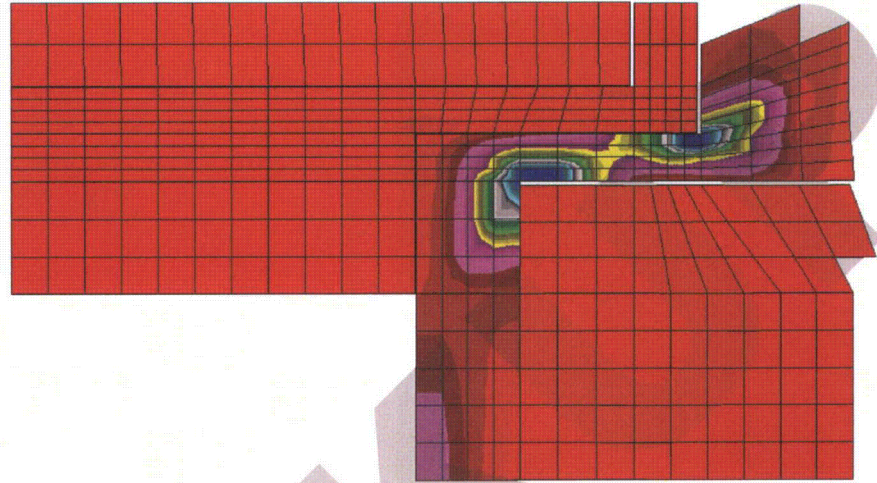
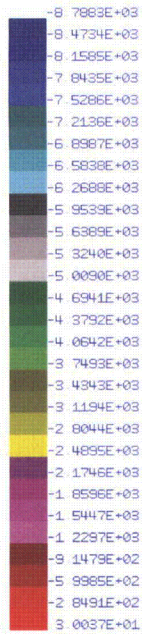


Figure 3-151. Case 3 – Maximum Principal Stress at Lid Corner

3.5.10 Justification for Use of LAST-A-FOAM 3700 Thermal Properties

The values used in the SAR analyses were taken from General Plastics Manufacturing Company data sheet for LAST-A-FOAM FR-3700. The latest thermal conduction data published by General Plastics differs from the data available when the SAR was prepared. Both are presented in Table 3-106.

Table 3-106. LAST-A-FOAM FR-3700 – Differences between SAR and Product's Current Values

Product	Old K Value (Btu/hr-ft ² /°F)	New K Value (Btu/hr-ft ² /°F)
FR-3710	0.279	0.213
FR-3718	0.356	0.324
FR-3720	0.376	0.349

The largest change is in FR-3710, where the new value is 76% of the old value. FR-3710 is the product used in the Model AOS-050 transport package. The effect of the change in conductivity is evaluated by recalculating temperatures and thermal stress in the Model AOS-050, using thermal conductivity values reduced by a 0.75 factor, and comparing the resulting margins of safety and maximum component temperatures to the SAR values.

Table 3-107 and Table 3-108 list the Model AOS-050 margins of safety for Normal conditions of transport. Table 3-107 presents values corresponding to the reduced K, while Table 3-108 contains the values provided in the SAR. A comparison of these two tables shows that the reduced K values produce no change in margins of safety for normal conditions.

Table 3-109 and Table 3-110 list the Model AOS-050 margins of safety for Hypothetical Accident conditions of transport. Table 3-109 presents values corresponding to the reduced K, while Table 3-110 contains the values provided in the SAR. A comparison of these two tables shows that the reduced K values produce small changes in margins of safety for accident conditions where margins of safety are high, but no change where accident margins of safety are less than 1.0.

Finally, Table 3-111 and Table 3-112 list the Model AOS-050 maximum component temperatures for the fire accident condition. Table 3-111 presents values corresponding to the reduced K, while Table 3-112 contains the values provided in the SAR. A comparison of these two tables shows that the reduced K values produce small changes in maximum component temperature. The maximum temperature change is a 16°F reduction in foam temperature, from 563°F to 547°F. Other maximum component temperatures increase by less than 3°F.

Table 3-107. Reduced K Min MS for Normal Conditions of Transport

Ld_Cmb	Load_Cases	Min_MS	Loc	Str_Cmb
101	102 201 211 0 0	5.819E+00	4	Pm+Pb
102	104 201 211 0 0	2.164E+00	5	Pm+Pb+Q
103	103 201 211 0 0	2.686E+00	5	Pm+Pb+Q
104	101 201 202 211 0	5.535E+00	4	Pm+Pb
105	105 201 202 211 0	5.535E+00	4	Pm+Pb
106	101 201 203 211 0	4.918E+00	4	Pm+Pb
107	105 201 203 211 0	4.918E+00	4	Pm+Pb
215	215 101 201 211 0	5.145E+00	4	Pm+Pb
216	216 101 201 211 0	1.285E+00	15	Pm
217	216 104 201 211 0	1.285E+00	15	Pm
221	221 101 201 211 0	5.812E+00	4	Pm+Pb
222	222 101 201 211 0	5.607E+00	4	Pm+Pb
223	223 101 201 211 0	5.408E+00	4	Pm+Pb
231	231 102 201 211 0	3.034E+00	4	Pm+Pb
232	232 102 201 211 0	1.032E+00	4	Pm+Pb

Table 3-108. SAR Min MS for Normal Conditions of Transport

Ld_Cmb	Load_Cases	Min_MS	Loc	Str_Cmb
101	102 201 211 0 0	5.819E+00	4	Pm+Pb
102	104 201 211 0 0	2.164E+00	5	Pm+Pb+Q
103	103 201 211 0 0	2.686E+00	5	Pm+Pb+Q
104	101 201 202 211 0	5.535E+00	4	Pm+Pb
105	105 201 202 211 0	5.535E+00	4	Pm+Pb
106	101 201 203 211 0	4.918E+00	4	Pm+Pb
107	105 201 203 211 0	4.918E+00	4	Pm+Pb
215	215 101 201 211 0	5.145E+00	4	Pm+Pb
216	216 101 201 211 0	1.285E+00	15	Pm
217	216 104 201 211 0	1.285E+00	15	Pm
221	221 101 201 211 0	5.812E+00	4	Pm+Pb
222	222 101 201 211 0	5.607E+00	4	Pm+Pb
223	223 101 201 211 0	5.408E+00	4	Pm+Pb
231	231 102 201 211 0	3.034E+00	4	Pm+Pb
232	232 102 201 211 0	1.032E+00	4	Pm+Pb

Table 3-109. Reduced K Min MS for Hypothetical Accident Conditions of Transport

Ld_Cmb	Load_Cases						Min_MS	Loc	Str_Cmb
-----	-----						-----	---	-----
301	301	102	201	211	0	0	3.491E+00	4	Pm+Pb
302	302	102	201	211	0	0	8.885E+00	4	Pm+Pb
303	303	102	201	211	0	0	3.318E+00	1	Pm
304	304	105	202	211	0	0	2.818E+00	4	Pm+Pb
305	305	105	202	211	0	0	7.495E+00	1	Pm+Pb
306	306	105	202	211	0	0	2.537E+00	1	Pm
310	204	101	211	0	0	0	3.028E+00	4	Pm+Pb
311	311	101	201	211	0	0	5.885E-01	15	Pm
312	311	104	201	211	0	0	5.885E-01	15	Pm
350	111	201	211	0	0	0	1.305E+01	4	Pm+Pb
351	112	201	211	0	0	0	1.305E+01	4	Pm+Pb
352	113	201	211	0	0	0	1.305E+01	4	Pm+Pb
353	114	201	211	0	0	0	1.305E+01	4	Pm+Pb
354	115	201	211	0	0	0	1.305E+01	4	Pm+Pb
355	116	201	211	0	0	0	1.305E+01	4	Pm+Pb

Table 3-110. SAR Min MS for Hypothetical Accident Conditions of Transport

Ld_Cmb	Load_Cases						Min_MS	Loc	Str_Cmb
-----	-----						-----	---	-----
301	301	102	201	211	0	0	3.741E+00	4	Pm+Pb
302	302	102	201	211	0	0	9.436E+00	4	Pm+Pb
303	303	102	201	211	0	0	3.466E+00	1	Pm
304	304	105	202	211	0	0	2.818E+00	4	Pm+Pb
305	305	105	202	211	0	0	7.495E+00	1	Pm+Pb
306	306	105	202	211	0	0	2.537E+00	1	Pm
310	204	101	211	0	0	0	3.028E+00	4	Pm+Pb
311	311	101	201	211	0	0	5.885E-01	15	Pm
312	311	104	201	211	0	0	5.885E-01	15	Pm
350	111	201	211	0	0	0	1.491E+01	4	Pm+Pb
351	112	201	211	0	0	0	1.491E+01	4	Pm+Pb
352	113	201	211	0	0	0	1.491E+01	4	Pm+Pb
353	114	201	211	0	0	0	1.491E+01	4	Pm+Pb
354	115	201	211	0	0	0	1.491E+01	4	Pm+Pb
355	116	201	211	0	0	0	1.491E+01	4	Pm+Pb

Table 3-111. Reduced K Fire Condition Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp
Outside Shell	101	2894	1107	4.2400E+02
Bottom Plate	3001	3232	3120	3.9480E+02
Lid	3233	3424	3233	3.9330E+02
Shell Cavity	4001	4998	4527	4.2570E+02
Plug	5001	5404	5001	4.0310E+02
Tungsten	6001	7656	6436	4.2210E+02
LAST-A-FOAM	8001	10791	10035	5.4670E+02

Table 3-112. SAR Fire Condition Maximum Component Temperatures

Component	Node_1	Node_2	Node	Max_Temp
Outside Shell	101	2894	1117	4.2140E+02
Bottom Plate	3001	3232	3120	3.9210E+02
Lid	3233	3424	3233	3.9160E+02
Shell Cavity	4001	4998	4522	4.2290E+02
Plug	5001	5404	5001	4.0080E+02
Tungsten	6001	7656	6440	4.1940E+02
LAST-A-FOAM	8001	10791	10034	5.6270E+02

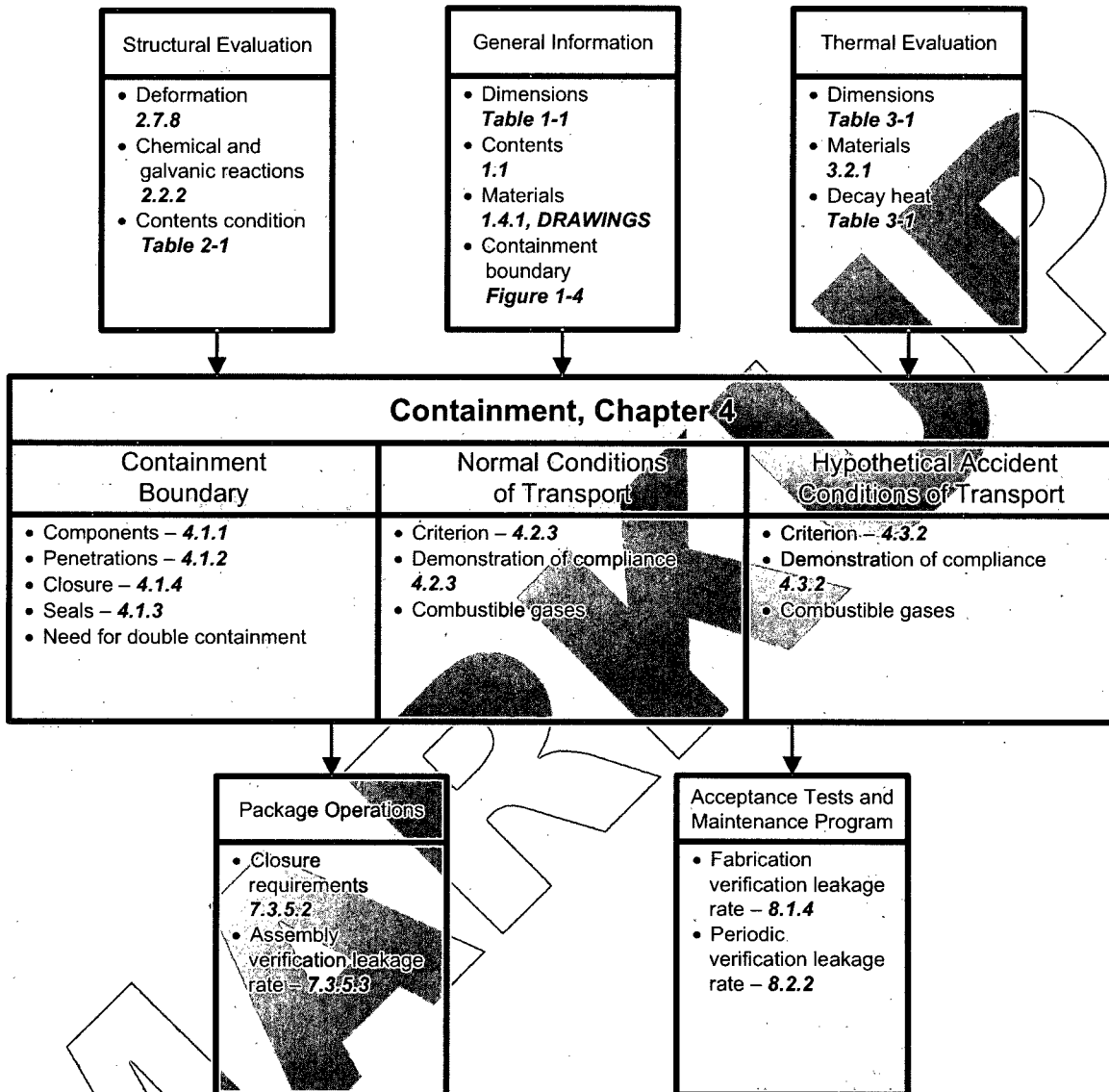
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4 CONTAINMENT



Note: Unless indicated otherwise, all information related to the Model AOS-100A is also applicable to the Model AOS-100A-S.

10 CFR 71 [4.1] requires that packaging in which large quantities of radioactive materials are shipped must maintain containment of radioactive contents, under Normal and Hypothetical Accident conditions of transport. This chapter discusses the AOS Radioactive Material Transport Packaging System's containment boundary and capabilities.

The Transport Packaging System is designed to meet the "leaktight" criteria provided in Reference [4.4], for the transportation of activated material in Normal and Special forms.

Table 4-1 through Table 4-3 provide general information of the AOS Transport Packaging System related to their dimensions; the maximum content allowed; and their components' materials of construction, respectively.

Table 4-1. AOS Transport Packaging System Dimensions and Cg Location – All Models

Model	Category	Dimensions (cm / in.)									
		Packaging		Cask		Cavity		Packaging Weight ^a (kg/lbs.)	Cg Location ^b		
		OD	Height	OD	Height	OD	Height		X	Y	Z
AOS-025A	III	28.96	39.62	17.78	22.86	4.14	12.70	71.4	19.05	19.05	26.34
		11.40	15.60	7.00	9.00	1.63	5.00	157	7.50	7.51	10.37
AOS-050A	III	57.96	79.25	35.56	45.72	8.26	25.40	511	41.91	41.91	46.28
		22.82	31.20	14.00	18.00	3.25	10.00	1,126	16.50	16.50	18.22
AOS-100A	II	115.93	158.50	71.12	91.44	16.51	50.80	3,950	91.44	89.15	80.03
		45.64	62.40	28.00	36.00	6.50	20.00	8,700	36.00	35.10	31.51
AOS-100B	III	115.93	158.50	71.12	91.44	16.51	50.80	3,232	91.44	89.15	80.03
		45.64	62.40	28.00	36.00	6.50	20.00	7,125	36.00	35.10	31.51
AOS-100A-S	II	115.93	158.50	71.12	91.44	16.51	50.80	3,901	91.44	89.15	80.03
		45.64	62.40	28.00	36.00	6.50	20.00	8,600	36.00	35.10	31.51
AOS-165A	I	191.26	264.16	117.35	150.88	27.23	83.82	18,234	152.40	121.41	121.92
		75.30	104.00	46.20	59.40	10.72	33.00	40,200	60.00	47.80	48.00
AOS-165B	I	191.26	264.16	117.35	150.88	27.23	83.82	15,535	152.40	121.41	121.92
		75.30	104.00	46.20	59.40	10.72	33.00	34,250	60.00	47.80	48.00

a. All AOS Transport Packaging System models have dimensions greater than 10 cm (4 in.).

b. Refer to Figure 2-13, "Center of Gravity – Model AOS-100."

Table 4-2. Activity Limits – All Models

Isotope ^a	Ci/Watt ^b	Model											
		AOS-025		AOS-050		AOS-100				AOS-165			
		A (10W)		A (100W)		A, A-S (400W)		B (400W)		A (7 kW)		B (2.5 kW)	
		TBq	Ci	TBq	Ci	TBq	Ci	TBq	Ci	TBq	Ci	TBq	Ci
Co-60	6.49E+01	8.73E-03	2.36E-01	1.05E-01	2.84E+00	7.47E+02	2.02E+04	5.99E+00	1.62E+02	1.68E+04	4.54E+05	6.01E+03	1.62E+05
Cs-137	1.99E+02	1.28E+00	3.45E+01	1.28E+01	3.46E+02	2.94E+03	7.95E+04	1.84E+01	4.97E+02	5.16E+04	1.39E+06	1.84E+04	4.98E+05
Hf-181	2.28E+02			6.25E+01	1.69E+03	3.38E+03	9.13E+04	9.25E+01	2.50E+03	5.91E+04	1.60E+06	2.11E+04	5.70E+05
Ir-192	1.63E+02	5.48E+00	1.48E+02	3.63E+01	9.81E+02	2.41E+03	6.53E+04	5.77E+01	1.56E+03	4.23E+04	1.14E+06	1.51E+04	4.08E+05
Zr/Nb-95	6.02E+01	-		2.09E+00	5.66E+01	8.92E+02	2.41E+04	3.74E+00	1.01E+02	1.56E+04	4.21E+05	5.57E+03	1.51E+05
C-14	3.41E+03	1.26E+03	3.41E+04	1.26E+04	3.41E+05	-	-	-	-	-	-	-	-
Fe-59	1.29E+02	2.16E-02	5.85E-01	2.02E-01	5.46E+00	-	-	-	-	-	-	-	-
Ho-166	2.33E+02	1.01E+00	2.74E+01	3.89E-01	1.05E+01	-	-	-	-	-	-	-	-
Na-24	3.61E+01	2.58E-03	6.97E-02	1.55E-02	4.19E-01	-	-	-	-	-	-	-	-
P-32	2.43E+02	8.98E+01	2.43E+03	8.98E+02	2.43E+04	-	-	-	-	-	-	-	-
P-33	2.20E+03	8.15E+02	2.20E+04	8.15E+03	2.20E+05	-	-	-	-	-	-	-	-
Sb-124	7.52E+01	1.16E-02	3.13E-01	1.62E-02	4.38E-01	-	-	-	-	-	-	-	-
Sc-46	7.94E+01	2.05E-02	5.55E-01	1.05E-01	2.84E+00	-	-	-	-	-	-	-	-
Se-75	4.15E+02	1.54E+02	4.15E+03	1.05E+02	2.84E+03	-	-	-	-	-	-	-	-
Sm-153	5.15E+02	1.91E+02	5.15E+03	8.73E+02	2.36E+04	-	-	-	-	-	-	-	-
Sr/Y-90	1.49E+02	5.52E+01	1.49E+03	5.52E+02	1.49E+04	-	-	-	-	-	-	-	-
Sr-89	2.89E+02	1.07E+02	2.89E+03	1.07E+03	2.89E+04	-	-	-	-	-	-	-	-
Yb-169	3.98E+02	1.47E+02	3.98E+03	2.10E+02	5.67E+03	-	-	-	-	-	-	-	-
Yb-175	1.00E+03	3.70E+02	1.00E+04	2.67E+03	7.21E+04	-	-	-	-	-	-	-	-
Shipping Configuration		Use of Liner 183C8485 is required		No additional shielding is required		Use of Axial Shielding Plates 183C8491 may be needed for large-quantity shipments of Co-60		Use of Axial Shielding Plates 183C8491 may be needed for large-quantity shipments of Co-60		No additional shielding is required.		Use of Liner 183C8499 is required	

a. Encapsulated solid material or solid metal that meets Normal or Special form criteria.

b. For detailed calculations of these values, refer to Chapter 5, Appendix 5.5.1, "AOS Cask Isotopic Heat Load for Numerous Isotopes Report."

Table 4-3. Material Selection of Major Transport Packaging System Components (Typical)

Component	Material Selection	1 st Alternate Material	2 nd Alternate Material	Reference Drawing ^a	Item No.
Cask					
Outer Shell	ASME SA-451/ASTM A451 GRADE CPF 8	ASME SA-351/ASTM A351, GRADE CF 8	ASME SA-182/ASTM A182 GRADE F304 or F316	105E9712G001	1
Cavity Shell	ASME SA-182/ASTM A182 GRADE F304 or F316	ASME SA-351/ASTM A351, GRADE CF 8	ASME SA-451/ASTM A451, GRADE CPF 8		3
Lid	ASME SA-240/ASTM A240 TYPE 304 or 316	ASME SA-182/ASTM A182 GRADE F304 or F316	-		2
Shielding Material	TUNGSTEN MIL/AMS-T-210.14 CLASS 3	CARBON STEEL FORGING PER ASME SA-105	-		4, 8, 12
Lid Plug	ASME SA-240/ASTM A240 TYPE 304 or 316	ASME SA-182/ASTM A182 GRADE F304 or F316	-		6
Cover Plate	ASME SA-240/ASTM A240 TYPE 304 or 316	ASME SA-182/ASTM A182 GRADE F304 or F316	-		7
Trunnion	ASME SA-479/ASTM A479 TYPE 316	-	-		5
Bottom Plate	ASME SA-240/ASTM A240 TYPE 304 or 316	ASME SA-182/ASTM A182 GRADE F304 or F316	-		13
Lid Attachment Bolts	ASME SB-637 UNS N07750 TYPE 3	-	-		15
Port Plug	ASME SA-182/ASTM A182 GRADE F304 or F316	ASME SA-479/ASTM A479 TYPE 316	-		16
Impact Limiter					
Shell and Ribs	ASME SA-240/ASTM A240 TYPE 304 or 316	-	-	105E9713	1 - 11
Foam	POLYURETHANE FOAM GP 3700 SERIES	-	-		12

a. The Model AOS-100A drawings are used for this tabulation.

4.1 CONTAINMENT SYSTEM DESCRIPTION

4.1.1 Containment Boundary

The transport package containment boundary (located within the cask component of the transport package) is composed of the following:

- Cask inside cylinder or cavity shell
- Two port plugs
- Seal components of the AOS Transport Packaging System cask

The boundary loops along the cask cavity shell walls and port plug walls, across the port opening, between its pipe plug and plug block, through the lid material and across the lid seal joint between each of the seal cross-sections. The dashed lines in Figure 4-1 illustrate the containment boundary (located within the cask component of the transport package).

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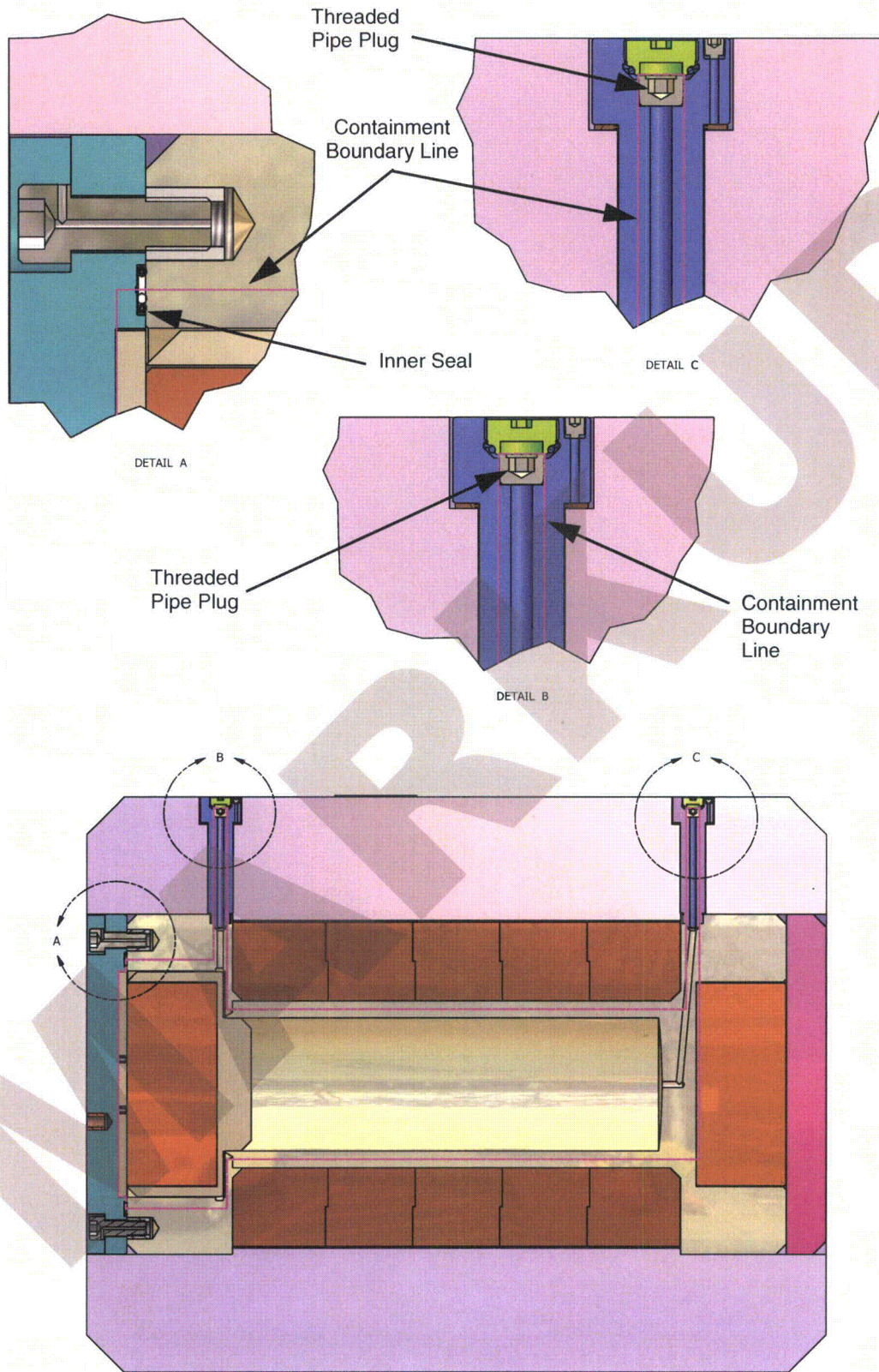


Figure 4-1. Containment Boundary

To protect the containment boundary and the lid during Hypothetical Accident conditions of transport, the lid is resealed within the wall of the outside cylinder. The cask is constructed of concentric stainless steel, and tungsten alloy or carbon steel cylinders. The tungsten alloy or carbon steel cylinders, which are embedded within the outside and inside stainless steel cylinders, are used for shielding. Stainless steel forgings, with an entrenched tungsten alloy or carbon steel cylinder, located at each end of the containment boundary, provide axial shielding. The cask lid/seal bolted joint and cavity bottom end close the containment boundary for the Transport Packaging System models. In the case of the Model AOS-100A-S transport package, the lid/seal bolted joints close both ends of the containment boundary.

The analytical results indicate that the containment boundary does not suffer any deformation that could impair its ability to contain its radioactive material payload. This was also proven by the Free-Drop test results. As discussed previously in Chapter 2, Subsection 2.2.2, "Chemical, Galvanic, or Other Reactions," there are no indications that a chemical, galvanic, nor other type of reaction, will occur.

The construction materials used for the containment boundary (located within the cask component of the transport package) meet the ASME Boiler Pressure and Vessel Code [4.2] requirements, except for the lid seal material. A structural weld encloses the containment boundary and shielding material cylinders inside the outside cylinder shell. The Model AOS-165 transport package has two (2) options for this structural weld joint – circumferential (ASME Code type A weld) or corner (ASME Code type C weld). The Model AOS-025, AOS-050, and AOS-100 transport packages use only the corner weld (Type C) joint design.

Figure 4-2 provides a detailed illustration of a corner weld joint on the cask cavity shell. Figure 4-3 provides a detailed illustration of a circumferential weld joint on the cask cavity shell.

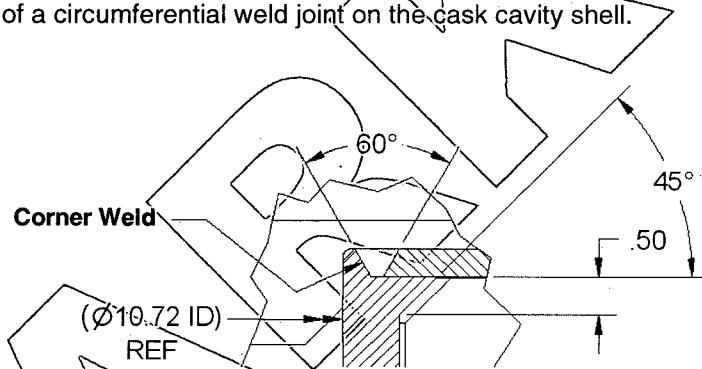


Figure 4-2. Sample Corner Cask Cavity Shell Weld Joint – All Models

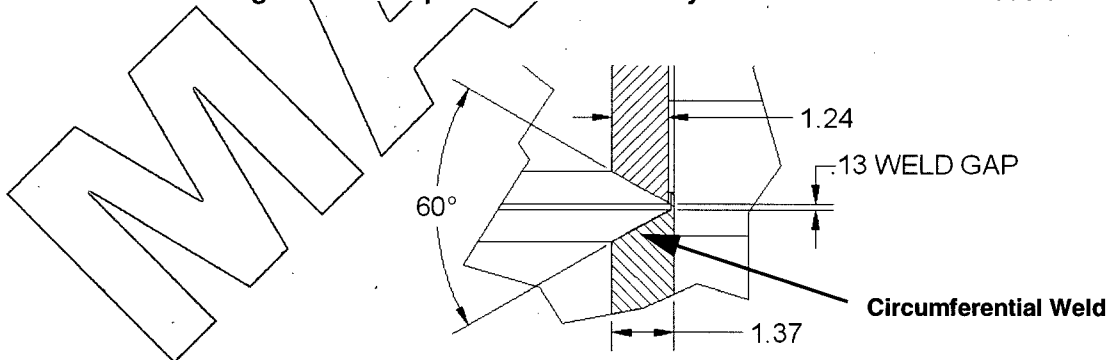


Figure 4-3. Sample Circumferential Cask Cavity Shell Weld Joint Option – Model AOS-165 Only

Notes: The dimensions shown in Figure 4-2 and Figure 4-3 are those of the Model AOS-165A transport package.

All dimensions are in inches.

4.1.2 Containment Penetrations (Ports)

The AOS Transport Packaging System transport packages have three (3) penetrations (also called "ports"):

- One (1) penetration, located on the cask lid, leads to the area between the "C" cross-section seals and is used to test the adequacy of the seal joint.
- Two (2) penetrations, the cask cavity drain and vent ports, consist of three (3) diametrical steps studded with a threaded end at the smaller diameter. Each of these two (2) port plugs connect to the cask cavity shell.

Figure 4-4 presents a detailed illustration of the port plug. The Model AOS-165A transport package's port plug has two design options, as illustrated in Figure 4-4 (a) and (b). The port plug of all other models is of the type (a) design. A socket head pipe plug (which is located within the containment boundary), followed by a cap, close each penetration. An elastomeric (Parker Silicon, 51224-70 compound, or equivalent) O-Ring, attached to the cap, provides a redundant seal to these penetrations. In addition, option (a) has a conduit, which is used to verify the integrity of the port plug, which is covered by a threaded pipe plug.

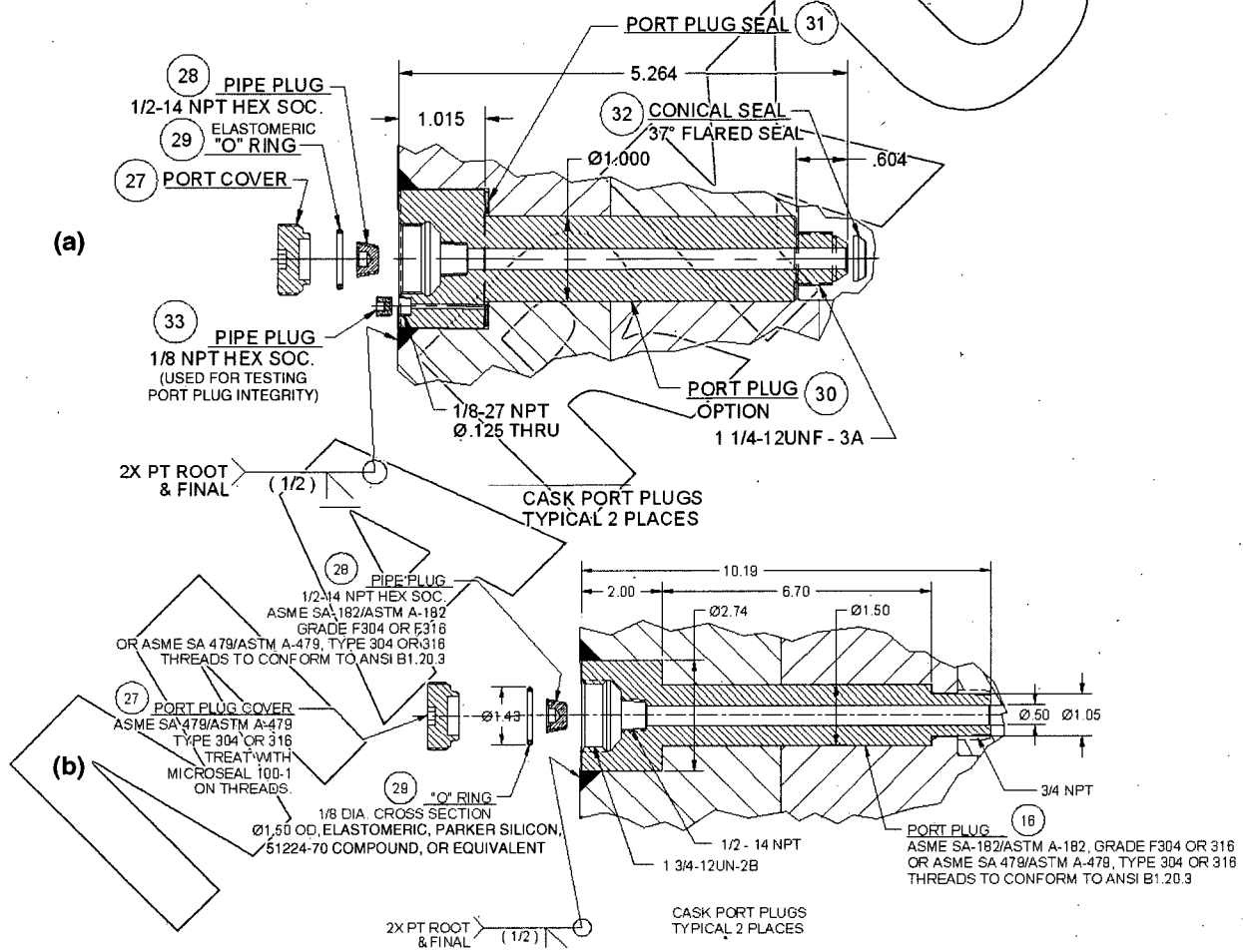


Figure 4-4. Port Plug Configuration Options – Model AOS-165A

Notes: The dimensions provided in Figure 4-4 are those of the Model AOS-165A transport package.

All dimensions are in inches.

The port plug seal material has been subjected to an environmental test, to demonstrate the seal's performance within the temperature environments listed in Table 4-5.

Table 4-4. Elastomeric Port Seal Testing Temperature Environments – All Models

Minimum		Typical		Maximum	
°C	°F	°C	°F	°C	°F
-54	-65	21	70	232	450

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4.1.3 Lid Seal

The AOS Transport Packaging System's metallic (stainless steel and silver) cask lid joint design includes a seal between the lid and cask cavity body. The sealing principle of the Helicoflex[®] family of metallic seals is based upon plastic deformation of a jacket of greater ductility than the flange materials. This occurs between the sealing face of a flange and an elastic core composed of a close-wound helical spring. The spring has a specific compression resistance, to prevent the seal from being crushed. During compression, the resulting specific pressure forces the jacket to yield and fill the flange surface imperfections, while ensuring positive contact with the flange sealing faces. Each coil of the helical spring functions independently, and allows the seal to conform to irregularities on the flange surface.

Figure 4-5 illustrates a cross-section of the metallic, double "C" cross-section arrangement lid seal.

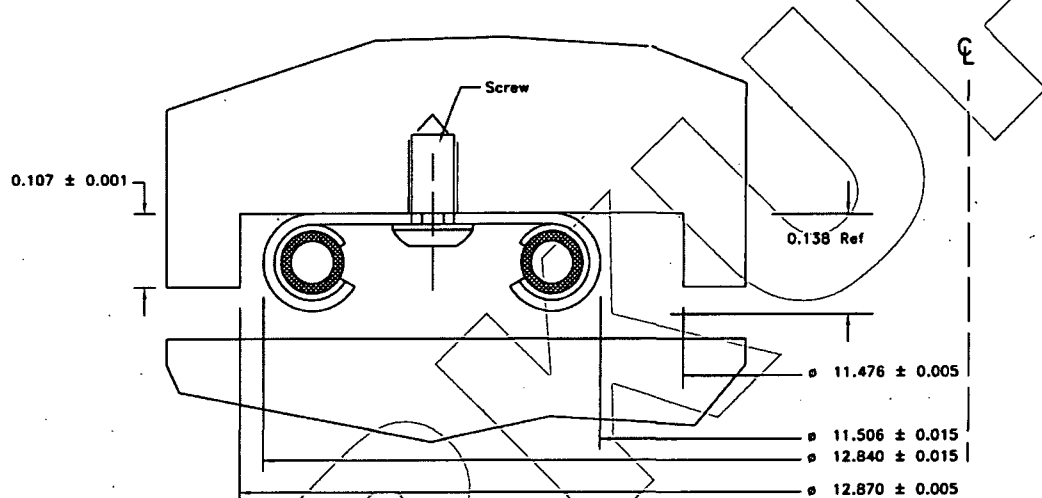


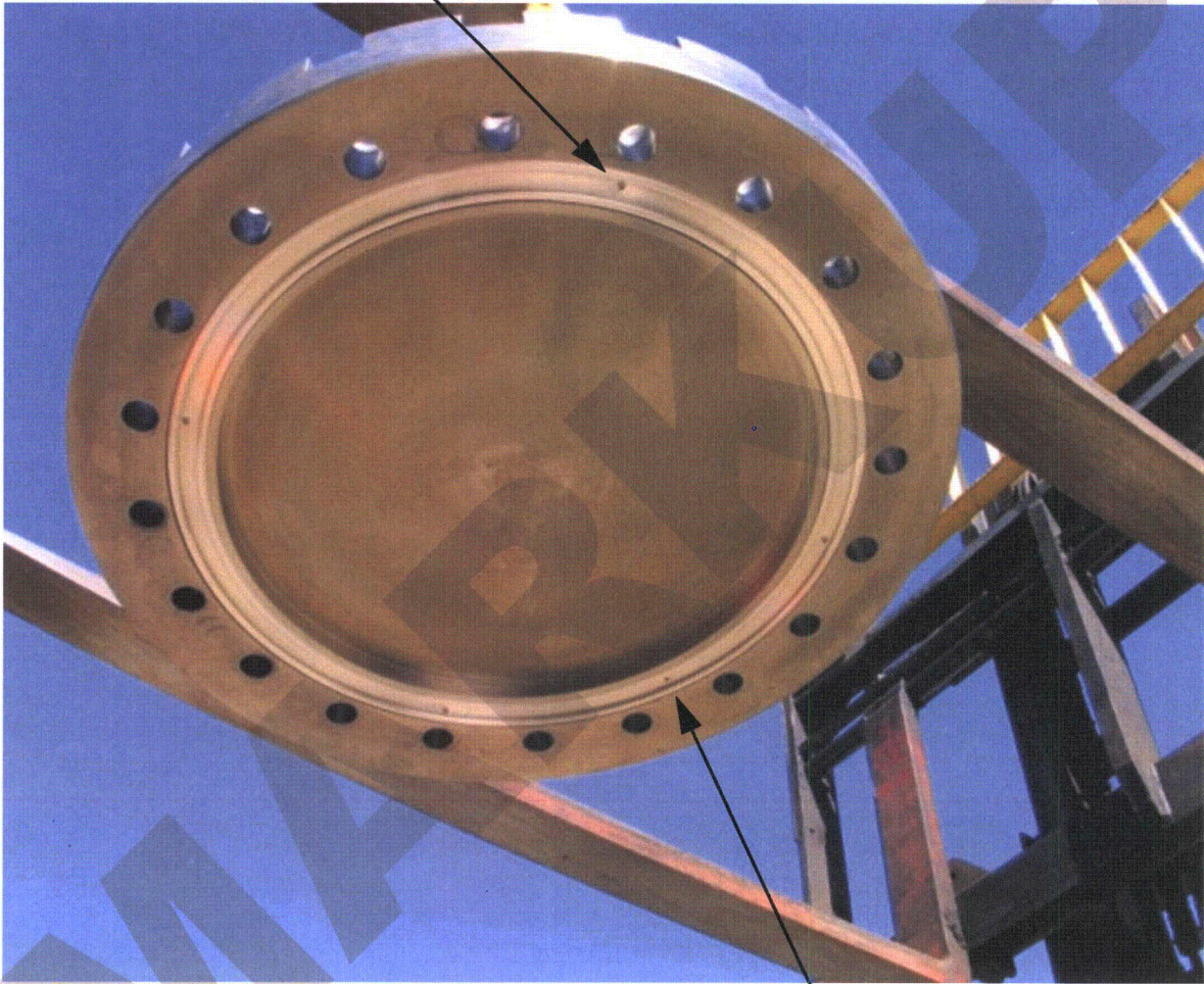
Figure 4-5. Lid Seal – Metallic (Stainless Steel and Silver), Double "C" Cross-Section Arrangement

- Notes:** The spring's compression resistance maintains the contact between the seal surface and surfaces being sealed.
- The dimensions provided in Figure 4-5 are those of the Model AOS-100A transport package.
- All dimensions are in inches.

Figure 4-6 illustrates how the seal is attached to the lid by four four (4) small screws. Located between the seal's two "C" cross-sections, the screws are sized and installed in such a way as to prevent the screws from interfering with the deformation of the "C" cross-sections when the lid bolts are being tightened.

Note: A callout for the hole used for testing is included in Figure 4-6, to differentiate it from the screws in the photograph.

Lid Seal Attachment Screws
(4 pl, evenly spaced around seal)



Hole Used for Testing

Figure 4-6. Lid Seal – Attachment by way of Four Screws, and Testing Hole

The lid seal material has been subjected to an environmental test, to demonstrate the seal's performance within the temperature environments listed in Table 4-5 and the test report provided in Appendix 4.5.1, "Helium Leak Qualification Test of Garlock Helicoflex H309352 and 309353-5."

Table 4-5. Metallic Lid Seal Testing Temperature Environments – All Models

Minimum		Typical		Maximum	
°C	°F	°C	°F	°C	°F
-40	-40	21	70	427	800

4.1.4 Closure

The lid seal assembly is attached to the cask body by a set of socket head bolts, ASME SB-637 UNS N07750 Type 3. This bolted joint is recessed within the cask body, to protect the joint from impact during loading. This design attribute was demonstrated during the Hypothetical Accident conditions of transport drop, by the use of pressure-sensitive paper, presented in Chapter 8, Appendix 8.3.2, "Impact (Free-Drop) Test Report." The closure bolt stress analysis followed the methodology and acceptance criteria given in NUREG/CR-6007, Reference [4.3].

Table 4-6 presents the pertinent information of each set of bolts, for each AOS Transport Packaging System model. Table 4-7 presents Reference [4.3] evaluation.

Table 4-6. Cask Bolt Input Summary – All Models

Item	Ambient Temperature, 100°F				Ambient Temperature, -40°F			
	AOS-025	AOS-050	AOS-100	AOS-165	AOS-025	AOS-050	AOS-100	AOS-165
Geometry Definitions								
Seal Type	Metallic	Metallic	Metallic	Metallic	Metallic	Metallic	Metallic	Metallic
Number of Bolts	8	10	14	20	8	10	14	20
Lid Diameter at Bolt Line (in.)	3.707	7.414	14.064	22.875	3.707	7.414	14.064	22.875
Arc Length Per Bolt (in.)	1.36	2.18	3.11	3.59	1.36	2.18	3.11	3.59
Lid Diameter at Gasket (in.)	3.052	6.131	12.309	20.08	3.052	6.131	12.309	20.08
Bolt Diameter (in.)	0.375	0.5	0.875	1.25	0.375	0.5	0.875	1.25
Lid Diameter – inside (in.)	2.7	5.5	10.99	18.25	2.7	5.5	10.99	18.25
Lid Diameter – outside (in.)	4.45	8.90	16.59	27.38	4.45	8.9	16.59	27.38
Lid Thickness (in.)	0.37	0.75	1.51	2.49	0.37	0.75	1.51	2.49
Lid Flange Thickness (in.)	0.48	0.97	1.94	3.2	0.48	0.97	1.94	3.2
Cask Wall Thickness (in.)	0.85	1.705	2.805	4.625	0.85	1.705	2.805	4.625
Bolt Length (in.)	0.15	0.41	1.06	1.95	0.15	0.41	1.06	1.95
Bolt Momentum of Inertia (in ⁴)	0.001	0.003	0.03	0.12	0.001	0.003	0.03	0.12

Table 4-6. Cask Bolt Input Summary – All Models (Continued)

Item	Ambient Temperature, 100°F				Ambient Temperature, -40°F			
	AOS-025	AOS-050	AOS-100	AOS-165	AOS-025	AOS-050	AOS-100	AOS-165
Material Properties								
Young Modulus – Lid (psi)	27.7E6	27.3E6	27.3E6	25.7E6	28.8E6	28.3E6	28.3E6	26.6E6
Young Modulus – Flange (psi)	27.7E6	27.3E6	27.3E6	25.7E6	28.8E6	28.3E6	28.3E6	26.6E6
Young Modulus – Cask (psi)	27.7E6	27.3E6	27.3E6	25.7E6	28.8E6	28.3E6	28.3E6	26.6E6
Young Modulus – Bolt (psi)	27.1E6	26.9E6	26.9E6	25.3E6	28.1E6	27.9E6	27.9E6	26.1E6
Poisson's Ratio – Lid	0.3	0.3	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	0.3	0.3
Lid – CTE	8.2E-6	8.3E-6	8.3E-6	8.9E-6	7.7E-6	7.8E-6	7.8E-6	8.5E-6
Bolt – CTE	7.2E-6	7.3E-6	7.3E-6	7.7E-6	7.1E-6	7.1E-6	7.1E-6	7.5E-6
Wall – CTE	8.2E-6	8.3E-6	8.3E-6	8.9E-6	7.7E-6	7.8E-6	7.8E-6	8.5E-6
Flange Coefficient Friction ^a	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
S _m (ksi)	96.0	94.7	94.7	90.7	100	100	100	92
S _y (ksi)	144	142	142	136	150	150	150	138
S _u (ksi)	178	176	176	168	185	185	185	171
Code Evaluation Code ^b	2	2	2	2	2	2	2	2

Table 4-6. Cask Bolt Input Summary – All Models (Continued)

Item	Ambient Temperature, 100°F				Ambient Temperature, -40°F			
	AOS-025	AOS-050	AOS-100	AOS-165	AOS-025	AOS-050	AOS-100	AOS-165
Mechanical Loads								
Inside Pressure at Lid (psia)	30	60	280	220	30	60	280	220
Outside Pressure at Lid (psia)	15	15	15	15	15	15	15	15
Inside Pressure at Wall (psia)	30	60	280	220	30	60	280	220
Outside Pressure at Wall (psia)	15	15	15	15	15	15	15	15
Temperature Change across Lid	59.1°C (138.4°F)	84.5°C (184.1°F)	79.17°C (174.5°F)	265.6°C (510°F)	-55.28°C (-67.5°F)	-25.4°C (-13.7°F)	-35.0°C (-31.0°F)	173.5°C (344.3°F)
Temperature Change across Bolt	59.1°C (138.4°F)	84.5°C (184.1°F)	79.17°C (174.5°F)	265.6°C (510°F)	-55.28°C (-67.5°F)	-25.4°C (-13.7°F)	-35.0°C (-31.0°F)	173.5°C (344.3°F)
Temperature Change across Wall	59.1°C (138.4°F)	84.6°C (184.2°F)	79.2°C (174.6°F)	265.6°C (510°F)	-55.2°C (-67.4°F)	-25.38°C (-13.7°F)	-35.0°C (-31.0°F)	173.5°C (344.3°F)
Temperature at outside of Lid	59.1°C (138.4°F)	84.83°C (184.7°F)	79.94°C (175.9°F)	272.7°C (522.8°F)	-55.28°C (-67.5°F)	-25.1°C (-13.2°F)	-34.17°C (-29.5°F)	181.28°C (358.3°F)
Temperature at inside of Lid	59.17°C (138.5°F)	84.94°C (184.9°F)	80.1°C (176.2°F)	273.8°C (524.8°F)	-55.2°C (-67.4°F)	-25.0°C (-13.0°F)	-33.94°C (-29.1°F)	182.5°C (360.5°F)
Weight of Cask Contents + (plug weight) (lbs.)	10 + 4 = 14	60 + 35 = 95	500 + 278 = 778	2,200 + 1,249 = 3,449	10 + 4 = 14	60 + 35 = 95	500 + 278 = 778	2,200 + 1,249 = 3,449
Weight of Cask Lid (lbs.)	2	12	99	445	2	12	99	445

Table 4-6. Cask Bolt Input Summary – All Models (Continued)

Item	Ambient Temperature, 100°F				Ambient Temperature, -40°F			
	AOS-025	AOS-050	AOS-100	AOS-165	AOS-025	AOS-050	AOS-100	AOS-165
Mechanical Loads (Continued)								
Head-On Drop								
Drop Angle of Impact	90	90	90	90	90	90	90	90
Impact Acceleration ^c	638	269	149	139	893	377	188	165
Side Drop								
Drop Angle of Impact	0	0	0	0	0	0	0	0
Impact Acceleration ^c	638	360	177	149	893	504	223	177
Corner Drop								
Drop Angle of Impact	45	45	45	45	45	45	45	45
Impact Acceleration ^c	461	192	116	85	645	269	146	101
Dynamic Load Factor	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
Puncture Load	0	0	0	0	0	0	0	0
Puncture Angle of Impact	45	45	45	45	45	45	45	45
Axial Vibration Acceleration ^d	0	0	0	0	0	0	0	0
Transverse Vibration Acceleration	0	0	0	0	0	0	0	0
Vibration Transmissibility	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Preload Torque (ft-lb) ^e	30	62.5	500	1,000	30	62.5	500	1,000
Nut Factor for Preload Torque	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Gasket Seating Width	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Gasket Seating Stress	0	3,000	3,000	4,568	0	3,000	3,000	4,568
Gasket Factor ^f	0	3.18	0.54	0.98	0	3.18	0.54	0.98

Table 4-6. Cask Bolt Input Summary – All Models (Continued)

Item	Ambient Temperature, 100°F				Ambient Temperature, -40°F			
	AOS-025	AOS-050	AOS-100	AOS-165	AOS-025	AOS-050	AOS-100	AOS-165
Geometry Loads								
Fatigue Stress for Normal Operation	144	142	142	136	150	150	150	138
Fatigue Stress for Vibration	13	13	13	13	13	13	13	13
Number of Threads per Inch	16	13	9	7	16	13	9	7

a. Used in bolt flange friction force computation.

b. Code evaluation options are: 1 = Normal, 2 = Accident.

c. The -40°F ambient condition impact accelerations are obtained by applying factors to the 100°F ambient impact accelerations:

Model	Factor
AOS-025	1.40
AOS-050	1.40
AOS-100	1.26
AOS-165	1.19

The 1.19 and 1.26 factors are from analyses using the increased foam stiffness.

The 1.4 factor is the increased foam stiffness due to temperature.

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

Axial	10
Lateral	5

e. Recommended bolt torque:

1 1/4"-7	1,000 ft-lb
7/8"-9	500 ft-lb
1/2"-13	62.5 ft-lb
3/8"-16	30 ft-lb

f. Model AOS-050 cask (Helicoflex spring seal, per Helicoflex calculations):

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

Model AOS-100 cask (Helicoflex spring seal, per Helicoflex calculations):

$$m = Y1 / (2 * \Delta P) = 286 / (2 * (280 - 150)) = 0.54$$

Model AOS-165 cask (Helicoflex spring seal, per Helicoflex calculations):

$$m = Y1 / (2 * \Delta P) = 400 / (2 * (220 - 15)) = 0.98$$

where Y1 = Linear load, to maintain sealing in service at low pressure.

MARKUP

Table 4-7. Bolt (Reference [4.3]) Evaluation – All Models^a

Item	Model and Ambient Temperatures							
	AOS-025		AOS-050		AOS-100		AOS-165	
	100°F	-40°F	100°F	-40°F	100°F	-40°F	100°F	-40°F
Bolt size (in.)	3/8		1/2		7/8		1 1/4	
Number of threads per in.	16		13		9		7	
Number of Bolts	8		10		14		20	
Torque, ft-lb	30		62.5		500		1,000	
Normal Conditions of Transport								
Axial Stress/S _m	0.08	0.07	0.17	0.15	0.40	0.36	0.30	0.27
Shear Stress/0.6S _m	0.26	0.25	0.22	0.21	0.30	0.28	0.20	0.20
Rt ² + Rs ²	0.07	0.07	0.08	0.06	0.25	0.21	0.13	0.12
Se/1.35S _m	0.46	0.44	0.42	0.39	0.67	0.62	0.46	0.44
Accumulated Fatigue Usage	0.07	0.06	0.15	0.13	0.37	0.34	0.27	0.25
Hypothetical Accident Conditions of Transport								
Head-On Drop								
Axial Stress/0.7S _u	0.48	0.62	0.60	0.74	0.76	0.82	0.87	0.96
Shear Stress/0.42S _u	0.20	0.19	0.17	0.16	0.23	0.22	0.16	0.16
Rt ² + Rs ²	0.27	0.42	0.39	0.58	0.63	0.72	0.78	0.94
Side Drop								
Axial Stress/0.7S _u	0.06	0.05	0.13	0.11	0.30	0.28	0.23	0.21
Shear Stress/0.42S _u	0.20	0.19	0.17	0.16	0.23	0.22	0.16	0.16
Rt ² + Rs ²	0.04	0.04	0.04	0.04	0.14	0.12	0.08	0.07
Corner Drop								
Axial Stress/0.7S _u	0.27	0.34	0.37	0.43	0.55	0.58	0.50	0.53
Shear Stress/0.42S _u	0.20	0.19	0.17	0.16	0.23	0.22	0.16	0.16
Rt ² + Rs ²	0.11	0.15	0.16	0.21	0.36	0.38	0.28	0.31

a. A detailed analysis of the bolt evaluation is presented in Appendix 4.5.2, "Analysis of Cask Closure Bolts by NUREG/CR-6007."

4.1.5 Keensert Device Evaluation

This section documents the evaluation of Keensert devices used in the AOS Cask component, for each of the AOS Transport Packaging System models.

Keensert devices are used in the AOS transport packages, to provide a threaded surface in the Cask Lid joint and the trunnion attachment area. Use of this device ensures that it is replaced, if the threads are damaged as a result of operational usage. The methodology used in the evaluation is taken from Reference [4.5] ("Fasteners" section), and is presented here for each model.

The critical areas of stress of mating screw threads are as follows:

- Effective cross-sectional area;
- Shear area of the external thread; and
- Shear area of the internal thread. If failure should occur, it is preferable for the screw to break, rather than to have the external or internal thread strip.

To prevent stripping of the external thread, the length of engagement should be not less than:

$$L_e = 2 * A_t / \{3.1416 * K_{nmax} * [1/2 + 0.57735 * n * (E_{smin} - K_{nmax})]\}$$

For steels of up to 100,000 psi ultimate tensile strength, the tensile area, A_t , is given by:

$$A_t = 0.7854 * (D - 0.9743 / n)^2$$

For steels of more than 100,000 psi ultimate tensile strength, the tensile area, A_t , is given by:

$$A_t = 3.1416 * (E_{smin} / 2 - 0.16238 / n)^2$$

If the internal thread is made of material of lower strength than the external thread, it is necessary to determine whether stripping of the internal thread occurs before the screw breaks. The relative strength of the external and internal threads is represented as the factor J, and is defined as:

$$J = A_s * S_{Uext} / (A_n * S_{Uint})$$

where:

$$A_s = 3.1416 * n * L_e * K_{nmax} * [1 / (2 * n) + 0.57735 * (E_{smin} - K_{nmax})]$$

$$A_n = 3.1416 * n * L_e * D_{smin} * [1 / (2 * n) + 0.57735 * (D_{smin} - E_{nmax})]$$

If J is less than or equal to 1, the length of engagement, L_e , is adequate to prevent stripping of the internal thread. However, if J is greater than 1, the required length of engagement, Q, to prevent stripping of the internal thread is:

$$Q = J * L_e$$

where:

A_n	=	Shear area of internal thread
A_s	=	Shear area of external thread
A_t	=	Tensile stress area of screw thread
D	=	Basic major diameter of the thread
D_{smin}	=	Minimum major diameter of external thread
E_{nmax}	=	Maximum pitch diameter of internal thread
E_{smin}	=	Minimum pitch diameter of external thread
J	=	Relative strength of external to internal thread ratio
K_{nmax}	=	Maximum minor diameter of internal thread
L_e	=	Minimum engagement length to prevent stripping of the external thread
n	=	Number of threads, per inch
Q	=	Required length of engagement, to prevent stripping of the internal thread
S_{uext}	=	Tensile strength of external thread material
S_{uint}	=	Tensile strength of internal thread material

4.1.5.1 Keensert Evaluation – Model AOS-025

Table 4-8. Keensert Evaluation – Model AOS-025

Parameter	3/8-in. Φ UNC	9/16-in. Φ
Number of threads, per inch	16	12
External thread class	3A	2A
Internal thread class	3B	2B
D (in.)	0.3750	0.5625
D _s min (in.)	0.3656	0.5495
E _n max (in.)	0.3387	0.5152
E _s min (in.)	0.3311	0.5016
K _n max (in.)	0.3182	0.4900
S _u ext (ksi)	185.0	89.9
S _u int (ksi)	89.9	75.0

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4.1.5.1.1 3/8-In. Φ Threaded Joint – Model AOS-025

4.1.5.1.1.1 Internal Thread Check – Model AOS-025

$$\begin{aligned} L_e &= (2) (0.0775) / \{(3.1416) (0.3182) [1/2 + (0.57735) (16) (0.3311 - 0.3182)]\} \\ &= 0.250 \text{ in.} \end{aligned}$$

where:

$$\begin{aligned} A_t &= (0.7854) (0.375 - 0.9743/16)^2 = 0.0775 \text{ in}^2 \\ J &= (0.155) (185) / (0.215) (89.9) \\ &= 1.484 \end{aligned}$$

where:

$$\begin{aligned} A_s &= (3.1416) (16) (0.250) (0.3182) [1 / (2 (16)) + (0.57735) (0.3311 - 0.3182)] \\ &= 0.155 \text{ in}^2 \\ A_n &= (3.1416) (16) (0.250) (0.3656) [1 / (2 (16)) + (0.57735) (0.3656 - 0.3387)] \\ &= 0.215 \text{ in}^2 \end{aligned}$$

J is greater than 1.0; therefore, the internal thread may strip.

The minimum internal thread engagement is:

$$Q = (1.484) (0.250) = 0.371 \text{ in. (required minimum engagement)}$$

The Keensert 3/8-inch bolt is catalog number KNH616J. The length of the insert is 0.50 inches. Therefore, the thread design is okay.

4.1.5.1.2 9/16-In. Φ Threaded Joint – Model AOS-025

4.1.5.1.2.1 External Thread Check – Model AOS-025

The Keensert external thread is 9/16"-12. Determine shear areas for internal and external threads. The external thread shear area is:

$$\begin{aligned} A_s &= (3.1416) (12) (0.250) (0.490) [1 / (2 (12)) + (0.57735) (0.5016 - 0.490)] \\ &= 0.223 \text{ in}^2 \end{aligned}$$

This area is greater than the internal shear area at the 3/8-inch bolted joint. Therefore, the minimum external thread engagement of 0.281 inches is okay.

The length of the insert is 0.50 inches. Therefore, the external thread design is okay.

4.1.5.1.2.2 Internal Thread Check – Model AOS-025

The internal thread shear area is:

$$\begin{aligned} A_n &= (3.1416) (12) (0.250) (0.5495) [1 / (2 (12)) + (0.57735) (0.5495 - 0.5152)] \\ &= 0.318 \text{ in}^2 \end{aligned}$$

The tensile strength of the lid is 75 ksi versus 89.9 ksi for the Keensert:

$$J = (0.223) (89.9) / (0.318) (75) = 0.84$$

The joint is okay.

4.1.5.2 Keensert Evaluation – Model AOS-050

Table 4-9. Keensert Evaluation – Model AOS-050

Parameter	1/2-in. Φ UNC	11/16-in. Φ^a
Number of threads, per inch	13	12
External thread class	3A	2A
Internal thread class	3B	2B
D (in.)	0.5000	0.6875
D _s min (in.)	0.4891	0.6745
E _n max (in.)	0.4548	0.6405
E _s min (in.)	0.4463	0.6264
K _n max (in.)	0.4284	0.6150
S _u ext (ksi)	185.0	89.9
S _u int (ksi)	89.9	75.0

a. The threading for this 1/2-inch insert is 11/16"-11, which is a non-standard thread. For this evaluation, 11/16"-12 threading is assumed.

4.1.5.2.1 1/2-In. Φ Threaded Joint – Model AOS-050

4.1.5.2.1.1 Internal Thread Check – Model AOS-050

$$\begin{aligned} L_e &= (2) (0.142) / \{(3.1416) (0.4284) [1 / 2 + (0.57735) (13) (0.4463 - 0.4284)]\} \\ &= 0.333 \text{ in.} \end{aligned}$$

where:

$$\begin{aligned} A_t &= (0.7854) (0.5 - 0.9743 / 13)^2 = 0.142 \text{ in}^2 \\ J &= (0.284) (185) / (0.388) (89.9) \\ &= 1.506 \end{aligned}$$

where:

$$\begin{aligned} A_s &= (3.1416) (13) (0.333) (0.4284) [1 / (2 (13)) + (0.57735) (0.4463 - 0.4284)] \\ &= 0.284 \text{ in}^2 \\ A_n &= (3.1416) (13) (0.333) (0.4891) [1 / (2 (13)) + (0.57735) (0.4891 - 0.4548)] \\ &= 0.388 \text{ in}^2 \end{aligned}$$

J is greater than 1.0; therefore, the internal thread may strip.

The minimum internal thread engagement is:

$$Q = (1.506) (0.333) = 0.501 \text{ in. (required minimum engagement)}$$

The Keensert 1/2-inch bolt is catalog number KNH813J. The length of the insert is 0.66 inches. Therefore, the thread design is okay.

4.1.5.2.2 11/16-In. Φ Threaded Joint – Model AOS-050

4.1.5.2.2.1 External Thread Check – Model AOS-050

The Keensert external thread is 11/16"-12. Determine shear areas for internal and external threads. The external thread shear area is:

$$\begin{aligned} A_s &= (3.1416) (12) (0.333) (0.615) [1 / (2 (12)) + (0.57735) (0.6264 - 0.615)] \\ &= 0.373 \text{ in}^2 \end{aligned}$$

This area is less than the internal shear area at the 1/2-inch bolted joint. Therefore, the minimum external thread engagement is:

$$Q = (0.501) (0.388 / 0.373) = 0.522 \text{ in. (required minimum engagement)}$$

The length of the insert is 0.66 inches. Therefore, the external thread design is okay.

4.1.5.2.2.2 Internal Thread Check – Model AOS-050

The internal thread shear area is:

$$\begin{aligned} A_n &= (3.1416) (12) (0.333) (0.6745) [1 / (2 (12)) + (0.57735) (0.6745 - 0.6405)] \\ &= 0.519 \text{ in}^2 \end{aligned}$$

The tensile strength of the lid is 75 ksi versus 89.9 ksi for the Keensert:

$$J = (0.373) (89.9) / (0.519) (75) = 0.86$$

The joint is okay.

4.1.5.3 Keensert Evaluation – Model AOS-100

Table 4-10. Keensert Evaluation – Model AOS-100

Parameter	7/8-in. Φ UNC	1 1/4-in. Φ UNF
Number of threads, per inch	9	12
External thread class	3A	2A
Internal thread class	3B	2B
D (in.)	0.875	1.25
D _s min (in.)	0.8611	1.2368
E _n max (in.)	0.8089	1.2039
E _s min (in.)	0.7981	1.1879
K _n max (in.)	0.7681	1.178
S _u ext (ksi)	185.0	89.9
S _u int (ksi)	89.9	75.0

MARK

4.1.5.3.1 7/8-In. Φ Threaded Joint – Model AOS-100

4.1.5.3.1.1 Internal Thread Check – Model AOS-100

$$\begin{aligned}L_e &= (2) (0.4617) / \{(3.1416) (0.7681) [1/2 + (0.57735) (9) (0.7981 - 0.7681)]\} \\ &= 0.583 \text{ in.}\end{aligned}$$

where:

$$\begin{aligned}A_t &= (0.7854) (0.875 - 0.9743 / 9)^2 = 0.4617 \text{ in}^2 \\ J &= (0.923) (185) / (1.216) (89.9) \\ &= 1.562\end{aligned}$$

where:

$$\begin{aligned}A_s &= (3.1416) (9) (0.583) (0.7681) [1 / (2 (9)) + (0.57735) (0.7981 - 0.7681)] \\ &= 0.923 \text{ in}^2 \\ A_n &= (3.1416) (9) (0.583) (0.8611) [1 / (2 (9)) + (0.57735) (0.8611 - 0.8089)] \\ &= 1.216 \text{ in}^2\end{aligned}$$

J is greater than 1.0; therefore, internal thread may strip.

The minimum internal thread engagement is:

$$Q = (1.562) (0.583) = 0.911 \text{ in. (required minimum engagement)}$$

The Keensert 7/8-inch bolt is catalog number KNH1409J. The length of the insert is 1.25 inches. Therefore, the thread design is okay.

4.1.5.3.2 1 1/4-In. Φ Threaded Joint – Model AOS-100

4.1.5.3.2.1 External Thread Check – Model AOS-100

The Keensert external thread is 1 1/4"-12. Determine shear areas for internal and external threads. The external thread shear area is:

$$\begin{aligned} A_s &= (3.1416) (12) (0.583) (1.178) [1 / (2 (12)) + (0.57735) (1.1879 - 1.178)] \\ &= 0.943 \text{ in}^2 \end{aligned}$$

This area is greater than the internal shear area at the 7/8-inch bolted joint. The minimum external thread engagement of 0.911 inches is okay.

The length of the insert is 1.25 inches. Therefore, the external thread design is okay.

4.1.5.3.2.2 Internal Thread Check – Model AOS-100

The internal thread shear area is:

$$\begin{aligned} A_n &= (3.1416) (12) (0.583) (1.2368) [1 / (2 (12)) + (0.57735) (1.2368 - 1.2039)] \\ &= 1.649 \text{ in}^2 \end{aligned}$$

The tensile strength of the lid is 75 ksi versus 89.9 ksi for the Keensert:

$$J = (1.227) (89.9) / (1.649) (75) = 0.89$$

The joint is okay.

4.1.5.4 Keensert Evaluation – Model AOS-165

Table 4-11. Keensert Evaluation – Model AOS-165

Parameter	1 1/4-in. Φ UNC	1 5/8-in. Φ UN
Number of threads, per inch	7	12
External thread class	2A	2A
Internal thread class	2B	2B
D (in.)	1.25	1.625
D _s min (in.)	1.2314	1.6118
E _n max (in.)	1.1668	1.5785
E _s min (in.)	1.1476	1.5632
K _n max (in.)	1.123	1.553
S _u ext (ksi)	185.0	89.9
S _u int (ksi)	89.9	75.0

MARK

4.1.5.4.1 1 1/4-In. Φ Threaded Joint – Model AOS-165

4.1.5.4.1.1 Internal Thread Check – Model AOS-165

$$\begin{aligned}L_e &= (2) (0.969) / \{(3.1416) (1.123) [1/2 + (0.57735) (7) (1.1476 - 1.123)]\} \\ &= 0.916 \text{ in.}\end{aligned}$$

where:

$$\begin{aligned}A_t &= (0.7854) (1.25 - 0.9743 / 7)^2 = 0.969 \text{ in}^2 \\ J &= (1.937) (185) / (2.697) (89.9) \\ &= 1.478\end{aligned}$$

where:

$$\begin{aligned}A_s &= (3.1416) (7) (0.916) (1.123) [1 / (2(7)) + (0.57735) (1.1476 - 1.123)] \\ &= 1.937 \text{ in}^2 \\ A_n &= (3.1416) (7) (0.916) (1.2314) [1 / (2(7)) + (0.57735) (1.2314 - 1.1668)] \\ &= 2.697 \text{ in}^2\end{aligned}$$

J is greater than 1.0; therefore, the internal thread may strip.

The minimum internal thread engagement is:

$$Q = (1.478) (0.916) = 1.354 \text{ in. (required minimum engagement)}$$

The length of the insert is 1.37 inches. Therefore, the thread design is okay.

4.1.5.4.2 1 5/8-In. Φ Threaded Joint – Model AOS-165

4.1.5.4.2.1 External Thread Check – Model AOS-165

The Keensert external thread is 1 5/8"-12. Determine shear areas for internal and external threads. The external thread shear area is:

$$\begin{aligned} A_s &= (3.1416) (12) (0.916) (1.553) [1 / (2 (12)) + (0.57735) (1.5632 - 1.553)] \\ &= 2.550 \text{ in}^2 \end{aligned}$$

This area is less than the internal shear area at the 1 1/4-inch bolted joint. Therefore, the minimum external thread engagement is:

$$Q = (1.354) (2.697 / 2.550) = 1.432 \text{ in. (required minimum engagement)}$$

The length of the insert is 1.81 inches. Therefore, the external thread design is okay.

4.1.5.4.2.2 Internal Thread Check – Model AOS-165

The internal thread shear area is:

$$\begin{aligned} A_n &= (3.1416) (12) (0.916) (1.6118) [1 / (2 (12)) + (0.57735) (1.6118 - 1.5785)] \\ &= 3.389 \text{ in}^2 \end{aligned}$$

The tensile strength of the lid is 75 ksi, versus 89.9 ksi for the Keensert:

$$J = (2.550) (89.9) / (3.389) (75) = 0.90$$

The joint is okay.

4.2 CONTAINMENT UNDER NORMAL CONDITIONS OF TRANSPORT

4.2.1 Containment of Radioactive Material

AOS Transport Packaging System containment is designed so that no release of radioactive materials can occur under all conditions of transport, nor will there be any significant increase in external radiation or reduction in package effectiveness. This conclusion is supported by the analyses and various component qualification tests presented throughout this report.

4.2.2 Pressurization of Containment Boundary

The AOS Transport Packaging System transport packages withstand pressures and temperatures in excess of those encountered in Normal conditions of transport. The maximum Normal and Hypothetical Accident pressure encountered are well within the Design Pressure of each transport package. These pressures correspond to the maximum temperature of Normal conditions of transport. This pressure value is based upon air at 100% relative humidity occupying the cavity interior. Table 4-12 presents the maximum temperatures and resulting pressures under Normal conditions of transport, as well as the Design Pressure for each transport package. Table 4-13 provides similar information, for Hypothetical Accident conditions of transport. The structural evaluation provided in Chapter-2, "Structural Evaluation," shows low stress values throughout the cask structure, especially in the seal area under Normal conditions of transport. In addition, the maximum temperatures are below the corresponding limits of the seal materials; therefore, they do not pose a threat to containment integrity.

Table 4-12. Maximum Cask Cavity Pressure Due to Normal Conditions of Transport – All Models

Model	Volume (V)		Temperature (T) ^a		Pressure (P) ^b			Design Pressure ^c	
	l	in ³	°C	°F	kPa	psia		kPa	psia
AOS-025	0.17	10	99	210	126	18	<	207	30
AOS-050	1.36	83	128	263	136	20	<	414	60
AOS-100A AOS-100A-S	11.21	684	126	258	135	20	<	1,931	280
AOS-100B	11.21	684	126	259	135	20	<	1,931	280
AOS-165A	49	2,978	365	689	209	30	<	1,517	220
AOS-165B	49	2,978	202	395	209	30	<	1,517	220

a. Temperatures listed are the maximum values obtained throughout Normal conditions of transport events.

b. Pressure calculation is based upon the ideal gas law, where:

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \Rightarrow \frac{P_1}{T_1} = \frac{P_2}{T_2}$$

Initial Condition

P₁ = 14.7 psia

T₁ = 78°F

Final Condition

P₂ = ?

T₂ = 256°F

$$P_2 = \frac{(256 + 460)}{(78 + 460)} * 14.7 = 19.56 \text{ psia}$$

c. **Model AOS-100 and AOS-165 transport packages** – Pressure value is based upon projected operating conditions.

Table 4-13. Maximum Cask Cavity Pressure Due to Fire Conditions – All Models

Model	Volume		Temperature ^a		Pressure			Design Pressure ^b	
	l	in ³	°C	°F	kPa	psia		kPa	psia
AOS-025	0.17	10	149	300	143	21	<	207	30
AOS-050	1.36	83	205	401	162	24	<	414	60
AOS-100A AOS-100A-S	11.21	684	174	346	155	23	<	1,931	280
AOS-100B	11.21	684	183	360	155	23	<	1,931	280
AOS-165A	49	2,978	375	707	220	32	<	1,517	220
AOS-165B	49	2,978	232	449	220	32	<	1,517	220

a. Temperature listed is the maximum value obtained throughout Hypothetical Accident conditions of transport events.

b. **Model AOS-100 and AOS-165 transport packages** – Pressure value is based upon design conditions.

4.2.3 Containment Criterion

AOS Transport Packaging System containments are designed, and verified by Leak test, to meet the "leaktight" criteria established in Reference [4.4].

MARKUP

4.3 CONTAINMENT UNDER HYPOTHETICAL ACCIDENT CONDITIONS OF TRANSPORT

Note: The design pressure for the transport packages does not account for the pressure contribution of fission gas inventory release, because fission gasses are not an authorized content for the AOS Transport Packaging System.

Under Hypothetical Accident conditions of transport, the pressure within the AOS Transport Packaging System models' cask cavity is well below the design pressures listed in Table 4-12. Temperatures at the lid seal and port cover seals are also below the temperature criteria for the applicable seal material listed in Chapter 3, Table 3-4, "Transport Package Temperature Summary – All Models."

Table 4-14 summarizes the maximum temperatures obtained during the fire transient evaluation, for each of the transport package models. The analytical evaluations under Hypothetical Accident conditions of transport, presented in Chapter 2, "Structural Evaluation," show that the stresses throughout the cask structure are below the failure criteria for the material. This is also demonstrated by the results of the Model AOS-165 transport package Free-Drop test, presented in Chapter 8, Appendix 8.3.2, "Impact (Free-Drop) Test Report." During the test, the cask structure did not suffer any measurable deformation on its entire surface and the cask leak tightness was maintained, despite the fact that the cask was dropped three (3) times.

Table 4-14. Maximum Temperatures during Fire Transient at Packaging Cask Cavity, Cask Seal Area, and Cask Test, Drain, and Vent Ports – All Models

Area	Maximum Temperatures											
	AOS-025A		AOS-050A		AOS-100A AOS-100A-S		AOS-100B		AOS-165A		AOS-165B	
	°C	°F	°C	°F	°C	°F	°C	°F	°C	°F	°C	°F
Cask Cavity	149	300	205	401	174	346	183	360	375	707	232	449
Cask Seal Area	148	299	200	392	185	365	172	341	326	619	204	400
Cask Test Port	148	299	200	393	175	346	172	342	314	597	202	395
Cask Drain Port	147	297	201	393	175	346	172	342	315	598	200	393
Cask Vent Port	149	300	199	391	174	345	171	340	326	619	204	399

4.3.1 Containment of Radioactive Material

The results of the structural and thermal analyses performed in Chapter 2, "Structural Evaluation," and Chapter 3, "Thermal Evaluation," respectively, and the Packaging Drop test results presented in Chapter 8, "Acceptance Tests and Maintenance Program," verify that the transport packages are capable of withstanding the Hypothetical Accident conditions of transport that meet the containment criteria provided in Reference [4.4].

4.3.2 Containment Criterion

AOS Transport Packaging System containments are designed, and verified by Leak test, to meet the "leaktight" criteria established in Reference [4.4].

4.3.3 Fission Gas Products

Note: Not applicable. Fuel is not an authorized content for the AOS Transport Packaging System.

4.4 LEAKAGE RATE TESTS FOR TYPE B PACKAGES

The Leakage Rate Test for Type B packages is performed by pressurizing the cask cavity to 1 atmosphere above the background pressure of the cavity filled with helium. To check for the presence of helium, the volume between the two seal rings on the lid seal, and in the seal ring around the threaded port plugs and the testing port cover in the vent and drain ports are tested. The testing is done with a Mass Spectrometer Leak Detector (MSLD) connected to the seal test port and the testing port cover.

Figure 4-7 illustrates a sample leak test setup for the lid seal. The cask cavity is evacuated prior to helium pressurization, to ensure as close to 100% (as possible) helium environment in the cask cavity. The MSLD is calibrated before and after the test, with a calibrated leak standard having a leak rate range value of at least 10^{-9} cc/sec He. The cask temperature at the test port area and calibrated leak identification number are recorded, as well as the acceptance criteria leak rate. The acceptance criteria can be compensated, to account for temperature variations. The pipe plugs on the drain and vent ports are tested in a similar manner.

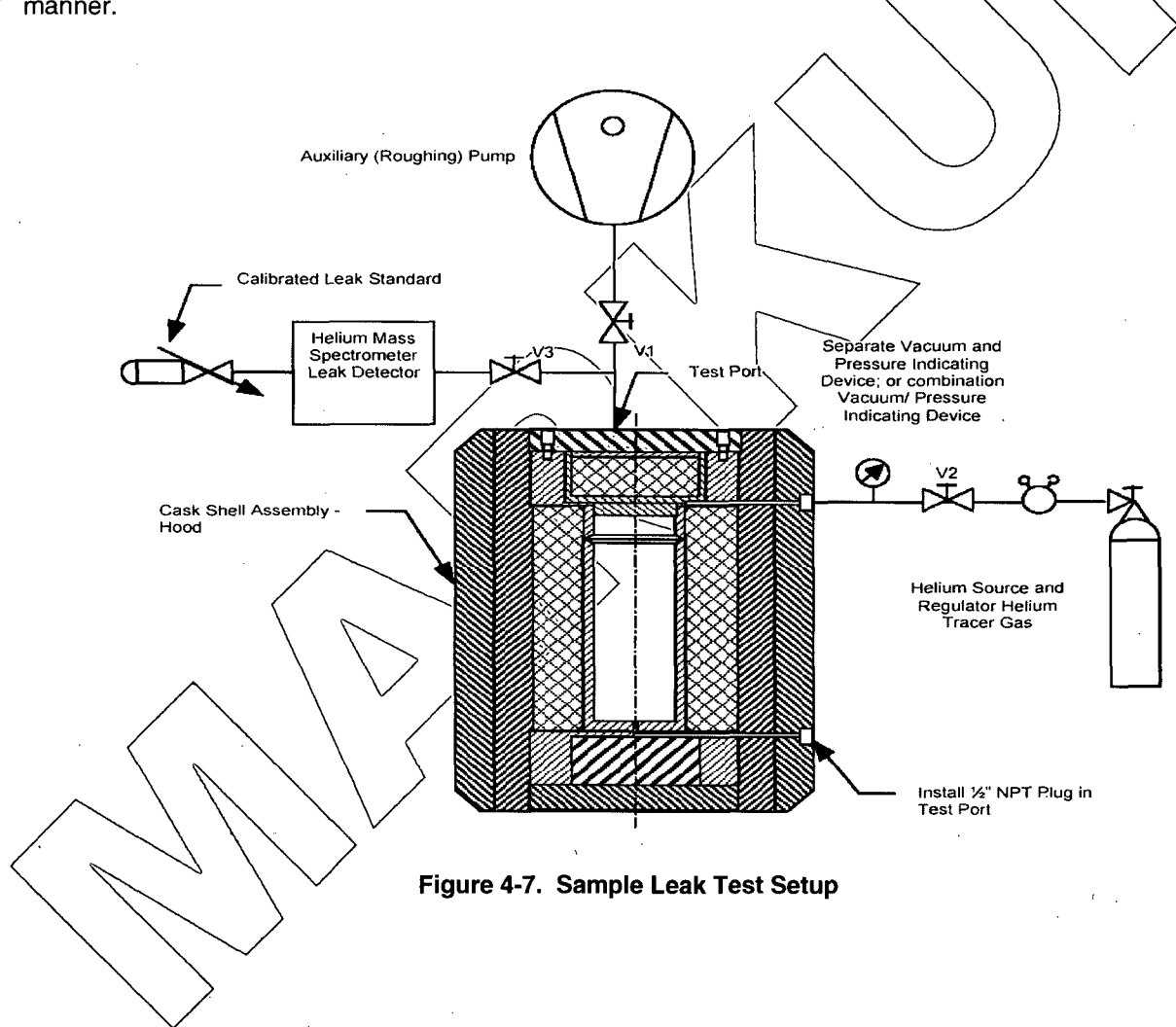


Figure 4-7. Sample Leak Test Setup

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4.5 APPENDIX

This appendix presents the following information:

- Helium Leak Qualification Test of Garlock Helicoflex H309352 and 309353-5
- Analysis of Cask Closure Bolts by NUREG/CR-6007

MARKUP

4.5.1 Helium Leak Qualification Test of Garlock Helicoflex H309352 and 309353-5

The test reported in this appendix was performed to demonstrate that the selected seal materials are able to perform at their temperature limits. It was not used to qualify the seal joint. The seal joint qualification test is performed with the actual joint using the cask, seal, lid, and bolting installed, as prescribed, in the Acceptance Test and Annual Test procedures. (Refer to Chapter 8, "Acceptance Tests and Maintenance Program.")

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HELIUM LEAK QUALIFICATION TEST OF GARLOCK HELICOFLEX H-309352 AND H-309353-5

ATS JOB # D114924-Rev. 1*

PURCHASE ORDER # 037467

Prepared for

KEVIN EZELL
GARLOCK HELICOFLEX
2770 THE BOULEVARD
COLUMBIA, SC 29290



GE Nuclear Energy

VPF No.	Base	Seq.	Sheets	Rev.
2200	0049	- 4144	- 197	- 0

Transmittal No. *GARLOCK 091007*

Signature	Date
<i>R. P. Murray</i>	09.10.07

<input checked="" type="checkbox"/> Approved	<input type="checkbox"/> Information only
<input type="checkbox"/> Approved with comments	<input type="checkbox"/> Approved - Need microfilmable copy
<input type="checkbox"/> Disapproved	

Prepared by

Eric Shiner, Materials Testing

Approved by

Shawn Murray, Materials Testing Supervisor

This Report May Not Be Reproduced Except In Full

This report represents interpretation of the results obtained from the test specimen and is not to be construed as a Guaranty or Warranty of the condition of the entire material lot.

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Purchase Order # 037467

Kevin Ezell
Garlock Helicoflex
2770 The Boulevard
Columbia, SC 29290

Subject

In order to qualify H-309352 & H-309353, leak tests were performed on Garlock Helicoflex test seals H-309646 and H-309353-5 in accordance with GE Specification 22A9424, "AOS Packages Cask Seals, Metallic and Elastomeric Materials".

Materials

H-309646 seals are constructed of metal and H-309353-5 seals are constructed of an elastomer. Test flange F-400282 was built of 300 series stainless steel by Garlock Helicoflex. An aluminum test fixture was constructed by Applied Technical Services (ATS). Various stainless steel fittings were used in the plumbing.

Objective and Background

The purpose of this test was to determine the helium leak rate of seals H-309646 and H-309353-5 at low, normal, and high temperatures. These seals are to be used in the transport of radioactive materials.

Test Procedure

Seals were installed per the Garlock Helicoflex Leak Test Procedure for H-309352 (Latest Revision) and H-309353 (Latest Revision) sections 3.2 and 4.2 for the metal and elastomer seals, respectively. The room temperature tests were performed beneath a fume hood. For the low temperature test, the test fixture was placed in an environmental chamber at the required test temperature. For the high temperature test, the test fixture was wrapped in ceramic heat treatment beads covered and blanketed with ceramic insulation. The part was heated to the required temperature. For all tests a thermocouple was attached to the part through the entirety of the tests. The test procedure can be seen in Appendix 2. Pictures of test setup can be seen in Figures 1-9.



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Test Results

Test data is reported in Table 1.

Table 1: Test Data

Seal	Test	Part Temperature (°F)	Pressure Differential (psi)	Helium Pressure (psi)	Test Duration	Pass/Fail Condition (cc/sec)	Observed Leak Rate (cc/sec)
Metal	Normal (70°F ± 5°)	72	30	15	3 min.	2.0 x 10 ⁻⁷	1.1 x 10 ⁻⁹
Metal	Normal (70°F ± 5°)	75	30	15	3 min.	2.0 x 10 ⁻⁷	8 x 10 ⁻¹⁰
Elastomer	Normal (70°F ± 5°)	71.7	30	15	3 min.	2.0 x 10 ⁻⁷	5.2 x 10 ⁻¹⁰
Metal	Cold (-40°F ± 10°)	-40	17	2	3 min.	3.1 x 10 ⁻⁷	1.9 x 10 ⁻¹⁰
Metal	Cold (-40°F ± 10°)	-36.6	17	2	3 min.	3.1 x 10 ⁻⁷	1.0 x 10 ⁻⁹
Elastomer	Cold (-40°F ± 10°)	-39	17	2	3 min.	2.6 x 10 ⁻⁷	6.9 x 10 ⁻⁹
Metal	Hot (800°F ± 5°)	804	17	2	3 min.	2.4 x 10 ⁻⁷	2.2 x 10 ⁻⁷
Metal	Hot (800°F ± 5°)	801	17	2	3 min.	2.4 x 10 ⁻⁷	3.8 x 10 ⁻⁹
Elastomer	Hot (450°F ± 5°)	455	17	2	3 min.	2.4 x 10 ⁻⁷	6.8 x 10 ⁻⁸

Test Summary and Conclusion

Garlock Helicoflex seals H-309352 & H-309353 were tested in accordance with GE Specification 22A9424, "AOS Packages Cask Seals, Metallic and Elastomeric Materials". Tested specimens were found to be acceptable in accordance with GE Specification 22A9424. Equipment Calibration sheets can be seen in Appendix 1.

*Added Test Summary and Conclusion and "Test Duration" to Table 1.



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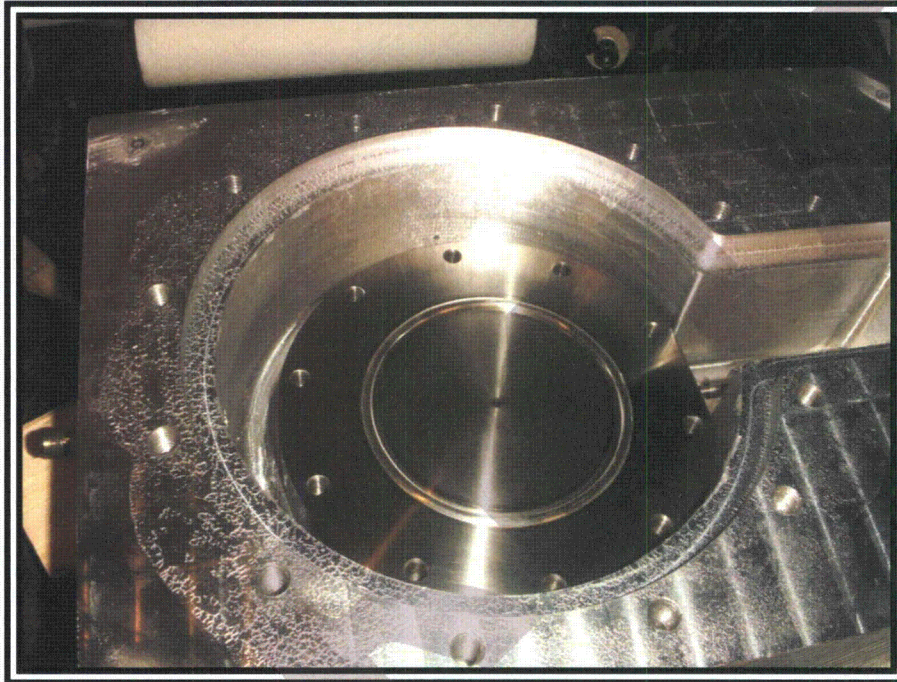


Figure 1: Test Flange in Test Chamber (Normal Temp. Test)

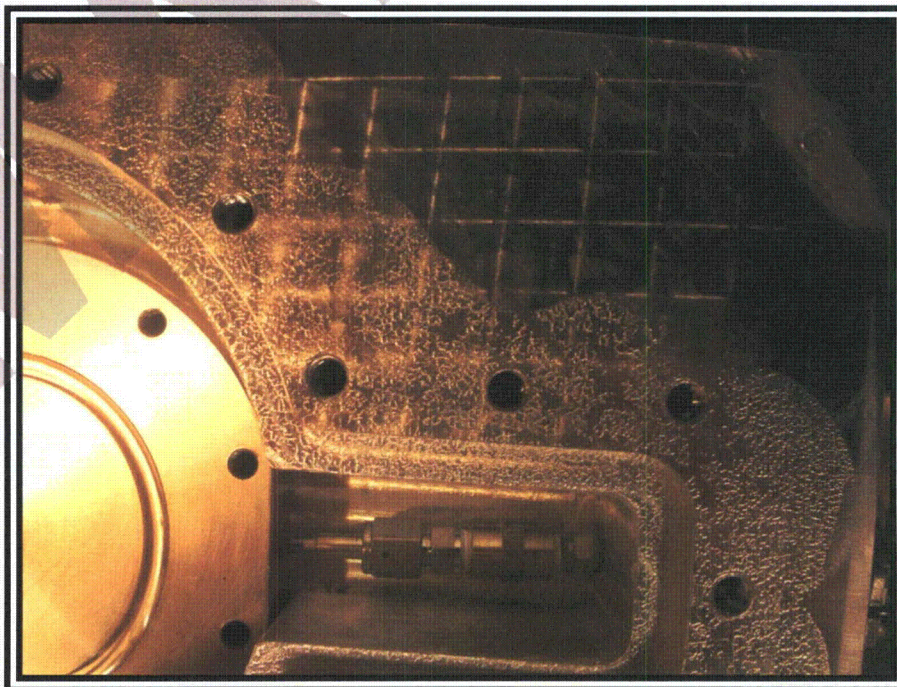


Figure 2: Fittings for Test Flange (Normal Temp. Test)



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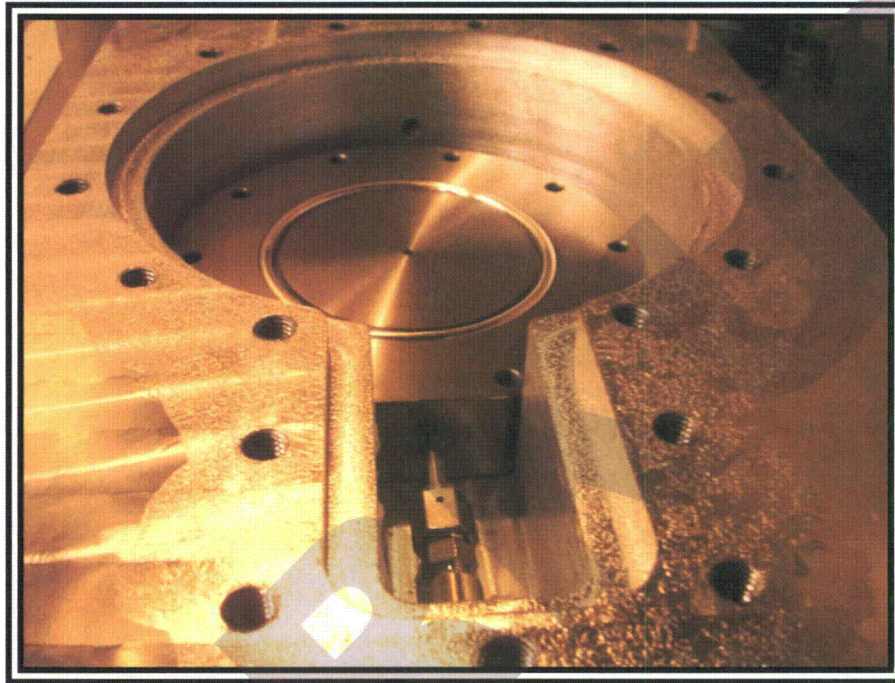


Figure 3: Metal Seal installed (Normal Temp. Test)

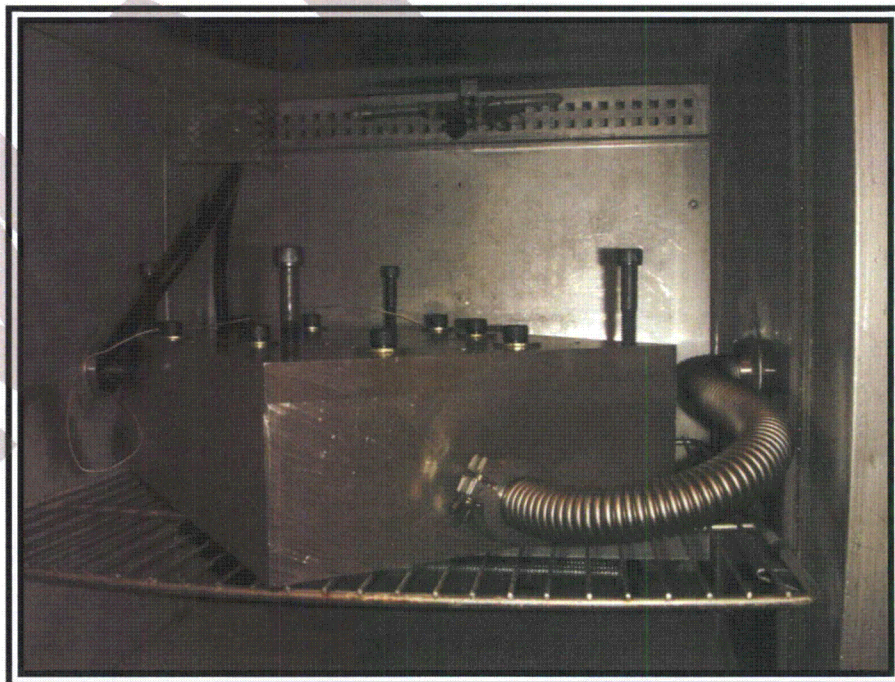


Figure 4: Test Chamber in Environmental Chamber
(Cold Temp. Test)



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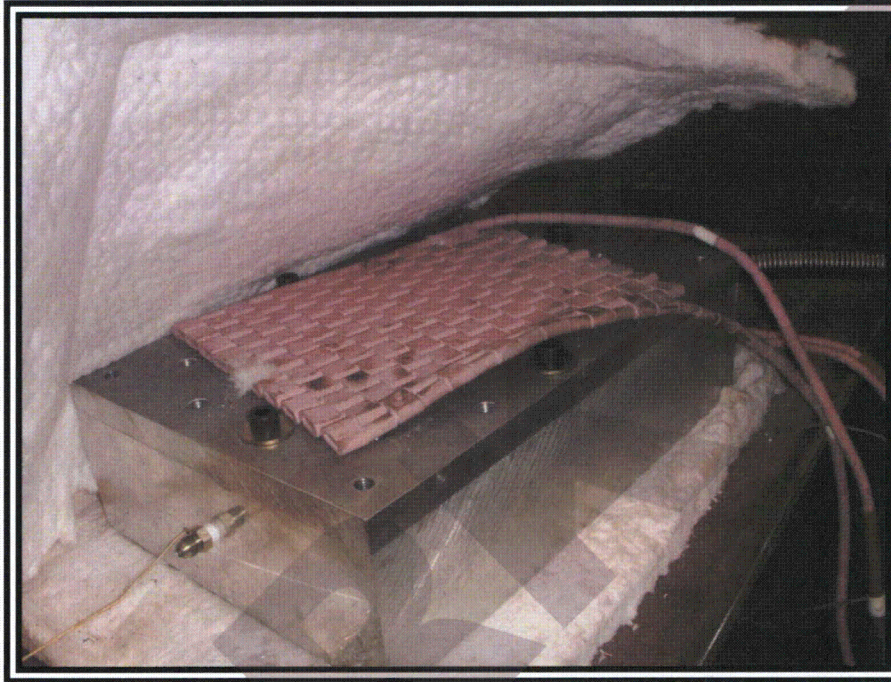


Figure 5: Ceramic beads on Test Chamber (Hot Temp. Test)

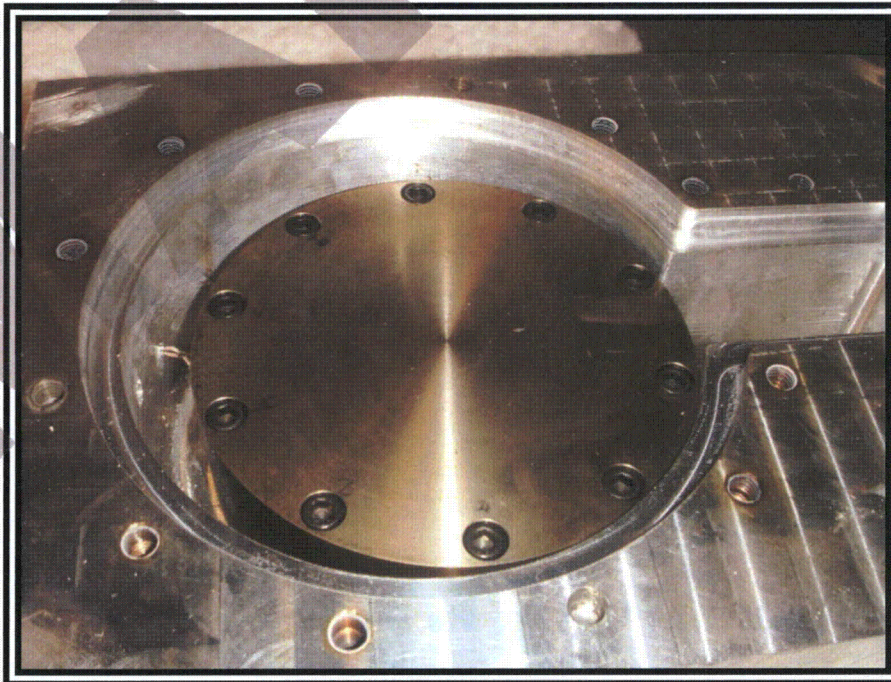


Figure 6: Test Flange after 450°F Test (Hot Temp. Test)



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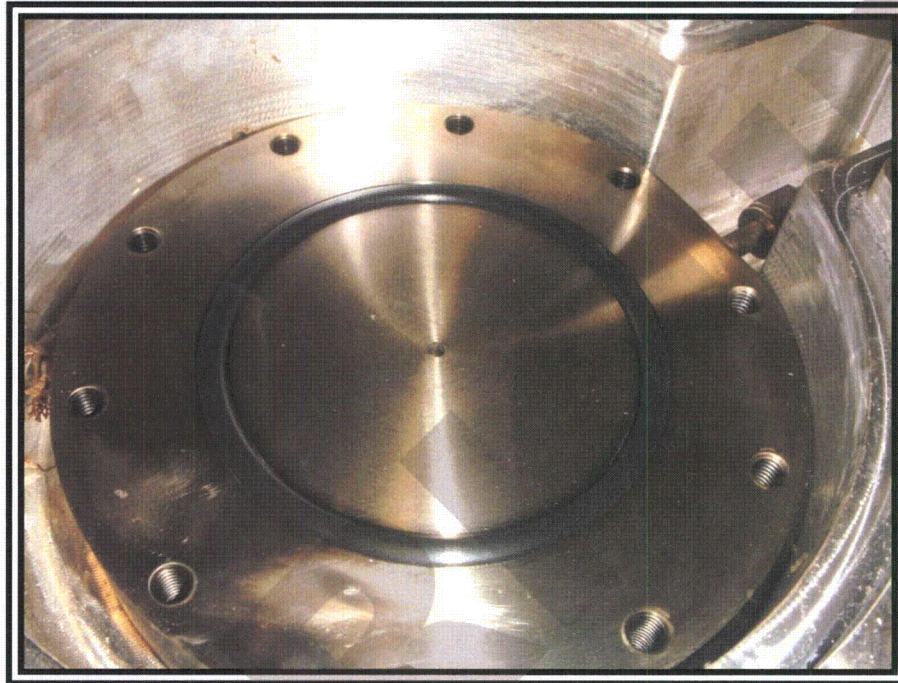


Figure 7: Elastomer seal after Test (Hot Temp. Test)

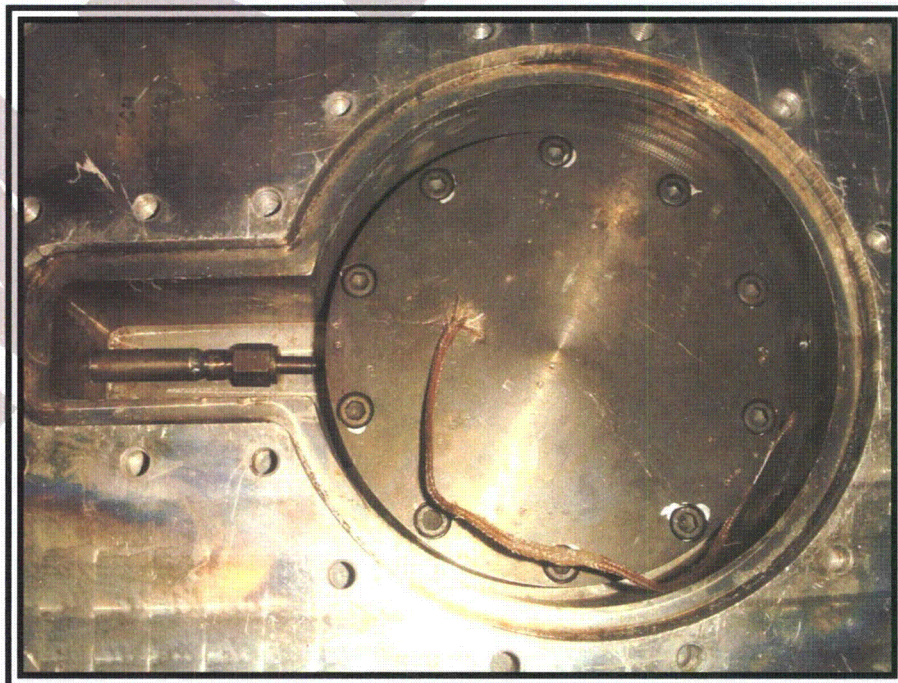


Figure 8: Test Fixture (Metal Seal Hot Temp. Test)



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Figure 9: Helium Leak Detector



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Appendix 1: Calibration Certificates

ATS-0909



Calibration Certificate for Helium Calibrated Leak

Applied Technical Services Inc
1049 Triad Ct
Marietta, GA 30062

Account#: 011600
Sales Order#: 154984
RA#:

VIC Leak Detection certifies that the calibrated gas-leak listed is traceable to the National Institute of Standards and Technology (NIST) test numbers 269870-04 of 270640-04. The total uncertainty in the measured leak rate of this gas leak standard is less than ±10%. This certification shall not be reproduced except in full.

This instrument is calibrated in accordance with Calibration Procedure No.: 931
Gas: Helium, Model: SC7, Type: Glass permeation, S/N: 0559, Part Number: 13701600

Calibration Date: 8/29/2007 Fill Pressure: 14.7 psia Fill Date: 8/29/2007 Reservoir volume: 75 cc
Calibration Temperature: 24°C Linear Temperature Coefficient: 3.0% % per C°

Certified Leak Rate Values		
	Helium Tracer Gas:	Air Equivalent:
atm*cc/sec:	4.83E-08	1.80E-08
mbar*l/sec:	4.89E-08	1.82E-08
Pa*m3/sec:	4.88E-09	1.82E-09
mcl/sec:	2.15E-12	8.03E-13
Recalibration or 10% Fall-Off Date: 8/28/2008		

Note: Air equivalent leak rates are calculated only for molecular flow helium calibrators.

VIC Traceability	
Trace S/N:	0001
Trace Model:	SC4
Trace Current Date:	02/2008
Uncertainty ±:	10.00%

As Received Calibrator Status	
As Received Leak Rate (atm*cc/sec):	4.83E-08
As Received Leak Rate in Calibration:	IN
A/R Note:	

Final Inspection By:

Sue Voigt, Calibration Laboratory Technician

VIC Leak Detection

Designers and Manufacturers of Leak Detectors, Gas Handling Equipment, and Complete Leak Detection Solutions
2099 Ninth Avenue • Ronkonkoma, New York 11779
Tel 631 737 0900 • Fax 631 737 1541 • sales@vicleakdetection.com • www.vicleakdetection.com



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For ATS-04184

VIC Leak Detection

CALIBRATION CERTIFICATE

In compliance with
ANSI/NCSL Z540-1-1994
ISO-10012-1:1992E

Vacuum Instrument Corp. certifies that the calibrated leak referenced below is accurate in accordance with a measurement technique that compares, through the use of a Mass Spectrometer Leak Detector, each unit against a primary standard, serial number 0001a and/or 0003b. These standards are certified and traceable to the National Institute of Standards and Technology (NIST). The Mass Spectrometer Leak Detector is continuously calibrated and becomes the instrument used to certify the Calibrated Leak. This instrument is calibrated in accordance with Calibration Procedure No. 931.

We recommend the Calibrated Leak be returned to Vacuum Instrument Corp. For recalibration annually.

NOTE: Calibrated Leaks should be stored and shipped with valve open.

Model: SC7

SERIAL NO: 0559

CAL DATE: 08/24/2006

CERTIFICATION NO: L08056

The above sensitivity calibrator has been calibrated as of this date with the following results:

Helium Leak Rate:
0.00432 ± 10% Micron cu.ft/hr.
4.32 x 10⁻⁸ ± 10% Std. Cc/sec.

Air Leak Rate Through Equivalent Leak:
0.0016 ± 10% Micron cu.ft/hr.
1.6 x 10⁻⁸ ± 10% Std. Cc/sec.

As Received In or Out of Calibration: IN
As Received As Calibrated

Calibration Temperature: 26 degrees C

Temperature Coefficient = ± 3% per degree C

Leak rate decreases less than 5% per year

Final Inspection By: Sue Voigt

Sue Voigt (Calibration Laboratory Technician)

This certificate shall not be reproduced except in full, with the written approval of Vacuum Instrument Corp.

a- NIST Test Number: 269870-04

b- NIST Test Number: 269870-04

ancert2

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Designers and Manufacturers of Leak Detectors, Gas Handling Equipment, and Complete Leak Detection Solutions
2099 Ninth Avenue • Ronkonkoma, New York 11779
Tel 631 737 0900 • Fax 631 737 1541 • VicSales@VacuumInst.com • www.vacuuminst.com

FRMQ023

Rev. C

Approved By: Craig O'Connor

Date: 8/9/00



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APPLIED TECHNICAL SERVICES, INCORPORATED
1280 Field Parkway, Marietta, GA 30066 (770) 514-3288

CALIBRATION DATA SHEET

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Customer: APPLIED TECHNICAL SERVICES - *Mobility Testing* Purchase Order: *ATS 01899*

Item Name: *THERMOCOUPLE THERMOMETER* Asset No: *ATS 01899* ATS Reference No.: *ATS 01899*

Manufacturer: *OMEGA* Model No: *HH 11* Proc. No: *1064* Rev.: *2*

Serial No: *400882* Date of Calibration: *4-10-07* Calibration Due: *4-10-08*

Reason For Service: Initial Calibration Due For Calibration Repair and Calibration

Equipment Used *ATS 4648* Due: *8-17-07* *MULTIPRODUCT CALIBRATOR*

Calibrated by: *Jim C O'Neil*

Customer Instrument Under Test

UNCERTAINTY (SEE NOTE)	FUNCTION AND RANGE	APPLIED	TOLERANCE	AS FOUND READING	AS CALIBRATED READING
0.18	Temperature	-50.0000 C	-48.85 - -51.15	-50	-50
0.16	Type K	0.0000 C	-1 - 1	-0.3	-0.3
0.16		50.0000 C	48.85 - 51.15	49.3	49.3
0.26		150.0000 C	148.55 - 151.45	150.2	150.2
0.26		500.0000 C	497.5 - 502.5	500	500
0.26		750.0000 C	746.75 - 753.25	752	752
0.26		1000.0000 C	994 - 1006	1001	1001
0.4		1250.0000 C	1242.75 - 1257.25	1250	1250

* Indicates out of tolerance readings.

Remarks: Measurement Uncertainty reported at coverage factor K = 2 or 95% confidence level.



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Customer: ATS - Materials Testing Purchase Order No.: N/A
Item Name: Dial Torque Wrench Asset No.: ATS - 0942 ATS-Reference No.: N/A
Manufacturer: CDI Model No.: 6002LDIN Proc. No.: 522 Rev.: 4
Serial No.: ATS - 0942 Calibration Date: 11/10/06 Calibration Due Date: 11/10/07

Reason For Service: [] Initial Calibration [x] Due For Calibration [] Repair and Calibration

Equipment Used: ATS-4070C Due: 1/5/07 Torque Transducer, 4 in 1 Unit
Due:
Due:
Due:
Due:

Calibrated By: [Signature]

Customer Instrument Under Test

Table with 6 columns: UNCERTAINTY (SEE NOTE) In-Lbs, RANGE In-Lbs, ATS STANDARD In-Lbs, TOLERANCE In-Lbs, AS FOUND READING In-Lbs, AS CALIBRATED READING In-Lbs. Contains 10 rows of calibration data.

* Indicates out of tolerance readings.

Remarks: Measurement Uncertainty reported at coverage factor K = 2 or 95% confidence level.



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Customer: ATS Material Testing Purchase Order No.: N/A
 Item Name: Temperature Meter Asset No.: ATS-01921 ATS Reference No.: ATS-01921
 Manufacturer: Omega Model No.: BS6000A Proc. No.: 1021 Rev.: 1
 Serial No.: 28988 Calibration Date: 6-22-06 Calibration Due Date: 6-22-07

Reason For Service: Initial Calibration Due For Calibration Repair and Calibration

Equipment Used: ATS-4248 Due: 9-20-06 Multiproduct Calibrator
 _____ Due: _____
 _____ Due: _____
 _____ Due: _____
 _____ Due: _____

Calibrated By: [Signature]

Customer Instrument Under Test

UNCERTAINTY (SEE NOTE)	FUNCTION AND RANGE	APPLIED	TOLERANCE	AS FOUND READING	AS CALIBRATED READING
±0.33°F	Type "K"	-200°F	±3°F	-202.0	-202.0
±0.33°F	-328 to 2502°F	-100°F	±3°F	-101.6	-101.6
±0.18°F		-50°F	±3°F	-51.5	-51.5
±0.16°F		0.0°F	±3°F	-1.3	-1.3
±0.16°F		100°F	±1.5°F	98.9	98.9
±0.26°F		400°F	±1.5°F	398.8	398.8
±0.26°F		800°F	±1.5°F	799.1	799.1
±0.26°F		1200°F	±1.5°F	1199	1199
±0.26°F		1600°F	±1.5°F	1600	1600
±0.26°F		2000°F	±1.5°F	2000	2000
±0.27°F	Type "J"	-200°F	±3°F	-201.2	-201.2
±0.16°F	-328 to 2192°F	-100°F	±3°F	-101.1	-101.1
±0.16°F		-50°F	±3°F	-51.2	-51.2
±0.14°F		0.0°F	±3°F	-1.1	-1.1
±0.14°F		100°F	±1.5°F	99.0	99.0
±0.17°F		400°F	±1.5°F	399.0	399
±0.23°F		800°F	±1.5°F	799.2	799.2
±0.23°F		1200°F	±1.5°F	1199	1199
±0.23°F		1600°F	±1.5°F	1600	1600
±0.23°F		2000°F	±1.5°F	2001	2001

* Indicates out of tolerance readings.

Remarks: Measurement Uncertainty reported at coverage factor K = 2 or 95% confidence level.



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Customer: ATS Material Testing Purchase Order No.: N/A
Item Name: Temperature Meter Asset No.: ATS-01921 ATS Reference No.: ATS:01921
Manufacturer: Omega Model No.: BS6000A Proc. No.: 1021 Rev.: 1
Serial No.: 28988 Calibration Date: 6-22-06 Calibration Due Date: 6-22-07

Customer Instrument Under Test

UNCERTAINTY (SEE NOTE)	FUNCTION AND RANGE	APPLIED	TOLERANCE	AS FOUND READING	AS CALIBRATED READING
$\pm 0.63^{\circ}\text{F}$	Type "T"	-200 $^{\circ}\text{F}$	$\pm 3^{\circ}\text{F}$	-201.7	-201.7
$\pm 0.24^{\circ}\text{F}$	-328 $^{\circ}\text{F}$ to 752 $^{\circ}\text{F}$	-100 $^{\circ}\text{F}$	$\pm 3^{\circ}\text{F}$	-101.4	-101.4
$\pm 0.24^{\circ}\text{F}$		-50 $^{\circ}\text{F}$	$\pm 3^{\circ}\text{F}$	-51.4	-51.4
$\pm 0.16^{\circ}\text{F}$		0.0 $^{\circ}\text{F}$	$\pm 3^{\circ}\text{F}$	-1.3	-1.3
$\pm 0.16^{\circ}\text{F}$		50 $^{\circ}\text{F}$	$\pm 1.5^{\circ}\text{F}$	48.7	48.7
$\pm 0.16^{\circ}\text{F}$		100 $^{\circ}\text{F}$	$\pm 1.5^{\circ}\text{F}$	98.9	98.9
$\pm 0.14^{\circ}\text{F}$		200 $^{\circ}\text{F}$	$\pm 1.5^{\circ}\text{F}$	198.9	198.9
$\pm 0.14^{\circ}\text{F}$		400 $^{\circ}\text{F}$	$\pm 1.5^{\circ}\text{F}$	399.1	399.1
$\pm 0.14^{\circ}\text{F}$		600 $^{\circ}\text{F}$	$\pm 1.5^{\circ}\text{F}$	599.3	599.3
$\pm 0.14^{\circ}\text{F}$		700 $^{\circ}\text{F}$	$\pm 1.5^{\circ}\text{F}$	699.3	699.3

* Indicates out of tolerance readings.

Remarks: Measurement Uncertainty reported at coverage factor K = 2 or 95% confidence level.



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Customer: ATS - MET Purchase Order No.: N/A
Item Name: Pressure Gauge Asset No.: ATS - 01347 ATS Reference No.: N/A
Manufacturer: USG Model No.: 0 - 200 PSI Proc. No.: 517 Rev.: 4
Serial No.: ATS - 01347 Calibration Date: 07/30/07 Calibration Due Date: 07/30/08
Reason For Service: [] Initial Calibration [x] Due For Calibration [] Repair and Calibration

Equipment Used: ATS-01401 Due: 02/02/08 High Range Pressure Calibrator
Due:
Due:
Due:
Due:

Calibrated By: [Signature]

Customer Instrument Under Test

Table with 6 columns: UNCERTAINTY (SEE NOTE) PSI, RANGE PSI, ATS STANDARD PSI, TOLERANCE PSI, AS FOUND READING PSI, AS CALIBRATED READING PSI. Rows include values like 40.00, 80.00, 120.00, 160.00, 200.00 and readings like 40, 80, 121, 161, 200.

* Indicates out of tolerance readings.

Remarks: Measurement Uncertainty reported at coverage factor K = 2 or 95% confidence level.



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Customer: ATS Materials Testing Purchase Order No.: N/A

Item Name: Heat Treat Console Asset No.: ATS-02408 ATS Reference No.: N/A

Manufacturer: Mannings USA Model No.: 16126 Proc. No.: 1013 Rev.: 2

Serial No.: 072991 Calibration Date: 06-06-07 Calibration Due Date: 12-06-07

Reason For Service: Initial Calibration Due For Calibration Repair and Calibration

Equipment Used: ATS 01848 Due: 10-27-07 Process Calibrator

Due: _____

Due: _____

Due: _____

Due: _____

Due: _____

Calibrated By: Jeff L Cook

Customer Instrument Under Test

UNCERTAINTY (SEE NOTE)	FUNCTION AND RANGE	APPLIED	TOLERANCE	AS FOUND READING	AS CALIBRATED READING
0.3 °F	Load TC 1	250.0	247 to 253	249	249
0.3 °F	Load TC 1	500.0	497 to 503	499	499
0.3 °F	Load TC 1	1000.0	997 to 1003	1000	1000
0.3 °F	Load TC 1	1500.0	1497 to 1503	1501	1501
0.3 °F	Load TC 2	250.0	247 to 253	250	250
0.3 °F	Load TC 2	500.0	497 to 503	500	500
0.3 °F	Load TC 2	1000.0	997 to 1003	1000	1000
0.3 °F	Load TC 2	1500.0	1497 to 1503	1501	1501
0.3 °F	Load TC 3	250.0	247 to 253	250	250
0.3 °F	Load TC 3	500.0	497 to 503	499	499
0.3 °F	Load TC 3	1000.0	997 to 1003	1000	1000
0.3 °F	Load TC 3	1500.0	1497 to 1503	1500	1500
0.3 °F	Load TC 4	250.0	247 to 253	250	250
0.3 °F	Load TC 4	500.0	497 to 503	500	500
0.3 °F	Load TC 4	1000.0	997 to 1003	1001	1001
0.3 °F	Load TC 4	1500.0	1497 to 1503	1501	1501
0.3 °F	Load TC 5	250.0	247 to 253	250	250
0.3 °F	Load TC 5	500.0	497 to 503	500	500
0.3 °F	Load TC 5	1000.0	997 to 1003	1001	1001
0.3 °F	Load TC 5	1500.0	1497 to 1503	1501	1501

* Indicates out of tolerance readings.

Remarks: Measurement Uncertainty reported at coverage factor K = 2 or 95% confidence level.



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Customer: ATS Materials Testing Purchase Order No.: N/A
 Item Name: Heat Treat Console Asset No.: ATS-02408 AT'S Reference No.: N/A
 Manufacturer: Mannings USA Model No.: 16126 Proc. No.: 1013 Rev.: 2
 Serial No.: 072991 Calibration Date: 06-06-07 Calibration Due Date: 12-06-07

Customer Instrument Under Test

UNCERTAINTY (SEE NOTE)	FUNCTION AND RANGE	APPLIED	TOLERANCE	AS FOUND READING	AS CALIBRATED READING
0.3 °F	Load TC 6	250.0	247 to 253	250	250
0.3 °F	Load TC 6	500.0	497 to 503	500	500
0.3 °F	Load TC 6	1000.0	997 to 1003	1001	1001
0.3 °F	Load TC 6	1500.0	1497 to 1503	1501	1501
0.3 °F	Recorder TC 1	250.0	247 to 253	250	250
0.3 °F	Recorder TC 1	500.0	497 to 503	500	500
0.3 °F	Recorder TC 1	1000.0	997 to 1003	1000	1000
0.3 °F	Recorder TC 1	1500.0	1497 to 1503	1500	1500
0.3 °F	Recorder TC 2	250.0	247 to 253	250	250
0.3 °F	Recorder TC 2	500.0	497 to 503	500	500
0.3 °F	Recorder TC 2	1000.0	997 to 1003	999	999
0.3 °F	Recorder TC 2	1500.0	1497 to 1503	1500	1500
0.3 °F	Recorder TC 3	250.0	247 to 253	250	250
0.3 °F	Recorder TC 3	500.0	497 to 503	500	500
0.3 °F	Recorder TC 3	1000.0	997 to 1003	1000	1000
0.3 °F	Recorder TC 3	1500.0	1497 to 1503	1500	1500
0.3 °F	Recorder TC 4	250.0	247 to 253	250	250
0.3 °F	Recorder TC 4	500.0	497 to 503	500	500
0.3 °F	Recorder TC 4	1000.0	997 to 1003	1000	1000
0.3 °F	Recorder TC 4	1500.0	1497 to 1503	1500	1500
0.3 °F	Recorder TC 5	250.0	247 to 253	250	250
0.3 °F	Recorder TC 5	500.0	497 to 503	500	500
0.3 °F	Recorder TC 5	1000.0	997 to 1003	1000	1000
0.3 °F	Recorder TC 5	1500.0	1497 to 1503	1500	1500
0.3 °F	Recorder TC 6	250.0	247 to 253	250	250
0.3 °F	Recorder TC 6	500.0	497 to 503	500	500
0.3 °F	Recorder TC 6	1000.0	997 to 1003	999	999
0.3 °F	Recorder TC 6	1500.0	1497 to 1503	1500	1500

* Indicates out of tolerance readings.

Remarks: Measurement Uncertainty reported at coverage factor K = 2 or 95% confidence level.



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Customer: ATS Materials Testing Purchase Order No.: N/A
Item Name: Heat Treat Console Asset No.: ATS-02408 ATS Reference No.: N/A
Manufacturer: Mannings USA Model No.: 16126 Proc. No.: 1013 Rev.: 2
Serial No.: 072991 Calibration Date: 06-06-07 Calibration Due Date: 12-06-07

Customer Instrument Under Test

UNCERTAINTY (SEE NOTE)	FUNCTION AND RANGE	APPLIED	TOLERANCE	AS FOUND READING	AS CALIBRATED READING
0.3 °F	Recorder TC 7	250.0	247 to 253	250	250
0.3 °F	Recorder TC 7	500.0	497 to 503	500	500
0.3 °F	Recorder TC 7	1000.0	997 to 1003	1001	1001
0.3 °F	Recorder TC 7	1500.0	1497 to 1503	1501	1501
0.3 °F	Recorder TC 8	250.0	247 to 253	250	250
0.3 °F	Recorder TC 8	500.0	497 to 503	500	500
0.3 °F	Recorder TC 8	1000.0	997 to 1003	1000	1000
0.3 °F	Recorder TC 8	1500.0	1497 to 1503	1500	1500
0.3 °F	Recorder TC 9	250.0	247 to 253	250	250
0.3 °F	Recorder TC 9	500.0	497 to 503	500	500
0.3 °F	Recorder TC 9	1000.0	997 to 1003	999	999
0.3 °F	Recorder TC 9	1500.0	1497 to 1503	1500	1500
0.3 °F	Recorder TC 10	250.0	247 to 253	250	250
0.3 °F	Recorder TC 10	500.0	497 to 503	500	500
0.3 °F	Recorder TC 10	1000.0	997 to 1003	1000	1000
0.3 °F	Recorder TC 10	1500.0	1497 to 1503	1500	1500
0.3 °F	Recorder TC 11	250.0	247 to 253	250	250
0.3 °F	Recorder TC 11	500.0	497 to 503	500	500
0.3 °F	Recorder TC 11	1000.0	997 to 1003	1000	1000
0.3 °F	Recorder TC 11	1500.0	1497 to 1503	1500	1500
0.3 °F	Recorder TC 12	250.0	247 to 253	250	250
0.3 °F	Recorder TC 12	500.0	497 to 503	500	500
0.3 °F	Recorder TC 12	1000.0	997 to 1003	1000	1000
0.3 °F	Recorder TC 12	1500.0	1497 to 1503	1500	1500

* Indicates out of tolerance readings.

Remarks: Measurement Uncertainty reported at coverage factor K = 2 or 95% confidence level.

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Appendix 2: Test Procedure**LEAK TEST PROCEDURE**

For H-309352 (Latest Revision) & H-309353 (Latest Revision) Test Coupons

1. SCOPE

- 1.1. This specification defines the requirements for AOS Package Cask Seal Testing, metallic and elastomeric materials.
- 1.2. The test must be completed by a Garlock Helicoflex approved testing facility.
- 1.3. Applicable Drawings & Specifications.
 - 1.3.1. Garlock Helicoflex Drawings
 - 1.3.1.1.H-309352 Latest Revision
 - 1.3.1.2.H-309353 Latest Revision
 - 1.3.2. Specifications:
 - 1.3.2.1.GE Specification 22A9424, "AOS Packages Cask Seals, Metallic and Elastomeric materials."
- 1.4. Responsibility
 - 1.4.1. The GHx is Responsible for compliance with all the requirements set forth in the specification. Deviation from this specification shall be acceptable only with the written approval of the GE.

2. REQUIREMENTS

- 2.1. Quality Assurance
- 2.2. Service Requirements
- 2.3. Material
 - 2.3.1. The materials for each component shall be in accordance with the requirements specified on the fabrication drawing.

3. TEST for H-309352 Latest Revision (Metal)

- 3.1. Coupons
 - 3.1.1. The coupon for the metal seal will be H-309646 Latest Revision. The materials used in the construction of the seal must be the *same heat lots as that of H-309352 latest revision.*
- 3.2. Test Fixture and Installation
 - 3.2.1. The test fixture will conform to the drawing in Appendix A.
 - 3.2.2. Clean groove cavity with IPA and lint free towels.
 - 3.2.3. Install Seal into groove cavity.
 - 3.2.4. Torque bolts in star pattern. Torque guideline is 24 ft-lbs. Apply 7 ft-lbs in first pass, 16 ft-lbs in second pass, and 22 ft-lbs in 3rd pass. Make one complete revolution of the bolt circle at 24 ft-lbs to ensure even application.

3.3. Test Setup

- 3.3.1. The test equipment shall be setup as required in Appendix B.

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3.4. The tests are designed to establish leak tight capability of the seal in an environment ranging from -40 °F to 800 °F with a pressure differential ranging from 1 to 2 atmospheres.

3.4.1. Qualification tests shall be performed and the results recorded on the Seal Environment Test Record found in Appendix C. Tests should be conducted for the required test duration as required by the following environmental conditions:

3.4.1.1. NORMAL Environment

Temperature 70 °F (±5 °F)
Pressure 30 psi (±1 psi) across seal
Media Helium
Test Duration 3 to 5 minutes
Pass Fail Condition: 2.0×10^{-7} cc/sec He @ -77° F

3.4.1.2. HOT Environment

Temperature 800 °F (±5 °F)
Pressure 15 psi (±1 psi) across seal
Media Helium
Test Duration 3 to 5 minutes
Pass Fail Condition: 3.1×10^{-7} cc/sec He @ 800° F

3.4.1.3. COLD Environment

Temperature -40 °F (±10 °F)
Pressure 15 psi (±1 psi) across seal
Media Helium
Test Duration 3 to 5 minutes
Pass Fail Condition: 2.4×10^{-7} cc/sec He @ -40° F

4. TEST for H-309353 Latest Revision (Elastomer)

4.1. Coupons

4.1.1. The coupon for the elastomer seal will be H-309353-5 Latest Revision. O-Ring may be spliced and vulcanized. O-Ring must be *from the same lot of material as supplied for Assembly H-309353 latest revision.*

4.2. Test Fixture

4.2.1. The test fixture will conform to the drawing in Appendix A.

4.2.2. Clean groove cavity with IPA and lint free towels.

4.2.3. Install Seal into groove cavity.

4.2.4. Torque bolts in star pattern. Torque guideline is 18 ft-lbs. Apply 6 ft-lbs in first pass, 10 ft-lbs in second pass, and 16 ft-lbs in 3rd pass. Make one complete revolution of the bolt circle at 18 ft-lbs to ensure even application.

4.3. Test Setup

4.3.1. The test equipment shall be setup as required in Appendix B.

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4.4. The tests are designed to establish leak tight capability of the seal in an environment ranging from -40 °F to 400 °F with a pressure differential ranging from 1 to 2 atmospheres.

4.4.1. Qualification tests shall be performed and the results recorded on the Seal Environment Test Record found in Appendix B. Tests should be conducted for the required test duration as required by the following environmental conditions:

4.4.1.1. NORMAL Environment

Temperature 70 °F (±5 °F)
Pressure 30 psi (±1 psi) across seal
Media Helium
Test Duration 3 to 5 minutes
Pass Fail Condition: 2.0×10^{-7} cc/sec He @ -77° F

4.4.1.2. HOT Environment

Temperature 450 °F (±5 °F)
Pressure 15 psi (±1 psi) across seal
Media Helium
Test Duration 3 to 5 minutes
Pass Fail Condition: 2.6×10^{-7} cc/sec He @ 400° F

4.4.1.3. COLD Environment

Temperature -40 °F (±10 °F)
Pressure 15 psi (±1 psi) across seal
Media Helium
Test Duration 3 to 5 minutes
Pass Fail Condition: 2.4×10^{-7} cc/sec He @ -40° F

Reviewed and Approved:

Kevin Ezell
Sr. Applications Engineer

Date:

Jim Powell
Quality Assurance Manager

Date:



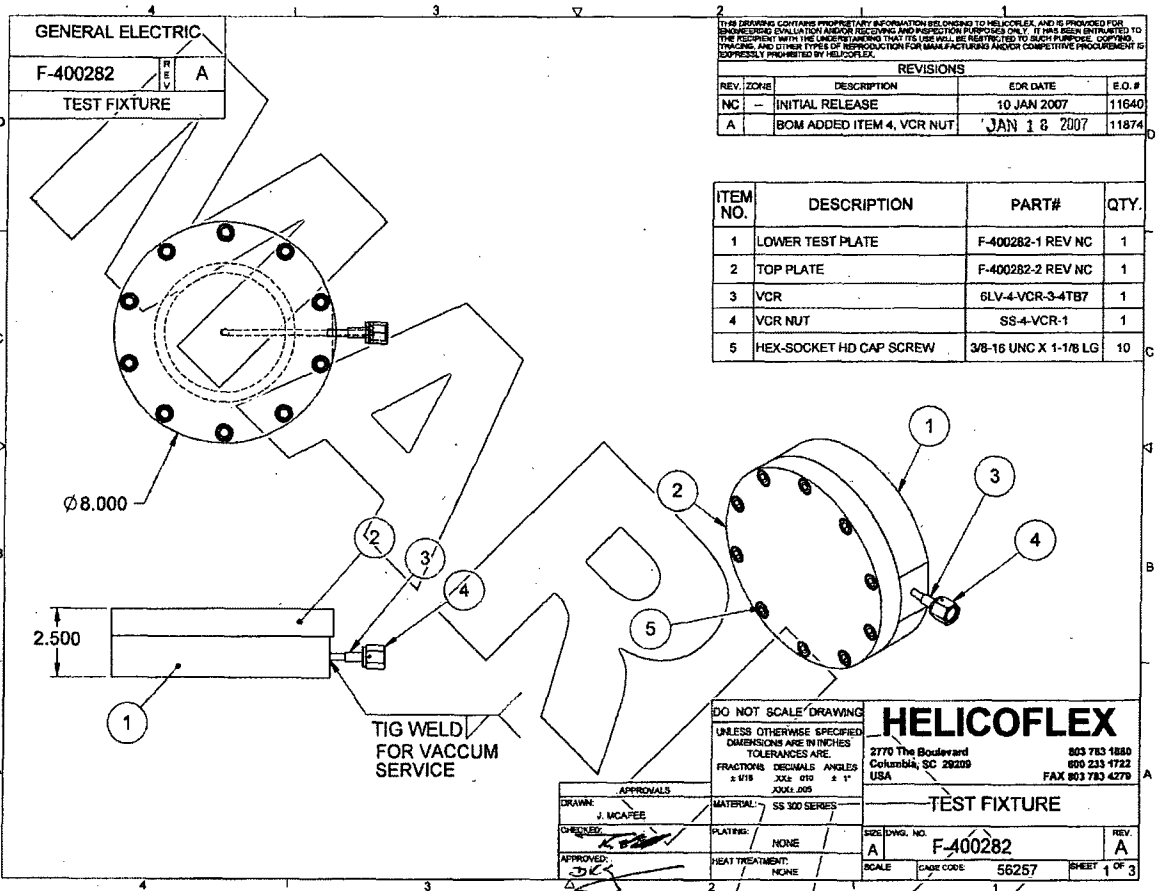
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APPENDIX A: Test Flange



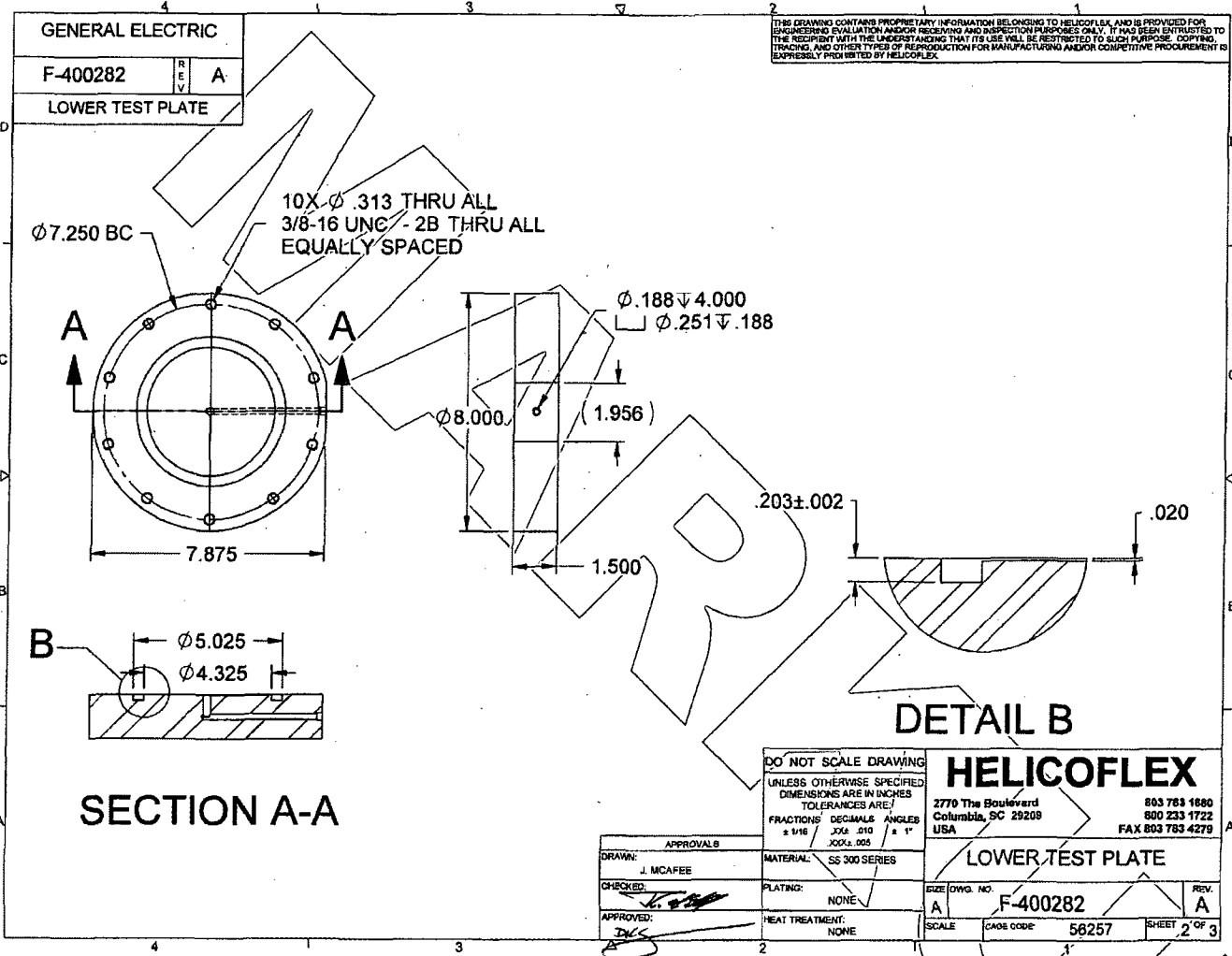


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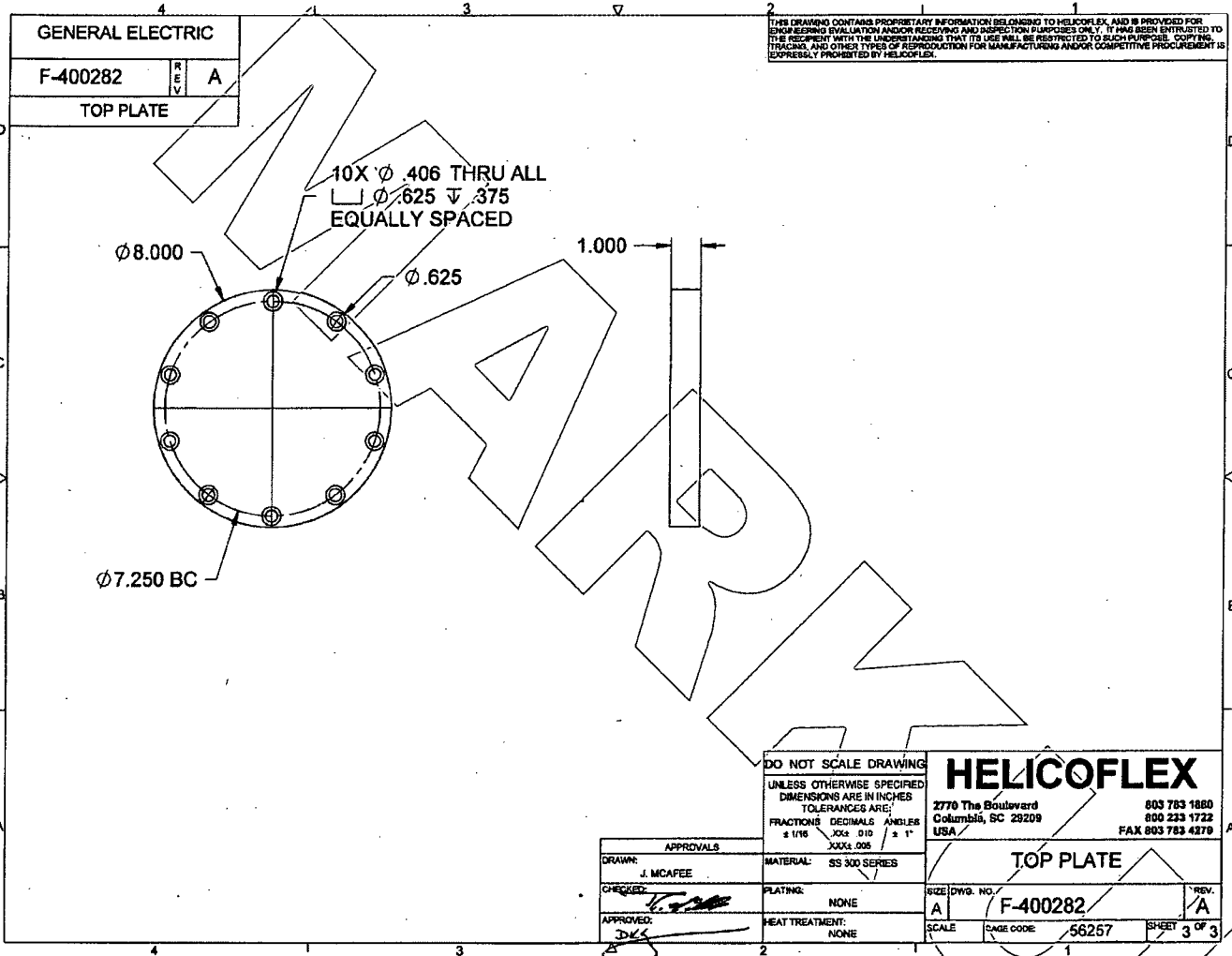
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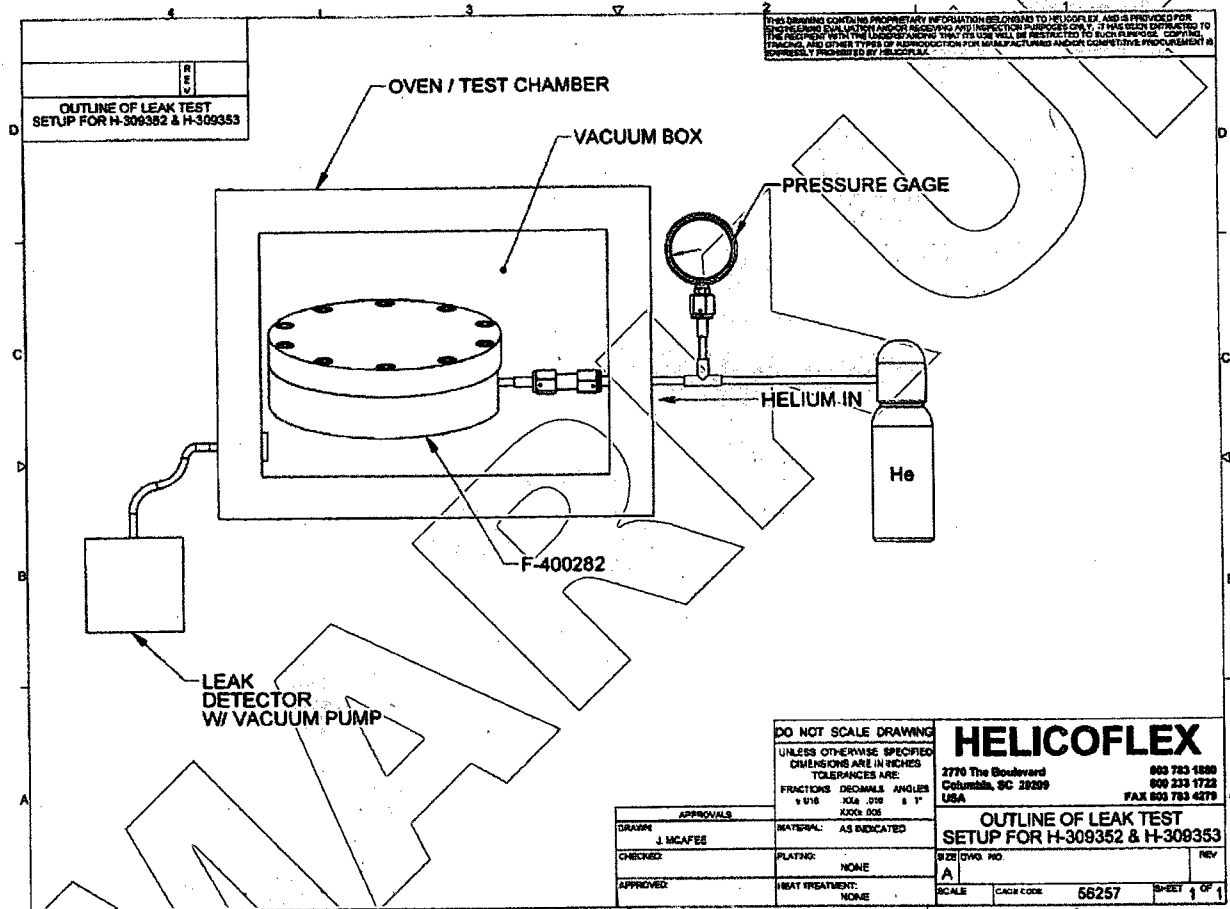
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Appendix B: Test Setup Diagram



4.5.2 Analysis of Cask Closure Bolts by NUREG/CR-6007

PROGRAM MAIN

ANALYSIS OF CASK CLOSURE BOLTS BY NUREG/CR-6007

***** DEFINITION OF VARIABLES *****

AB - COEFFICIENT OF THERMAL EXPANSION FOR BOLT
AC - COEFFICIENT OF THERMAL EXPANSION FOR CASK WALL
ACCI - IMPACT ACCELERATION DUE TO CG/CORNER DROP
AL - COEFFICIENT OF THERMAL EXPANSION FOR LID
AVA - AXIAL VIBRATION ACCELERATION
AVT - TRANSVERSE VIBRATION ACCELERATION
ACCI - IMPACT ACCELERATION DUE TO CG/CORNER DROP
BCF - BOLT CLAMPING FORCE
BD - BOLT DISPLACEMENT
BL - BOLT LENGTH
BXA - BOLT X-SECTION AREA
CET - CODE EVALUATION TYPE: 1-NORMAL, 2-ACCIDENT
DB - NOMINAL BOLT DIAMETER
DLB - LID DIAMETER AT BOLT CIRCLE
DLI - LID DIAMETER AT INNER EDGE
DLO - LID DIAMETER AT OUTER EDGE
DPNB - DOUBLE PRECISION VALUE OF NB
DYLF - DYNAMIC LOAD FACTOR (1.0-1.5)
DLG - LID DIAMETER AT GASKET
EB - YOUNG'S MODULUS FOR BOLT
EC - YOUNG'S MODULUS FOR CASK
EL - YOUNG'S MODULUS FOR LID
ELF - YOUNG'S MODULUS FOR LID FLANGE
FA_i - BOLT TENSILE FORCE
FCF - FLANGE COEFFICIENT OF FRICTION
FF_i - LID EDGE FORCE
FS_i - BOLT SHEAR FORCE
FSO - FATIGUE STRESS FOR OPERATING CONDITIONS
FSV - FATIGUE STRESS FOR VIBRATIONS
GB - GASKET SEATING WIDTH (ASME BPV CODE, SECT III, APP E)
GM - GASKET FACTOR (ASME BPV CODE, SECT III, APP E)
GY - GASKET SEATING STRESS (ASME BPV CODE, SECT III, APP E)
MF_i - LID EDGE MOMENT
NB - NUMBER OF BOLTS
NTI - NUMBER OF BOLT THREADS / IN
PCI - INSIDE PRESSURE AT CASK WALL
PCO - OUTSIDE PRESSURE AT CASK WALL
PLI - INSIDE PRESSURE AT LID
PLO - OUTSIDE PRESSURE AT LID
PUNC - PUNCTURE LOAD
Q - PRELOAD TORQUE
QK - NUT FACTOR FOR PRELOAD TORQUE
SM - Sm STRESS

```

C      SY      - Sy STRESS
C      Su      - Su STRESS
C      TC      - THICKNESS OF CASK WALL
C      TEMPB   - TEMPERATURE CHANGE ACROSS BOLT
C      TEMPC   - TEMPERATURE CHANGE ACROSS CASK WALL
C      TEMPL   - TEMPERATURE CHANGE ACROSS LID
C      TEMPLI  - TEMPERATURE AT INSIDE OF LID
C      TEMPLO  - TEMPERATURE AT OUTSIDE OF LID
C      TL      - THICKNESS OF LID
C      TLF     - THICKNESS OF LID FLANGE
C      TM_i    - BOLT TORSIONAL MOMENT
C      VTR     - VIBRATION TRANSMISSIBILITY FACTOR BETWEEN SUPPORT & CASK
C      WC      - WEIGHT OF CASK CONTENTS
C      WCK     - TOTAL WEIGHT OF CASK
C      WL      - WEIGHT OF CASK LID
C      XIB     - BOLTS AREA MOMENT OF INERTIA / CIRCUMFERENCE OF BOLT CIRCLE
C      XI_DROP - ANGLE OF IMPACT (DEGREES) FOR DROP
C      XI_PUNC - ANGLE OF IMPACT (DEGREES) FOR PUNCTURE
C      XNUC    - POISSON'S RATIO FOR CASK
C      XNUL    - POISSON'S RATION FOR LID
C
C      IMPLICIT REAL*8(A-H,O-Z)
C      CHARACTER*80 TITLE
C
C      OPEN INPUT/OUTPUT FILES
C
C      OPEN(5,FILE='CASKBOLT.DAT')
C      OPEN(6,FILE='CASKBOLT.OUT')
C      OPEN(1,FILE='TEMP.DAT')
C
C      READ & ECHO DATA
C
C      READ(5,'(A)') TITLE
C      WRITE(6,'(//,A,//)') TITLE
C      WRITE(6,'(//,44H ***** INPUT DATA *****)' )
C
C      CALL DATA(DPNB)
C      NB=INT(DPNB)
C      CALL DATA(DLB )
C      CALL DATA(DLG )
C      CALL DATA(DB  )
C      CALL DATA(DLI )
C      CALL DATA(DLO )
C      CALL DATA(TL  )
C      CALL DATA(TLF )
C      CALL DATA(TC  )
C      CALL DATA(BL  )
C      CALL DATA(XIB )
C
C      WRITE(6,'(1H)')
C      WRITE(6,10) NB,DLB,DLG,DB,DLI,DLO,TL,TLF,TC,BL,XIB

```

```

10 FORMAT(43H NUMBER OF BOLTS .....(NB),I12 ,/,
.      43H LID DIAMETER AT BOLT CIRCLE .....(DLB),E12.5,/,
.      43H LID DIAMETER AT GASKET .....(DLG),E12.5,/,
.      43H NOMINAL BOLT DIAMETER .....(DB),E12.5,/,
.      43H LID DIAMETER AT INNER EDGE .....(DLI),E12.5,/,
.      43H LID DIAMETER AT OUTER EDGE .....(DLO),E12.5,/,
.      43H THICKNESS OF LID .....(TL),E12.5,/,
.      43H THICKNESS OF LID FLANGE .....(TLF),E12.5,/,
.      43H THICKNESS OF CASK WALL .....(TC),E12.5,/,
.      43H BOLT LENGTH .....(BL),E12.5,/,
.      43H BOLT MOMENT OF INERTIA / CIR .....(XIB),E12.5

```

C

```

CALL DATA(EL )
CALL DATA(ELF )
CALL DATA(EC )
CALL DATA(EB )
CALL DATA(XNUL)
CALL DATA(XNUC)
CALL DATA(AL )
CALL DATA(AB )
CALL DATA(AC )
CALL DATA(FCF )

```

C

```

WRITE(6, '(1H ) ')
WRITE(6,20) EL,ELF,EC,EB,XNUL,XNUC,AL,AB,AC,FCF
20 FORMAT(43H YOUNG'S MODULUS FOR LID .....(EL),E12.5,/,
.      43H YOUNG'S MODULUS FOR LID FLANGE .....(ELF),E12.5,/,
.      43H YOUNG'S MODULUS FOR CASK .....(EC),E12.5,/,
.      43H YOUNG'S MODULUS FOR BOLT .....(EB),E12.5,/,
.      43H POISSON'S RATIO FOR LID .....(XNUL),E12.5,/,
.      43H POISSON'S RATIO FOR CASK .....(XNUC),E12.5,/,
.      43H LID THERMAL EXPANSION COEFF .....(AL),E12.5,/,
.      43H BOLT THERMAL EXPANSION COEFF .....(AB),E12.5,/,
.      43H WALL THERMAL EXPANSION COEFF .....(AC),E12.5,/,
.      43H FLANGE COEFFICIENT OF FRICTION .....(FCF),E12.5

```

C

```

CALL DATA(PLI)
CALL DATA(PLO)
CALL DATA(PCI)
CALL DATA(PCO)

```

C

```

WRITE(6, '(1H ) ')
WRITE(6,40) PLI,PLO,PCI,PCO
40 FORMAT(43H INSIDE PRESSURE AT LID .....(PLI),E12.5,/,
.      43H OUTSIDE PRESSURE AT LID .....(PLO),E12.5,/,
.      43H INSIDE PRESSURE AT CASK WALL .....(PCI),E12.5,/,
.      43H OUTSIDE PRESSURE AT CASK WALL .....(PCO),E12.5

```

C

```

CALL DATA(TEMPL )
CALL DATA(TEMPB )
CALL DATA(TEMPC )
CALL DATA(TEMPLO)
CALL DATA(TEMPLI)

```

C

```

WRITE(6, '(1H)')
WRITE(6,50)  TEMPL,TEMPB,TEMPC,TEMPLO,TEMPLI
50 FORMAT(43H TEMPERATURE CHG ACROSS LID .....(TEMPL),E12.5,/,
.         43H TEMPERATURE CHG ACROSS BOLT .....(TEMPB),E12.5,/,
.         43H TEMPERATURE CHG ACROSS WALL .....(TEMPC),E12.5,/,
.         43H TEMPERATURE AT OUTSIDE OF LID ....(TEMPLO),E12.5,/,
.         43H TEMPERATURE AT INSIDE OF LID .....(TEMPLI),E12.5  )

C

CALL DATA(WC      )
CALL DATA(WL      )
CALL DATA(XI_DROP)
CALL DATA(ACCI    )
CALL DATA(DYLF    )

C

WRITE(6, '(1H)')
WRITE(6,60)  WC,WL,XI_DROP,ACCI,DYLF
60 FORMAT(43H WEIGHT OF CASK CONTENTS .....(WC),E12.5,/,
.         43H WEIGHT OF CASK LID .....(WL),E12.5,/,
.         43H DROP ANGLE OF IMPACT, deg .....(XI_DROP),E12.5,/,
.         43H CG/CORNER IMPACT ACCEL, g .....(ACCI),E12.5,/,
.         43H DYNAMIC LOAD FACTOR .....(DYLF),E12.5  )

C

CALL DATA(PUNC    )
CALL DATA(XI_PUNC)

C

WRITE(6, '(1H)')
WRITE(6,70)  PUNC,XI_PUNC
70 FORMAT(43H PUNCTURE LOAD .....(PUNC),E12.5,/,
.         43H PUNCTURE ANGLE OF IMPACT, deg ... (XI_PUNC),E12.5  )

C

CALL DATA(AVA)
CALL DATA(AVT)
CALL DATA(VTR)

C

WRITE(6, '(1H)')
WRITE(6,80)  AVA,AVT,VTR
80 FORMAT(43H AXIAL VIBRATION ACCELERATION .....(AVA),E12.5,/,
.         43H TRANSVERSE VIBRATION ACCELERATION ... (AVT),E12.5,/,
.         43H VIBRATION TRANSMISSIBILITY FACTOR ... (VTR),E12.5  )

C

CALL DATA(Q      )
CALL DATA(QK     )
CALL DATA(GB     )
CALL DATA(GY     )
CALL DATA(GM     )

C

WRITE(6, '(1H)')
WRITE(6,90)  Q,QK,GB,GY,GM
90 FORMAT(43H PRELOAD TORQUE .....(Q),E12.5,/,
.         43H NUT FACTOR FOR PRELOAD TORQUE .....(QK),E12.5,/,
.         43H GASKET SEATING WIDTH .....(GB),E12.5,/,
.         43H GASKET SEATING STRESS .....(GY),E12.5,/,
.         43H GASKET FACTOR .....(GM),E12.5  )

C

```

```

CALL DATA(SM )
CALL DATA(SY )
CALL DATA(SU )
CALL DATA(CET)
ICET=INT(CET)
C
WRITE(6,'(1H)')
WRITE(6,93) SM,SY,SU,ICET
93 FORMAT(43H Sm STRESS .....(SM),E12.5,/,
.      43H Sy STRESS .....(SY),E12.5,/,
.      43H Su STRESS .....(SU),E12.5,/,
.      43H CODE EVALUATION TYPE.....(CET),I12)
C
CALL DATA(FSO)
CALL DATA(FSV)
CALL DATA(XTI)
NTI=INT(XTI)
C
WRITE(6,'(1H)')
WRITE(6,92) FSO,FSV,NTI
92 FORMAT(43H OPERATING FATIGUE STRESS (ksi) .....(FSO),E12.5,/,
.      43H VIBRATION FATIGUE STRESS (ksi) .....(FSV),E12.5,/,
.      43H NUMBER OF BOLT THREADS / INCH .....(NTI),I12)
N=0
C
100 CONTINUE
IF(N.NE.0) THEN
WRITE(*,110) N
110 FORMAT(///,' ERROR IN INPUT DATA LINE',I3,///)
STOP
ENDIF
C
C
C FORCES & MOMENT DUE TO PRESSURE (TABLE 4.3)
C
PIE = 3.141592654
FA_1 = PIE*DLG**2*(PLI-PLO)/(4*DPNB)
FS_1 = PIE*EL*TL*(PCI-PLO)*DLB**2/(2*DPNB*EC*TC*(1.0-XNUL))
FF_1 = DLB*(PLI-PLO)/4.0
FM_1 = (PLI-PLO)*DLB**2/32.0
C
WRITE(6,'(///) 41H ***** BOLT LOADS & STRESSES *****')
WRITE(6,'(//)')
WRITE(6,'(43H BOLT FORCES DUE TO PRESSURE, TABLE 4.3)')
WRITE(6,120)
120 FORMAT(52H -----)
WRITE(6,'(37H AXIAL LOAD DUE TO PRESSURE.....,E15.5)') FA_1
WRITE(6,'(37H SHEAR LOAD DUE TO PRESSURE.....,E15.5)') FS_1
WRITE(6,'(37H EDGE LOAD DUE TO PRESSURE.....,E15.5)') FF_1
WRITE(6,'(37H EDGE MOMENT DUE TO PRESSURE.....,E15.5)') FM_1
C
C
C FORCES & MOMENT DUE TO TEMPERATURE (TABLE 4.4)
C

```

```

FA_2 = 0.25*PIE*DB**2*EB*(AL*TEMPL-AB*TEMPB)
FS_2 = PIE*EL*TLF*DLB*(AL*TEMPL-AC*TEMPC)/(NB*(1.0-XNUL))
FF_2 = 0.0
FM_2 = EL*AL*TL**2*(TEMPLO-TEMPLI)/(12.0*(1.0-XNUL))

```

C

```

WRITE(6,'(//)')
WRITE(6,'(43H BOLT FORCES DUE TO TEMPERATURE, TABLE 4.4)')
WRITE(6,120)
WRITE(6,'(37H AXIAL LOAD DUE TO TEMPERATURE.....,E15.5)') FA_2
WRITE(6,'(37H SHEAR LOAD DUE TO TEMPERATURE.....,E15.5)') FS_2
WRITE(6,'(37H EDGE LOAD DUE TO TEMPERATURE.....,E15.5)') FF_2
WRITE(6,'(37H EDGE MOMENT DUE TEMPERATURE.....,E15.5)') FM_2

```

C

C

C

C

FORCES & MOMENT DUE TO CG/CORNER IMPACT (TABLE 4.5)

```

XI = XI_DROP*PIE/180.0
FA_3 = 1.34*DSIN(XI)*DYLF*ACCI*(WL+WC)/DPNB
FS_3 = DCOS(XI)*ACCI*WL/DPNB
FF_3 = 1.34*DSIN(XI)*DYLF*ACCI*(WL+WC)/(PIE*DLB)
FM_3 = 1.34*DSIN(XI)*DYLF*ACCI*(WL+WC)/(8.0*PIE)

```

C

```

WRITE(6,'(//)')
WRITE(6,'(43H BOLT FORCES DUE TO IMPACT, TABLE 4.5)')
WRITE(6,120)
WRITE(6,'(37H AXIAL LOAD DUE TO IMPACT.....,E15.5)') FA_3
WRITE(6,'(37H SHEAR LOAD DUE TO IMPACT.....,E15.5)') FS_3
WRITE(6,'(37H EDGE LOAD DUE TO IMPACT.....,E15.5)') FF_3
WRITE(6,'(37H EDGE MOMENT DUE IMPACT.....,E15.5)') FM_3

```

C

C

C

C

FORCES & MOMENT DUE TO PUNCTURE LOAD (TABLE 4.7)

```

XI = XI_PUNC*PIE/180.0
FA_4 = -DSIN(XI)*PUNC/DPNB
FS_4 = DCOS(XI)*PUNC/DPNB
FF_4 = -DSIN(XI)*PUNC/(PIE*DLB)
FM_4 = -DSIN(XI)*PUNC/(4.0*PIE)

```

C

```

WRITE(6,'(//)')
WRITE(6,'(43H BOLT FORCES DUE TO PUNCTURE, TABLE 4.7)')
WRITE(6,120)
WRITE(6,'(37H AXIAL LOAD DUE TO PUNCTURE.....,E15.5)') FA_4
WRITE(6,'(37H SHEAR LOAD DUE TO PUNCTURE.....,E15.5)') FS_4
WRITE(6,'(37H EDGE LOAD DUE TO PUNCTURE.....,E15.5)') FF_4
WRITE(6,'(37H EDGE MOMENT DUE PUNCTURE.....,E15.5)') FM_4

```

C

C

C

C

FORCES & MOMENT DUE TO VIBRATION LOAD (TABLE 4.8)

```

FA_5 = VTR*AVA*WL/DPNB
FS_5 = VTR*AVT*WL/DPNB
FF_5 = VTR*AVA*WL/(PIE*DLB)
FM_5 = VTR*AVA*WL/(8.0*PIE)

```



```

C
WRITE(6,'(//)')
WRITE(6,'(43H BOLT FORCES DUE TO VIBRATION, TABLE 4.8  )')
WRITE(6,120)
WRITE(6,'(37H AXIAL LOAD DUE TO VIBRATION.....,E15.5)') FA_5
WRITE(6,'(37H SHEAR LOAD DUE TO VIBRATION.....,E15.5)') FS_5
WRITE(6,'(37H EDGE LOAD DUE TO VIBRATION.....,E15.5)') FF_5
WRITE(6,'(37H EDGE MOMENT DUE VIBRATION.....,E15.5)') FM_5

C
C
C
FORCES & TORQUES DUE TO PRELOAD TORQING (TABLES 4.1 & 4.2)
C

FA_6 = Q/(QK*DB)
TM_6 = 0.5*Q
FA_7 = PIE*DLG*GB*GY/DPNB
TM_7 = 0.5*PIE*QK*DB*DLG*GB*GY/DPNB
FA_8 = 2.0*PIE*DLG*GB*GM*(PLI-PLO)/DPNB

C
WRITE(6,'(//)')
WRITE(6,'(43H BOLT FORCES DUE TO PRELOAD, TABLE 4.1, 4.2)')
WRITE(6,120)
WRITE(6,'(37H AXIAL LOAD DUE TO PRELOAD.....,E15.5)') FA_6
WRITE(6,'(37H AXIAL LOAD DUE TO GASKET SEATING.....,E15.5)') FA_7
WRITE(6,'(37H AXIAL LOAD DUE TO GASKET OPERATION.....,E15.5)') FA_8
WRITE(6,'(37H TORQUE DUE TO PRELOAD.....,E15.5)') TM_6
WRITE(6,'(37H TORQUE DUE TO GASKET.....,E15.5)') TM_7

C
C
C
TENSILE BOLT FORCE (TABLE 4.9)
C

FA = FA_1 + FA_2 + FA_3 + FA_4 + FA_5 + FA_6 + FA_8
FA_PT = FA_2 + FA_6
FA_AL = FA_1 + FA_3 + FA_4 + FA_5 + FA_8

C
WRITE(6,'(//)')
WRITE(6,'(43H TOTAL NON-PRYING BOLT FORCES, TABLE 4.9  )')
WRITE(6,120)
WRITE(6,'(37H TOTAL NON-PRYING AXIAL LOAD.....,E15.5)') FA
WRITE(6,'(37H TEMP & PRELOAD NON-PRYING AXIAL LD.,E15.5)') FA_PT
WRITE(6,'(37H AXIAL LOAD LESS TEMP & PRELOAD.....,E15.5)') FA_AL

C
IF(FA_PT .GE. FA_AL) THEN
FA_C = FA_PT
ELSE
FA_C = FA_AL
ENDIF
IF(FA_C .LT. 0.0) FA_C=0.0

C
FF_C = FF_1 + FF_2 + FF_3 + FF_4 + FF_5
FM_C = FM_1 + FM_2 + FM_3 + FM_4 + FM_5

C
WRITE(6,'(37H TOTAL EDGE LOAD.....,E15.5)') FF_C
WRITE(6,'(37H TOTAL EDGE MOMENT.....,E15.5)') FM_C

C

```

```

C
C   PRYING TENSILE BOLT FORCE (TABLES 2.1 & 2.2)
C
C   C1 = 1.0
C   C2 = ( 8.0/(3.0*(DLO-DLB)**2) )
C       *( EL*TL**3/(1.0-XNUL) + (DLO-DLI)*ELF*TLF**3/DLB )
C       *( BL/(DPNB*DB**2*EB) )
C
C   B = FA_PT
C   IF(FF_C .GT. FA_PT) B = FF_C
C
C   FAP_C = (PIE*DLB/DPNB)
C       *( 2.0*FM_C/(DLO-DLB) - C1*(B - FF_C) - C2*(B - FA_PT) )
C       /(C1 + C2)
C
C   XKB = (DPNB/BL)*(EB/DLB)*(DB**4/64.0)
C   XKI = EL*TL**3/
C       ( 3.0*DLB*(1.0-XNUL**2) + (1.0-XNUL)**2*(DLB/DLO)**2 )
C
C   BMB = (PIE*DLB/DPNB)*(XKB/(XKB+XKI))*FM_C
C
C   WRITE(6,'(//)')
C   WRITE(6,'(43H PRYING ACTION FORCES, TABLE 2.1 & 2.2      )')
C   WRITE(6,120)
C   WRITE(6,'(37H AXIAL LOAD DUE TO PRYING.....,E15.5)') FAP_C
C   WRITE(6,'(37H BENDING MOMENT DUE TO PRYING.....,E15.5)') BMB
C
C
C   TOTAL BOLT LOADS
C
C   FAT - TOTAL BOLT AXIAL LOAD
C   FST - TOTAL BOLT SHEAR LOAD
C   BMT - TOTAL BOLT BENDING MOMENT
C   BTT - TOTAL BOLT TORSIONAL MOMENT
C
C   FAT = FA_C + FAP_C
C   FST = FS_1 + FS_2 + FS_3 + FS_4 + FS_5
C   BMT = FM_C + BMB
C   BTT = TM_6
C
C   WRITE(6,'(//)')
C   WRITE(6,'(43H TOTAL BOLT FORCES                          )')
C   WRITE(6,120)
C   WRITE(6,'(37H TOTAL BOLT AXIAL LOAD.....,E15.5)') FAT
C   WRITE(6,'(37H TOTAL BOLT SHEAR LOAD.....,E15.5)') FST
C   WRITE(6,'(37H TOTAL BOLT BENDING MOMENT.....,E15.5)') BMT
C   WRITE(6,'(37H TOTAL BOLT TORSIONAL MOMENT.....,E15.5)') BTT
C
C
C   BOLT STRESSES
C
C   DBA=DB-0.9743/DBLE(NTI)
C   BXA=PIE*(DBA/2)**2

```

```

XI=PIE*DBA**3/32
XJ=PIE*DBA**3/16
SIG_A0=FAT/BXA
SIG_A1=SIG_A0+BMT/XI
SIG_A2=SIG_A0-BMT/XI
SIG_A=SIG_A1
IF(SIG_A2 .GT. SIG_A) SIG_A=SIG_A2
SIG_S =DABS(FST/BXA)+DABS(BTT/XJ)
SIG_S0=DABS(FST/BXA)+DABS(BTT/XJ)/2

```

C

```

WRITE(6,'(//)')
WRITE(6,'(43H TOTAL BOLT STRESSES )')
WRITE(6,120)
WRITE(6,'(37H TOTAL BOLT DIRECT STRESS (+MC/I) ... ,E15.5)') SIG_A1
WRITE(6,'(37H TOTAL BOLT DIRECT STRESS (-MC/I) ... ,E15.5)') SIG_A2
WRITE(6,'(37H AVE BOLT DIRECT STRESS ..... ,E15.5)') SIG_A0
WRITE(6,'(37H TOTAL BOLT SHEAR STRESS ..... ,E15.5)') SIG_S
WRITE(6,'(37H AVE BOLT SHEAR STRESS ..... ,E15.5)') SIG_S0

```

C

C

C

C

CODE STRESS EVALUATION FOR NORMAL CONDITION (TABLE 6.1)

```

IF(CET.EQ.1) THEN
SM=1000.0*SM
RT=SIG_A0/SM
RS=SIG_S/(0.6*SM)
RC=RT**2 + RS**2
RB=SIG_A/(1.5*SM)
SE=DSQRT(SIG_A**2+4.0*SIG_S**2)
RV=SE/(1.35*SM)

```

C

```

WRITE(6,'(//)')
WRITE(6,'(43H CODE EVALUATION FOR NORMAL COND, TABLE 6.1)')
WRITE(6,120)
WRITE(6,'(37H Rt (AXIAL_STRESS/Sm) ..... ,E15.5)') RT
WRITE(6,'(37H Rs (SHEAR_STRESS/0.6Sm) ..... ,E15.5)') RS
WRITE(6,'(37H Rty+Rsy ..... ,E15.5)') RC
WRITE(6,'(37H VON MISES EQUIVALENT STRESS (Se) ... ,E15.5)') SE
WRITE(6,'(37H Se/1.35Sm ..... ,E15.5)') RV
ENDIF

```

C

C

C

C

CODE STRESS EVALUATION FOR ACCIDENT CONDITION (TABLE 6.3)

```

IF(CET.EQ.2) THEN
SU1=700.0*SU
SY1=1000.0*SY
SA=SU1
IF(SA.GT.SY1) SA=SY
SU1=420*SU
SY1=600*SY
TA=SU1
IF(TA.GT.SY1) TA=SY1
RT=SIG_A0/SA

```

```

RS=SIG_S0/TA
RC=RT**2 + RS**2
C
WRITE(6,'(//)')
WRITE(6,'(43H CODE EVALUAT. FOR ACCIDENT COND, TABLE 6.3)')
WRITE(6,120)
WRITE(6,'(37H ALLOWABLE TENSILE STRESS (Sa) .....E15.5)') SA
WRITE(6,'(37H ALLOWABLE SHEAR STRESS (Ta) .....E15.5)') TA
WRITE(6,'(37H Rt (AVE AXIAL STRESS/Sa) .....E15.5)') RT
WRITE(6,'(37H Rs (AVE SHEAR_STRESS/Ta) .....E15.5)') RS
WRITE(6,'(37H Rtý+Rsý .....E15.5)') RC
ENDIF
C
C
C BOLT CLAMPING FORCE = FA_AL (APPLIED LOADS LESS TEMP LOAD & PRE LOAD)
C + FAP_C (LOAD DUE TO PRYING ACTION)
C - FA_PT (PRE LOAD & TEMP LOAD)
C
BCF = DABS(FA_AL) + DABS(FAP_C) - DABS(FA_PT)
BD = BCF*BL/(BXA*EB)
BDA = 0.003
FF = FCF*BCF
C
WRITE(6,'(//)')
WRITE(6,'(43H FLANGE SEPARATION EVALUATION ..... )')
WRITE(6,120)
WRITE(6,'(37H BOLT CLAMPING FORCE .....E15.5)') BCF
WRITE(6,'(37H DISPLACEMENT ACROSS BOLT .....E15.5)') BD
WRITE(6,'(37H ALLOWABLE FLANGE SEPARATION .....E15.5)') BDA
WRITE(6,'(37H FLANGE FRICTION FORCE .....E15.5)') FF
WRITE(6,'(37H TOTAL BOLT SHEAR FORCE .....E15.5)') FST
C
C
C FATIGUE ANALYSIS
C
IF(CET.EQ.1) THEN
IF(FSQ.GT.0.0 .OR. FSV.GT.0.0) THEN
R1 = SIG_A/(1000.0*ESO)
R2 = (FA_5/BXA)/(1000.0*FSV)
R3 = R1+R2
C
WRITE(6,'(//)')
WRITE(6,'(43H FATIGUE EVALUATION ..... )')
WRITE(6,120)
WRITE(6,'(37H USEAGE FOR NORMAL OPERATION .....E15.5)') R1
WRITE(6,'(37H USEAGE FOR VIBRATION .....E15.5)') R2
WRITE(6,'(37H ACCUMULATIVE FATIGUE USEAGE .....E15.5)') R3
ENDIF
ENDIF
C
C
END
SUBROUTINE DATA(X)
C

```

```
C   READ NEXT DATA ITEM ON INPUT FILE
C
   REAL*8 X
   CHARACTER*80 BUFFER
C
100 CONTINUE
   READ(5, '(A)', ERR=200, END=200) BUFFER
   IF(BUFFER(1:1).EQ.'*') GOTO 100
   BUFFER(1:43)=CHAR(32)
   REWIND 1
   WRITE(1, '(A)') BUFFER
   REWIND 1
   READ(1, *, ERR=100, END=200) X
   RETURN
200 CONTINUE
   WRITE(6, 210)
   STOP
210 FORMAT(// ' ERROR READING INPUT DATA FILE' )
C
   RETURN
   END
```

4.6 REFERENCES

- [4.1] U.S. Nuclear Regulatory Commission (NRC), *Title 10, Code of Federal Regulations, Part 71 (10 CFR 71)*, "Packaging and Transportation of Radioactive Material," January 26, 2004.
- [4.2] ASME, *Boiler Pressure and Vessel Code*, Section III, Division 3, 2004, No Addendums.
- [4.3] *NUREG/CR-6007*, "Stress Analysis of Closure Bolts for Shipping Casks," April, 1992.
- [4.4] American National Standards Institute, *ANSI N14.5-1977*, "Radioactive Materials – Leakage Tests on Packages for Shipment," January 1, 1997.
- [4.5] *Machinery's Handbook*, "Fasteners" Section, Industrial Press, 26th Edition, 1988.

MARKUP