ENERGYSOLUTIONS

June 11, 2009
E&L-062-09

Michele M. Sampson, Senior Project Manager
Licensing Section
Division of Fuel Storage and Transportation
Office of Nuclear Material Safety and Safeguards
U.S. Nuclear Regulatory Commission
Washington, DC 20555

Dear Ms. Sampson:

Subject: Response to THIRD ROUND REQUEST FOR ADDITIONAL INFORMATION FOR REVIEW OF THE MODEL NO. 10-160B (Docket No. 71-9204 TAC No. L24162)

Energy*Solutions* provides our response to the 3rd request for additional information dated May 27, 2009. As noted in the response (Attachment 1), responding to the questions required revision to Chapter 3 of the SAR. The revised Chapter is provided as Attachment 2. The revised supplemental 2-D analysis is Attachment 3 and a DVD containing the analysis files is Attachment 4.

The four attachments to this letter are listed below:

Attachment 1 Response to the request, the NRC question is followed by our response.

Attachment 2 Revised SAR Chapter; please replace the previously provided Chapter 3 with the Chapter 3 in this attachment.

Attachment 3 2-D Thermal Analysis

Attachment 4 DVD with Thermal Analysis input and output files

Should you or members of your staff have questions about the responses, please contact Mark Whittaker at (803) 758-1898.

Sincerely,

Mirza I. Baig
Technical Services Manager – Engineering & Licensing

Attachments: As stated

Attachment 1
Response to RAI

3-0 THERMAL EVALUATION

3-1 *Revise the 2-D calculation of the package response to the hypothetical accident condition (HAC) fire to apply an average surface absorptivity of 0.8 and an ambient temperature of 1475°F.*

The current analysis assumes the absorptivity and emissivity of the fire shield and the environment are 0.8 and 0.9, respectively, and derived an average emissivity of 0.7347 by the equation in the 2-D model of radiation heat transfer between the fire shield and the environment. The submitted analysis may not adequately treat the radiation heat transfer into the package and does not appear to be compliant with the specific values specified in 10 CFR 71.73.
The requirements of 10 CFR 71.51(a) specify containment and shielding standards for the package under HAC conditions in 10 CFR 71.73. The requirements of 10 CFR 71.73(c)(4) specify a hydrocarbon fuel/air fire with conditions resulting in an average emissivity coefficient of at least 0.9, with an average flame temperature of at least 800°C. For purposes of calculation, the surface absorptivity coefficient must be either that value which the package may be expected to possess if exposed to the fire specified, or 0.8, whichever is greater.

The revised HAC model should apply an average surface absorptivity of at least 0.8 and emissivity of 0.9, as appropriate, with an ambient temperature of 1475°F under a uniform internal heat loading. The response should include a summary of the parameters used in the analysis, and the key component temperatures during the HAC transient, to verify that the performance requirements of 10 CFR Part 71.51 are still met with the application of the specific regulatory values in 10 CFR Part 71.73

This information is required to show compliance with 10 CFR 71.33, 71.51, and 71.73.

RESPONSE

The 2-D model has been revised to apply an average surface absorptivity of 1.0 and an emissivity of 0.9, as documented in the revised supplemental 2-d finite element analyses, which is provided as an attachment to the RAI response, along with a DVD of the input and output files. The change resulted in a slight increase in temperatures of the cask components. These increased temperatures have been included in a revised Chapter 3 of the SAR, which is also attached. The increased temperatures are less than the conservative assumed temperatures that were used in subsequent analyses to demonstrate compliance with regulatory requirements.

Attachment 2
Revised Chapter 3

3. THERMAL EVALUATION

This chapter identifies, describes, discusses, and analyzes the principal thermal engineering design of the 10-160B cask. Compliance with the performance requirements of 10 CFR 71 is demonstrated.

3.1 Discussion

Two components contribute to the thermal protection of the cask body. These components are the impact limiters which provide thermal protection to the top and bottom of the cask and the fire shield which protects the side walls between the impact limiters. The impact limiters are sheet metal enclosures filled with polyurethane foam which acts as an insulation barrier to heat flow. The fire shield is 0.104 inch thick steel plate with a 0.156 inch thick air gap between it and the outer structural shell of the cask. These components reduce the heat load on the cask body during the hypothetical fire accident. Thus, temperatures of the containment and shielding components of the cask are kept within their service limits. Figure 3.1 shows the location of the components considered in the thermal analysis.

Results of the thermal analysis are summarized in Tables 3.1-1 and 3.1-2. Initial conditions and assumptions are listed in Table 3.2.

The results summarized in Tables 3.1-1 and 3.1-2 are discussed in detail in Sections 3.4 and 3.5. The decay heat load assumed for all analyses is 200 watts.

An optional steel insert being installed in the cask will have very minor effects on the calculations performed in this Chapter.

Table 3.1-1
Summary of Thermal Results
Normal Conditions of Transport (NCT)

Quantity	Calculated[1] Value (1-d Model)	Calculated[2] Value (2-d Model)	Maximum Allowable
Maximum temperature difference across the cask body (°F)	0.16	0.2	[3]
Maximum temperature difference across the outer shell (°F)	0.05	0.0	[3]
Maximum temperature difference across the inner shell (°F)	0.03	0.0	[3]
Maximum average wall temperature (°F)	168	173	[3]
Maximum lead temperature (°F)	168	173	622
Maximum cask body temperature (°F)	168	175	[3]
Maximum seal temperature (°F)	-	174	250[4]
Average bulk air temperature (°F)	-	188	[4]
Maximum internal pressure (PSIG)	12.22		[3]

NOTES:
(1) The values presented in these columns are the results obtained from the analyses presented in this chapter.
(2) The values presented in these columns are the results obtained from the supplemental analysis, using 2-d FEM. See Section 3.5.1.3 and Reference 11.
(3) Set by stress considerations.
(4) See Section 3.4.2

Table 3.1-2
Summary of Thermal Results
Hypothetical Accident Conditions (HAC)

Quantity	Calculated(1) Value (1-d Model)	Calculated(2) Value (2-d Model)	Analyzed(3)	Maximum Allowable
Maximum temperature difference across the cask body (°F)	30.3	39.8	45	(4)
Maximum temperature difference across the outer shell (°F)	15.3	20.2	24	(4)
Maximum temperature difference across the inner shell (°F)	1.7	2.3	2	(4)
Maximum average wall temperature (°F)	243	279	334	(4)
Maximum lead temperature (°F)	243	274	335	622
Maximum cask body temperature (°F)	252	289	352	(4)
Maximum seal temperature (°F)	-	164	352	400(5)
Average bulk air temperature (°F)	-	188	200	200
Maximum internal pressure (PSIG)	15.42		94.3(6)	(4)

NOTES:
(1) The values presented in these columns are the results obtained from the analyses presented in this chapter.
(2) The values presented in these columns are the results obtained from the supplemental analysis, using 2-d FEM. See Section 3.5.1.3 and Reference 11.
(3) The values presented in these columns are obtained by conservatively increasing the results from the analyses presented in this chapter.
(4) Set by stress considerations.
(5) See Section 3.5.
(6) See Section 3.5.4

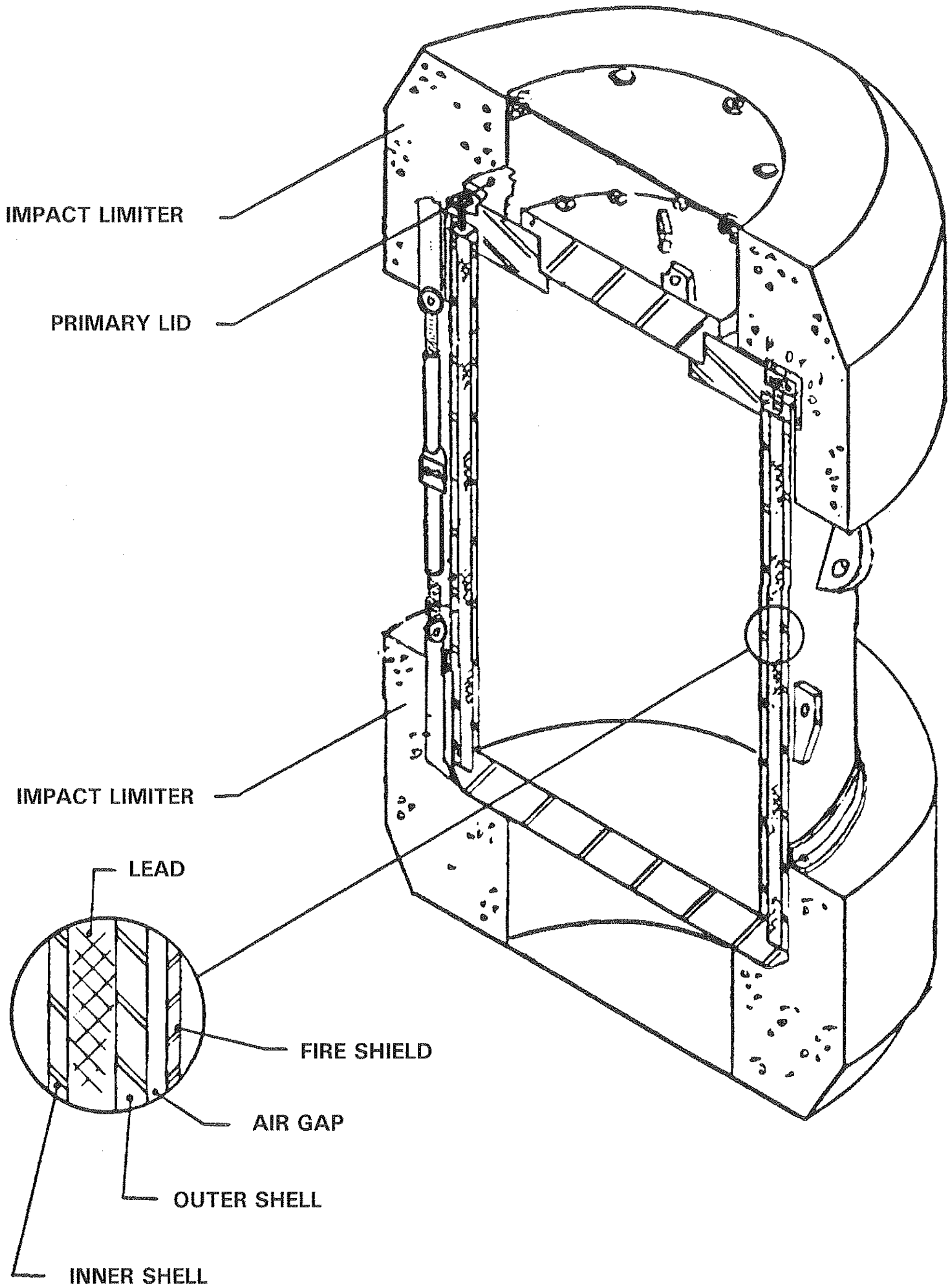

Figure 3.1
Location of Components Analyzed in Thermal Design

Table 3.2

Summary of Initial Conditions and Assumptions

Condition or Assumption	Normal Conditions	Hypothetical Accident
Ambient temperature for radiation (°F)	100	1475 during the fire; 100 thereafter
Ambient temperature for convection (°F)	100	1475 during the fire; 100 thereafter
Insolation (gcal/sq cm)	400	0 during the fire; 400 thereafter
Outside surface emissivity	0.8	0.8
Environment emissivity	0.9	0.9
Gap surfaces emissivity	0.15	0.15

3.2 Summary of Thermal Properties of Materials

Thermal properties of the materials included in the thermal model of the cask are shown in Table 3.3 (a) and 3.3 (b). The properties of the elastomer seals will vary depending on the type of elastomer used. The elastomer chosen for use shall have thermal properties such that the usable temperature range meets or exceeds the range required to meet the Normal Conditions of Transport (minimum= -40°F, maximum= +250°F) and meets or exceeds the temperature required to meet the Hypothetical Accident Conditions (+400°F for 1 hour). The thermal properties may be determined from manufacturer's recommended temperature ranges or from independent testing. An example of manufacturer's recommendations is found in Reference 6. Elastomers that have been evaluated and have passed the criteria listed above are butyl rubber, ethylene propylene rubber, and silicone rubber.

Note that the outside surface of the fire shield must be conservatively assumed to have an emissivity, ε, of at least 0.8 during the fire accident according to the Code of Federal Regulations (10CFR71.73). This same emissivity is used in analyzing the normal conditions of transport.

Table 3.3a

Temperature-Independent Thermal Properties

Material	Property	Ref.:Page	Value
Steel	Density	2:536	488 lb/ft^3
	ε (Outside)	3:648	0.8
	ε (Inside)	4:133	0.15
Lead	Density	2:535	710 lb/ft3
	Spec. Heat	2:535	0.0311 Btu/lb-°F
	Melting Point	5:B-29	621.5 °F

3.3 Technical Specifications of Components

Not applicable.

Table 3.3 (b)
Temperature-Dependent Thermal Properties

Temp.	Stainless Steel		Carbon Steel		Lead	Air		
(°F)	Sp. Heat	Cond.	Sp. Heat	Cond.	Cond.	Dens.	Sp. Heat	Cond.
70	0.117	8.6	0.104	35.1	20.1	0.07518	0.2402	0.01490
100	0.117	8.7	0.106	34.7	19.9	0.07105	0.2404	0.01546
150	0.120	9.0	0.109	34.1	19.7	0.06483	0.2408	0.01686
200	0.122	9.3	0.113	33.6	19.4	0.05992	0.2414	0.01804
250	0.125	9.6	0.115	32.9	19.1	0.05592	0.2421	0.01921
300	0.126	9.8	0.118	32.3	18.8	0.05237	0.2429	0.02032
350	0.128	10.1	0.122	31.6	18.5	0.04892	0.2438	0.02141
400	0.129	10.4	0.124	30.9	18.2	0.04619	0.2450	0.02248
450	0.130	10.6	0.126	30.3	17.9	0.04358	0.2461	0.02354
500	0.131	10.9	0.128	29.5	17.7	0.04141	0.2474	0.02457
550	0.132	11.1	0.131	28.8	17.4	0.03936	0.2490	0.02558
600	0.133	11.3	0.133	28.0	17.1	0.03747	0.2511	0.02654
650	0.134	11.6	0.135	27.3	16.8	0.03578	0.2527	0.02749
700	0.135	11.8	0.139	26.6	16.8	0.03422	0.2538	0.02843
750	0.136	12.0	0.142	25.9	16.8	0.03280	0.2552	0.02933
800	0.136	12.2	0.146	25.2	16.8	0.03141	0.2568	0.03022
900	0.138	12.7	0.154	23.8	16.8	0.02920	0.2596	0.03201
1000	0.139	13.2	0.163	22.4	16.8	0.02715	0.2628	0.03371
1100	0.141	13.6	0.172	20.9	16.8	0.02544	0.2659	0.03532
1200	0.141	14.0	0.184	19.5	16.8	0.02393	0.2689	0.03691
1300	0.143	14.5	0.205	18.0	16.8	0.02254	0.2717	0.03844
1400	0.144	14.9	0.411	16.4	16.8	0.02134	0.2742	0.04011
1500	0.145	15.3	0.199	15.7	16.8	0.02023	0.2766	0.04193

Units:	
Specific Heat:	BTU/lbm-F
Conductivity:	BTU/hr-ft-F
Density:	lbm/cu ft

References:	
Stainless Steel Properties:	Reference 1, Page 88
Carbon Steel	Reference 1, Page 83
Lead Properties:	Reference 2, Page 535
Air Properties:	Reference 2, Page 542

3.4 Thermal Evaluation for Normal Conditions of Transport

3.4.1 Thermal Model

3.4.1.1 Analytical Model. Normal conditions of transport are calculated with a steady state ANSYS (Reference 7) finite element thermal model of the cask. The location of the nodes and elements in the ANSYS model are shown in Figure 3.2. The model is a one-dimensional model through the cask axial midplane.

Cask surfaces which are covered by the impact limiters are given insulated boundary conditions. Convection and radiation are modeled on the fire shield outside surfaces. Equation 1 gives the relationship used to model convection (Reference 4, page 135).

(Equation 1) $$h = C\left(T_s - T_a\right)^{1/3}$$

where:

C = 0.19 (assumes the cask is vertical)
h = Heat transfer coefficient (BTU/hr-sq ft-F)
T_s = cask surface temperature (Degrees F)
T_a = ambient temperature (Degrees F)

Convection is modeled from a 100°F bulk air temperature and radiation is modeled from a 100°F environment. The 200 watt decay heat load is modeled as a constant heat flux over the exposed side wall inner surface of the cask. The heat flow rate across the inner surface of the cask inner shell set equal to the decay heat load. This is a conservative approximation during the fire transient, since, in reality, some of the heat from the fire would be transferred to the waste. Thus, the waste would act as a heat sink lowering the wall temperature.

Equation 2 (Reference 7, Page 4.31.1) gives the radiation heat transfer equation solved by the model.

(Equation 2) $$q = \sigma\, \varepsilon\, F\, A \left(T_I^4 - T_J^4\right)$$

where:

q = heat flow rate (BTU/hr)
σ = Stefan-Boltzmann Constant
= 1.7136×10^{-9} (BTU/hr-sq ft-R^4)
ε = emissivity
F = geometric form factor
A = area (sq ft)
T = temperature (°R)
I = first node number
J = second node number

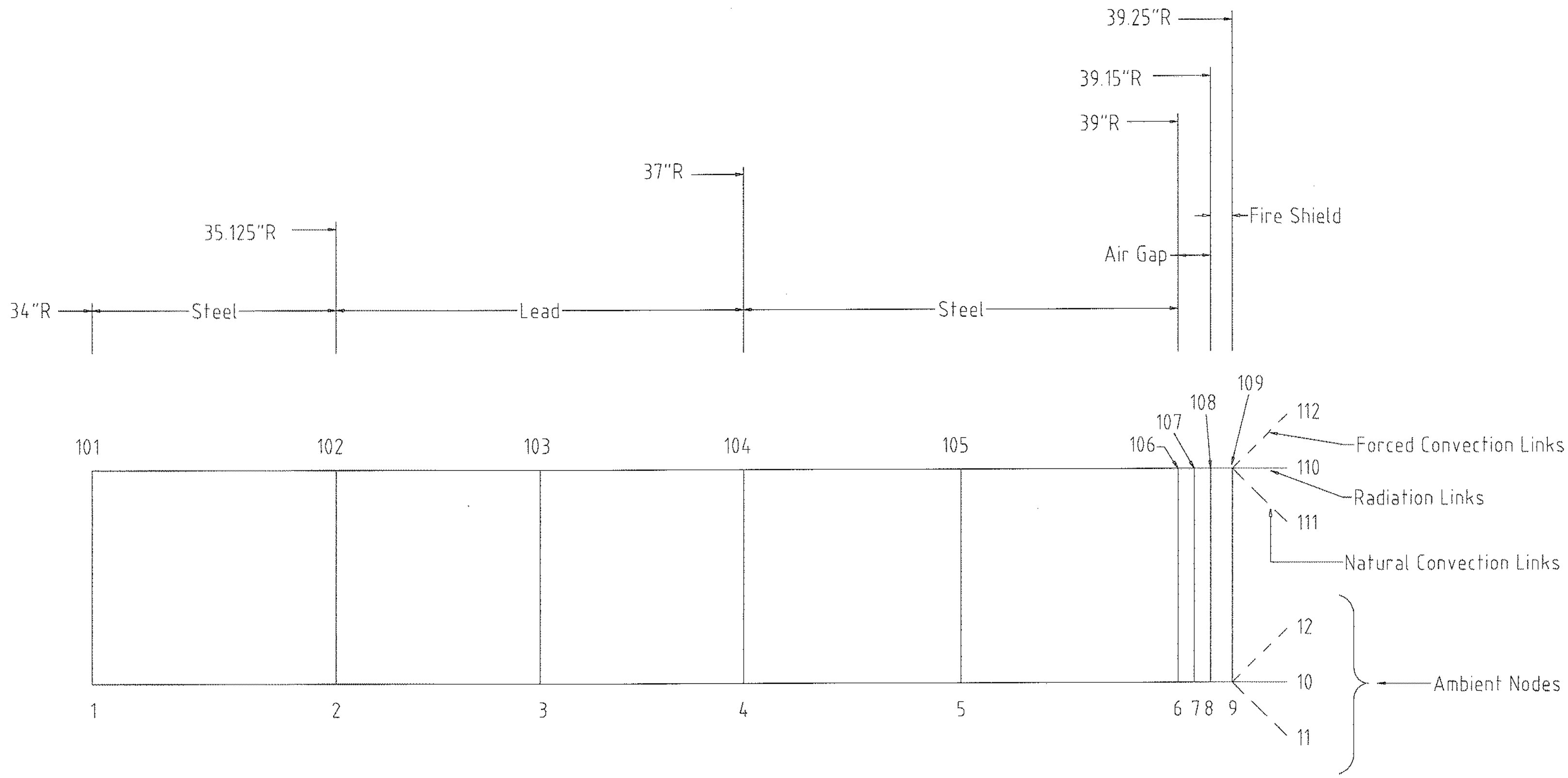

Figure 3.2

Node and Element Locations in the 10-160B Cask
Thermal Finite Element Model

Two radiation heat transfer systems are modeled: (1) radiation heat transfer between the fire shield outside surface and the environment, and (2) radiation between the fire shield inside surface and the structural shell outside surface. Emissivity, area, and geometric form factors are defined in both systems.

The overall emissivity for radiation heat transfer between the fire shield and the environment is set equal to the overall emissivity, ε, for heat transfer between two infinite parallel planes as given by equation 3 (Reference 2, page 336).

(Equation 3)
$$\varepsilon = \frac{\varepsilon_1 \varepsilon_2}{\varepsilon_2 + \varepsilon_1 - \varepsilon_1 \varepsilon_2}$$

where:

ε = overall emissivity
ε_1 = surface 1 emissivity
ε_2 = surface 2 emissivity

The Code of Federal Regulations (10CFR71.73) requires the use of a fire emissivity coefficient of at least 0.9. Thus, an environment emissivity coefficient of 0.9 was assumed in both the normal conditions of transport and in the hypothetical accident. The emissivities of the outside of the fire shield and the environment are 0.8 and 0.9, respectively. Thus, the overall emissivity is calculated by equation 4 to be 0.7347. The area of this radiation heat transfer system is set equal to the area of the outside surface of the fire shield and the geometric form factor is set to 1.0.

Radiation heat transfer between the fire shield inside surface and the structural shell outside surface is approximated by the equation for radiation heat transfer between long concentric cylinders as given by equation 4 (Reference 2, page 336).

(Equation 4)
$$q = \frac{\sigma A_1 \left(T_1^4 - T_2^4\right)}{\frac{1}{\varepsilon_1} + \frac{(A_1)(1/\varepsilon_2 - 1)}{A_2}}$$

The parameters in equation 4 are the same as defined previously and subscripts 1 and 2 refer to the inside cylinder and the outside cylinder, respectively. Since $\varepsilon = \varepsilon_1 = \varepsilon_2$, a form factor may be defined by equation 5 to put equation 4 in the same form as equation 2.

(Equation 5)
$$F = \frac{1}{\varepsilon} \frac{1}{\frac{1}{\varepsilon} + \frac{(A_1)(1/\varepsilon - 1)}{A_2}}$$

The area in equation 2 is set equal to the area of the inside cylinder and the emissivity is set equal to the minimum emissivity of the radiating surfaces, 0.15.

The total insolation is required to be 400 gcal/sq cm for a 12-hour period for curved surfaces according to the Code of Federal Regulations (10CFR71.71). The total insolation of 400 gcal/sq cm is divided by 12 hours of assumed sunlight to yield an average insolation rate. The average insolation rate is then multiplied by the surface emissivity specified in Section 3.2 above (0.8) yielding an insolation rate of 1.897E-4 BTU/sq in/sec. This insolation heat load is applied to the outside surface of the fire shield. Both the ambient air temperature and the environment temperature and the environment temperature are set to 100°F in accordance with the Code of Federal Regulations (10CFR71.71).

3.4.1.2 Test Model. Not applicable.

3.4.2 Maximum Temperatures

The maximum temperature of the cask occurs at the inside surface of the secondary lid, and is calculated to be 175°F (see table 3.1-1). The maximum temperature of the gas mixture within the cask, determined from the 2-d finite element model, is 188°F on the 100°F day. This is well within the service temperature of all materials and components used within the cask. The maximum temperature of the seals, calculated by the 2-d finite element model, is 174°F. The NCT temperature criterion for the seal material is conservatively set at 250°F for continuous use. The maximum temperature of the contents depends on its physical characteristics. Based on the 2-d finite element model analysis, the maximum temperature of the waste liner is calculated to be 236.4°F (see Reference 11). This temperature is well below the value at which deterioration of the waste can be expected .

3.4.3 Minimum Temperature

The waste transported with the cask may not be a heat source, so the minimum temperature the cask can reach is the minimum ambient temperature, -40°F. All components used in the cask are serviceable at this temperature (see Section 3.2).

3.4.4 Maximum Internal Pressures

The maximum internal pressure of the cask is calculated assuming that the gas within the cask, a mixture of air and water vapor, behaves as an ideal gas. The inside surface of the cask is assumed to be dry.

The temperature of the gas mixture within the cask is determined from the 2-d FEM. The maximum temperature of the gas mixture is 188°F on the 100°F day. Assuming that atmospheric pressure, P_2, exists inside the cask at 70°F, the pressure in the cask at 188°F, P_1, may be calculated by the ideal gas relationship given in equation 6.

(Equation 6)

$$P_1 = \frac{T_1}{T_2} * P_2$$

$$P_1 = \frac{(460+188°R)}{(460+70°R)} * 14.70 PSIA$$

$$P_1 = 17.97 PSIA$$

The vapor pressure contributed by water in the cavity at 188°F is 8.95 psia (Reference 10). The gauge pressure in the cask under normal conditions of transport is equal to the absolute pressure of the gas mixture within the cask minus the outside ambient pressure. Equation 7 expresses the maximum gauge pressure for this cask during normal conditions of transport (MNOP).

(Equation 7) 17.97 PSIA + 8.95 PSIA - 14.7 PSIA = 12.22 PSIG

Section 2.6.1 discusses the impact of the internal pressure on cask performance. Pressure calculations for TRU waste transportation are detailed in Appendix 4.10.2.

3.4.5 Maximum Thermal Stresses

The temperature gradient through the side wall under normal conditions of transport is due to the decay heat of 200 watts. The temperature difference between the outside surface of the outer shell and the inside surface of the inner steel shell is only 0.2°F on the 100°F ambient temperature. Stresses resulting from this temperature gradient are insignificant. Section 2.6.1 discusses the effect of thermal stresses in detail.

3.4.6 Evaluation of Package Performance for Normal Conditions of Transport

All temperatures and stresses within the package due to normal conditions of transport are within allowable service ranges for all components and materials used in the cask. Seal temperatures range from -40 to 174°F and are within the required elastomer seal operating region of -40 to 250°F. All structural materials are below their melting points.

The temperature difference between the inside surface of the inner shell and the outside surface of the outer shell is only 0.2°F. Thermal stresses resulting from this thermal gradient are discussed in section 2.6.1. The average temperature at the inside surface of the inner shell and at the outside surface of the outer shell is 168°F. The average wall temperature is also used in the thermal stress calculations of section 2.6.1.

3.5 Hypothetical Accident Thermal Evaluation

3.5.1 Thermal Model

3.5.1.1 Analytical Model. The thermal model used to evaluate the hypothetical accident is identical to the model used to evaluate normal conditions of transport.

Initial conditions for the hypothetical accident are steady state with a 100°F ambient and no convection nor insolation. These initial conditions are consistent with those required by the Code of Federal Regulations for the hypothetical accident (10CRF71.73).

The initial steady state solution is followed by a 0.5 hour fire transient in which the 100°F ambient is replaced by a 1475°F fire temperature as required by the Code of Federal Regulations (10CFR71.73). The effect of the fire is represented by radiative and convective heat flux, the average temperature of which is 1475°F and an emissivity of 0.9. Based on the explanatory material for the IAEA regulations in Safety Series No.37 (Reference 9), the pool fire gas velocity is taken to be 10 m/sec (32.8 ft/sec). The forced convection heat transfer coefficient for large casks, according to Reference 9, is:

$$h = 10 \frac{\mathrm{W}}{\mathrm{m}^2 \, {}^\circ\mathrm{C}}$$

$1\ W = 9.4804\times10^{-4}$ Btu/sec
$1\ m = 39.37$ inch
$1°C = 1.8°F$

Therefore,

$$h = \frac{10 \times 9.4804 \times 10^{-4}}{39.37^2 \times 1.8} = 3.398 \times 10^{-6} \frac{\text{Btu}}{\text{sec} - \text{in}^2 - {}^\circ\text{F}}$$

The convective heat transfer per unit area between the cask and the atmosphere, q, is governed by the equation:

(Equation 8) $$q = hA\left(T_s - T_a\right)$$

where:

h = Heat transfer coefficient (BTU/hr-sq ft-F)
A = Area (sq ft)
T_s = cask surface temperature (Degrees F)
T_a = ambient temperature (Degrees F)

Finally, the fire transient is followed by a 1.0 hour cooldown transient. The 1475°F fire temperature is replaced by a 100°F ambient during the cooldown transient. Also, the forced convection is replaced with the natural convection, as described in section 3.4.1 of this SAR. The solar insolation is included during the cooldown.

The ANSYS time increment size is set at 5 seconds. The ANSYS (Reference 7) computer program observes the second derivative of temperature with respect to time (curvature) for each node and automatically increases the time increment when its default transient thermal optimization criterion is met. A total of 65 time increments were required to analyze the hypothetical accident.

3.5.1.2 Test Model Not applicable.

3.5.1.3 Supplemental Analyses

In order to obtain the temperatures of the waste content, and the primary and secondary lid seals, during the NCT and HAC fire, supplemental analyses, using a 2-dimensional finite element model, have been performed. The details of these analyses are provided in Reference 11. In these analyses, the overall emissivity of 0.9 has been used to model the heat transfer between the cask and the environment due to radiation.
The results of the analyses of the 2-dimensional finite element model are also included in the Summary Tables 3.1-1 and 3.1-2. The more conservative of the 1-d or 2-d model results have been used for the calculation of the design and operating pressures as well as the structural analyses.

3.5.2 Package Conditions and Environment

Damage to the package caused by free drop and puncture tests will not significantly alter the thermal characteristics of the package. Even after crushing the impact limiters continue to act as thermal barriers.

3.5.3 Package Temperatures

The maximum temperatures in the fire shield, cask structure, and the lead all occur halfway up the cask. Table 3.4 summarizes the location, time of occurrence measured from the start of the fire, and value of the maximum temperature in each cask component. The cask seals are not explicitly modeled in the 1-d finite element model. The maximum temperatures of the primary and secondary lid seals are obtained from the 2-d finite element model analysis described in Section 3.5.1.3 and documented in Reference 11. It is shown that the seals attain a maximum temperature of 166.4°F 23.9 hours after the start of the fire. The HAC temperature criterion (maximum allowable) for the seal material is conservatively set at 400°F with a duration of 1 hour.

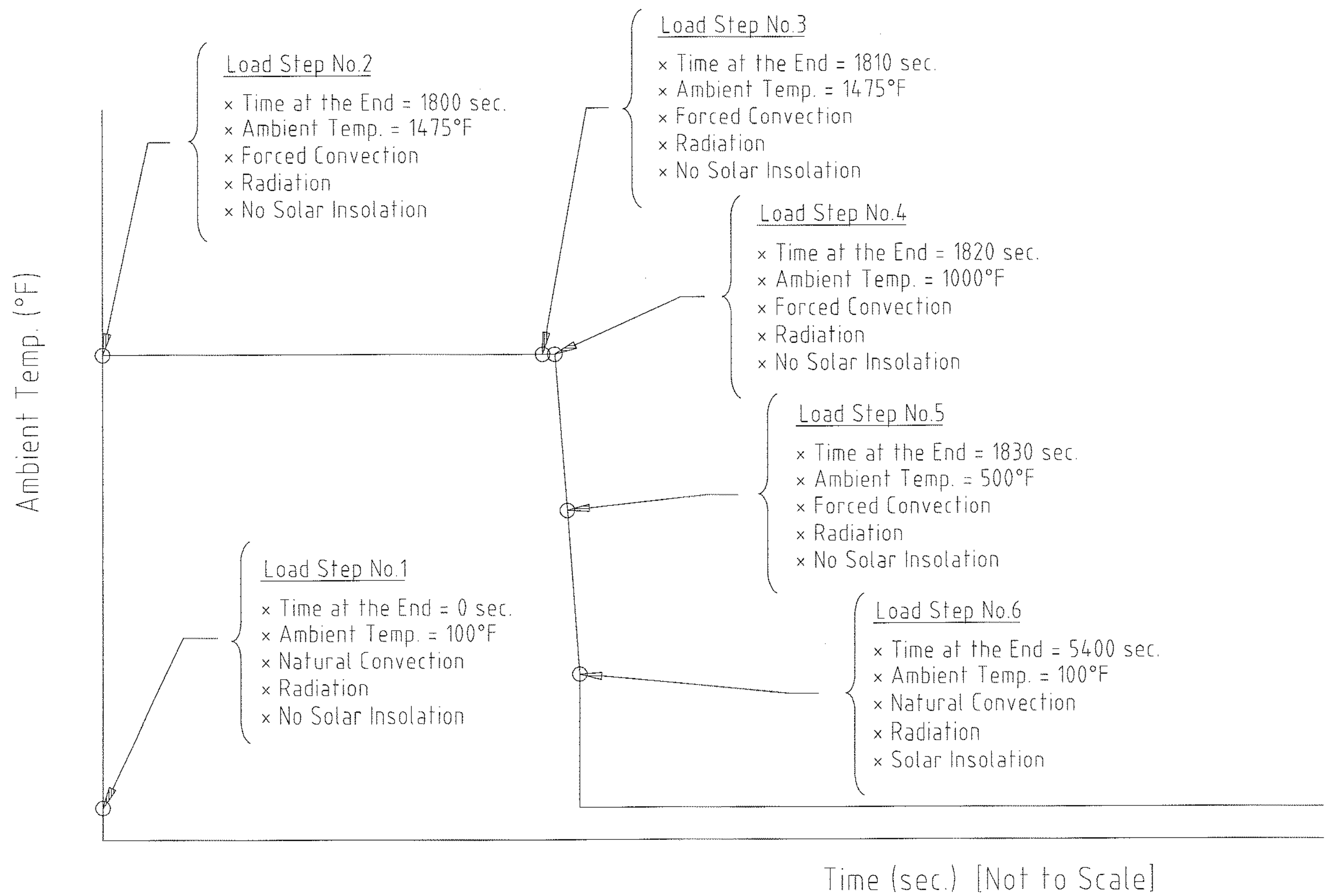

Figure 3.3
Transient Fire Analysis - Load Step and Boundary Conditions Schematic

Table 3.4

Summary of Maximum Hypothetical Accident Temperatures

Component	Maximum Calculated Temp. Location	Time (hrs)	Value (°F)	Maximum Allowable Temperature (°F)
Fire Shield	Mid-Plane	0.5	1361[1]	N.A.
Structural Shell	Mid-Plane	0.5	289[2]	800
Lead	Mid-Plane	0.73	274[2]	622
Seals	N.A.	8.5	164[2]	400

NOTES:
(1) From 1-d finite element model analysis.
(2) From 2-d finite element model analysis (Reference 11)

The maximum calculated temperatures are less than the maximum allowable temperatures for each component. Figure 3.3 plots the temperature during the fire transient of selected points in the model versus time. Figure 3.4 plots the temperature during the subsequent cooldown of the same points.

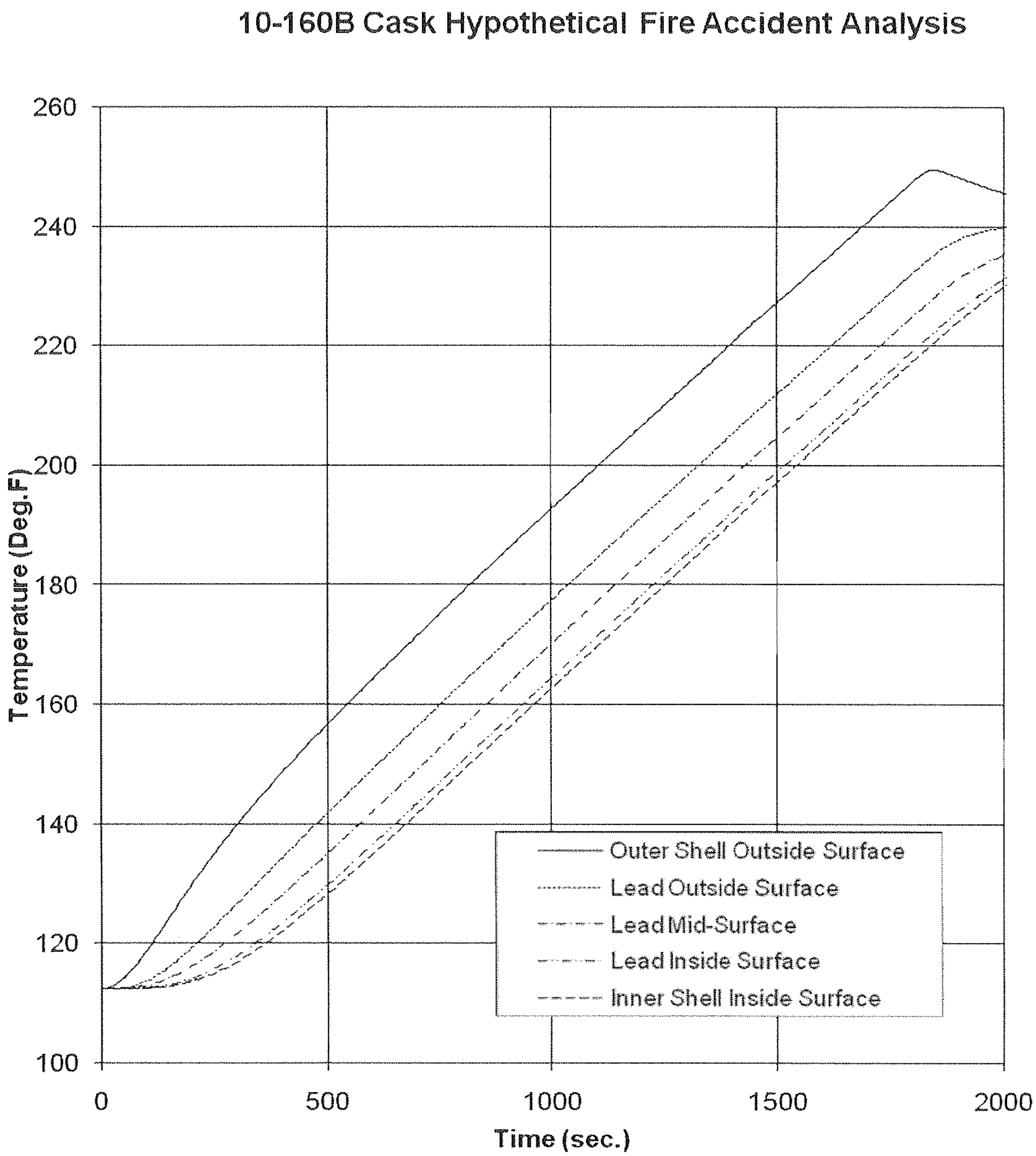

Figure 3.4

Hypothetical Accident - Fire Transient:
Temperature Versus Time

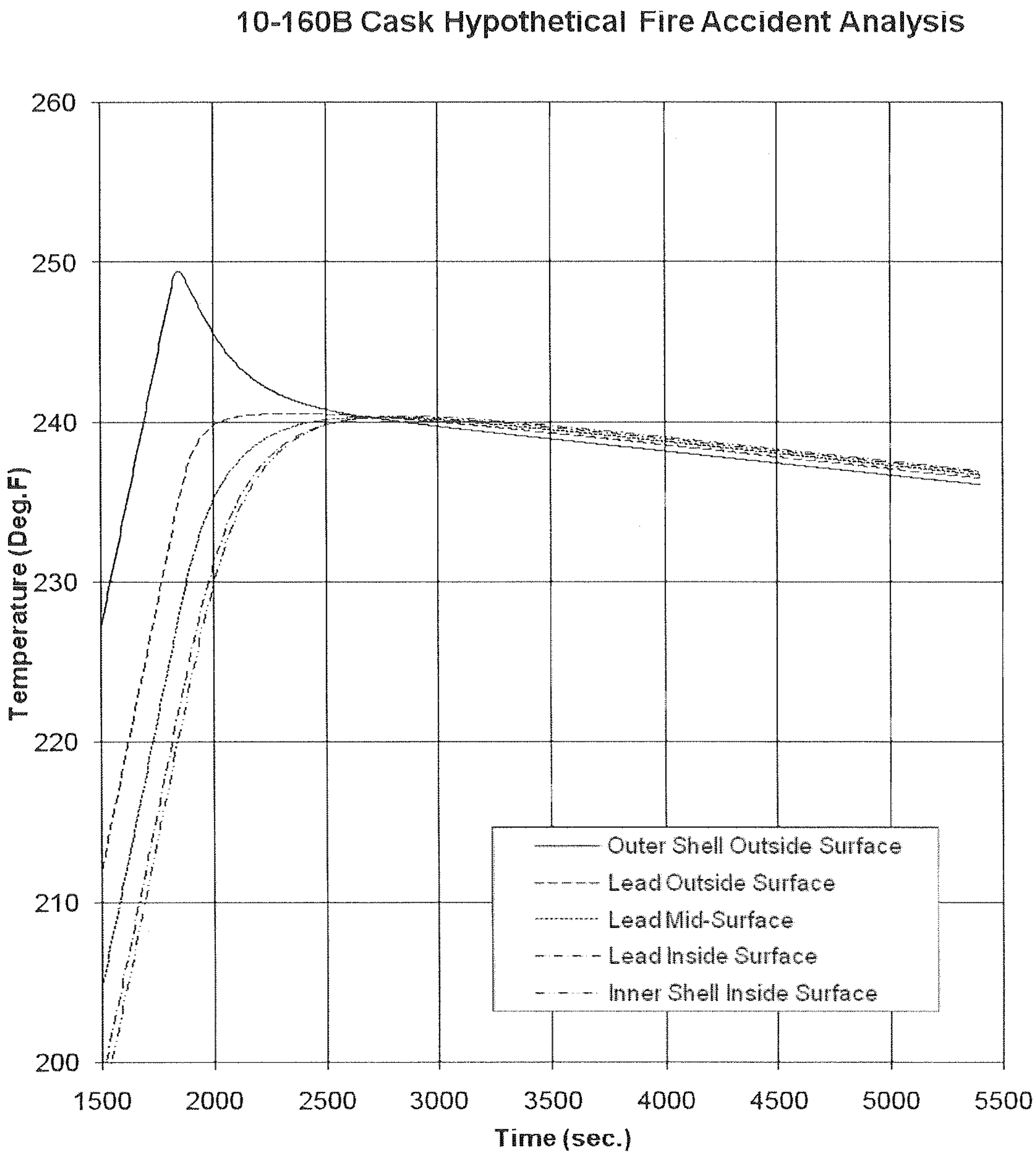

Figure 3.5

Hypothetical Accident - Cooldown:
Temperature Versus Time

3.5.4 Maximum Internal Pressures

The maximum internal pressure of the cask is calculated assuming that the gas within the cask, a mixture of air and water vapor, behaves as an ideal gas. The inside surface of the cask is assumed to be dry.

The temperature of the gas mixture within the cask is determined from the 2-d FEM. The analysis gives the maximum temperature as 188°F but the gas temperature is conservatively set as 200°F. Assuming that atmospheric pressure exists inside the cask at 70°F, the partial pressure of the gas mixture in the cask at 200°F, P_1, may be calculated by the ideal gas relationship given in equation 8.

(Equation 9)

$$P_1 = \frac{T_1}{T_2} * P_2$$

$$P_1 = \frac{(460+200°R)}{(460+70°R)} * 14.70 PSIA$$

$$P_1 = 18.31 PSIA$$

The vapor pressure contributed by water in the cavity at 200°F is 11.81 psia (Reference 10). The maximum gauge pressure in the cask during the hypothetical accident is equal to the pressure within the cask given by Equation 9 plus the water vapor pressure minus the outside ambient pressure. Equation 10 expresses the maximum gauge pressure for this cask during the hypothetical accident.

(Equation 10) 18.31 PSIA + 11.81 PSIA - 14.7 PSIA = 15.42 PSIG

An internal pressure of 94.3 PSIG is conservatively used in calculating the effects of combined thermal and pressure loading as discussed in Attachment 5 to Chapter 2. The allowable pressure due to buildup of gases in the cask (see Appendix 4.10.2) is conservatively set at 31.2 psig.

3.5.5 Maximum Thermal Stresses

The maximum temperature difference between the outside surface of the outer shell and the inside surface of the inner shell during the hypothetical accident is 39.8° F and occurs 30 minutes after the start of the fire. The maximum temperature difference across the outer shell is 20.2°F (occurring 30 minutes after the start of the fire) and the maximum temperature difference across the inner shell is 2.3°F (occurring 30.5 minutes after the start of the fire). The maximum average cask wall temperature (average of the temperatures at the inside surface of the inner shell and the outside surface of the outer shell) is 289°F and occurs at 45 minutes after the start of the fire. Thermal stresses resulting from temperature gradients during the hypothetical accident are discussed in Section 2.7.3.

3.5.6 Evaluation of Package Performance for the Hypothetical Accident Thermal Conditions

All temperatures in the package components due to the hypothetical accident thermal conditions are below their maximum allowable limits. The maximum HAC seal temperature is calculated to be 164.4°F during the cool-down period of the fire transient (see Reference 11). The seals material is specified to meet the minimum temperature requirement of 400°F, which is well over the expected temperature during the NCT and HAC fire conditions. The maximum temperature in the lead shielding is calculated to be 274.4°F, which occurs at 0.73 hours after the start of the fire. This temperature is well below its melting point of 622°F. The steel body is also well below its service limit.

3.6 References

1. ASME Boiler and Pressure Vessel Code an American Standard, Section II, Part B Materials, The American Society of Mechanical Engineers, New York, NY, 1995.

2. Heat Transfer, J.P. Holman, Mc-Graw Hill Book Company, New York, Fifth Edition, 1981.

3. Code of Federal Regulations Title 10 Parts 71, Packaging and Transportation of Radioactive Material, 1998.

4. Cask Designers Guide, L.B. Shappert, et. al, Oak Ridge National Laboratory, February 1970, ORNL-NSIC-68.

5. CRC Handbook of Chemistry and Physics, Robert C. Weast and Melvin J. Astel, eds., CRC Press, Inc., Boca Raton, Florida, 62nd ed., 1981.

6. O-Ring Handbook, Parker Seal Company, Lexington, Kentucky, January 1977.

7. ANSYS Rev. 11 Computer Software, ANSYS Inc., Cannonsburgh, Pennsylvania, 2007.

8. IAEA Safety Series No.6, Regulations for the Safe Transport of Radioactive Material, 1985 Edition (As Amended 1990), International Atomic Energy Agency, Vienna, 1990.

9. IAEA Safety Series No.37, Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material - 1985 Edition, International Atomic Energy Agency, Vienna, 1990.

10. Chemical Engineers' Handbook, Fifth Edition, Robert H. Perry and Cecil H. Chilton, McGraw-Hill Book Company, 1973.

11. EnergySolutions Document CSG-01.1000, Rev.2, 10-160B Transportation Cask Thermal Analyses.

Attachment 3
Thermal Analysis
CSG-01-1000 Rev. 2

ENERGYSOLUTIONS Spent Fuel Division	CALCULATION PACKAGE	Calc. Pkg No. CSG-01.1000 File No.: CSG-01.1000 Revision: 2

PROJECT/CUSTOMER:

Energy*Solutions* Commercial Services Group, Columbia, S.C.

TITLE:

10-160B Transportation Cask Thermal Analysis

SCOPE:

Product:	☐ Fuel*Solutions*™	☐ VSC-24		☒ Other 10-160B Cask
Service:	☐ Storage	☒ Transportation		☐ Other ________
Conditions:	☒ Normal	☐ Off-Normal	☒ Accident	☐ Other ________

Component(s):

10-160B Transportation Cask

Prepared by: Kent C. Smith

Kent C Smith 6-5-2009

Verified by: Steve Sisley

06-05-09

Approved by Engineering Manager: Steve Sisley

06-05-09

RECORD OF REVISIONS

REV.	AFFECTED PAGES	AFFECTED MEDIA	DESCRIPTION	NAMES (Print or Type) PREPARER	CHECKER
0	1 through 74	1 CD	Initial issue	Kent C. Smith	Steven E. Sisley
1	13, 22 thru 41, 54 thru 58, 63, 66 thru 77, 79 thru 81	1 CD	Revised fire shield air gap to 5/32-inch, revised transient convection coefficient, revised list of assumptions, added Table 4, and misc editorial changes	Kent C. Smith	Steven E. Sisley
2	10,15, 25,26,27, 31-39,58, 68,69	1 CD	Revised the external surface emissivity / absorptivity of the cask for the HAC fire case to 0.9. Editorial corrections to temperature vs time print command, minor changes to transient temp figures and figure cross-references.	Kent C. Smith	Steven E. Sisley

RECORD OF VERIFICATION

	YES	NO	N/A
(a) The objective is clear and consistent with the analysis.	☒	☐	
(b) The inputs are correctly selected and incorporated into the design.	☒	☐	☐
(c) References are complete, accurate, and retrievable.	☒	☐	☐
(d) Basis for engineering judgments is adequately documented.	☒	☐	☐
(e) The assumptions necessary to perform the design activity are adequately described and reasonable.	☒	☐	☐
(f) Assumptions and references, which are preliminary, are noted as being preliminary.	☐	☐	☒
(g) Methods and units are clearly identified.	☒	☐	☐
(h) Any limits of applicability are identified.	☒	☐	☐
(i) Computer calculations are properly identified.	☒	☐	☐
(j) Computer codes used are under configuration control.	☒	☐	☐
(k) Computer codes used are applicable to the calculation.	☒	☐	☐
(l) Input parameters and boundary conditions are appropriate and correct.	☒	☐	
(m) An appropriate design method is used.	☒	☐	
(n) The output is reasonable compared to the inputs.	☒	☐	
(o) Conclusions are clear and consistent with analysis results.	☒	☐	

COMMENTS:

None.

Verifier: Steven E. Sisley

06-05-09

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LIST OF FIGURES

1. INTRODUCTION

1.1 Objective

The objective of the calculation is to provide a 2-D thermal response assessment of the Energy*Solutions* 10-160B Transportation Cask for normal conditions of transport (NCT) and the fire case hypothetical accident conditions (HAC). All calculation design input and/or associated assumptions herein are referenced from the Duratek prepared 1-D thermal analyses for the 10-160B Transportation Cask NCT conditions [3.1.2] and the HAC conditions [3.1.1]. The 2-D thermal analysis presented herein augments these two Duratek 1-D calculations.

All analysis is performed using ANSYS Mechanical (Version 11.0).

1.2 Purpose

The purpose of the calculation is to determine the maximum material temperatures and cavity bulk air average temperatures associated with operation of the 10-160B Transportation Cask with a waste liner containing irradiated waste and a total heat generation rate of 200 Watts, maximum.

1.3 Scope

The thermal analysis as presented herein is valid for the applicable design basis 10-160B Transportation Cask normal (NCT hot day) and hypothetical accident conditions (HAC fire case) as defined in the associated Duratek 10-160B Transportation Cask thermal calculations (references [3.1.1] and [3.1.2]).

2. REQUIREMENTS

2.1 Design Input

Not applicable.

2.2 Regulatory Commitments

None.

3. REFERENCES

3.1 Calculation Packages

3.1.1 Duratek Doc I.D. #TH-018, *Hypothetical Fire Accident Analysis of the 10-160B Cask Using a 1-D FEM*, Revision 2.

Use: This calculation reference is used as the primary basis for the ambient temperatures, emissivities and material properties and associated heat transfer methodologies as used within the calculation presented herein.

3.1.2 Duratek Doc. I.D. #TH-019, *Thermal Analysis of the 10-160B Cask Under Normal Conditions Using a 1-D FEM*, Revision 2.

Use: This calculation reference is used as the primary basis for the NCT insolation values and associated heat transfer methodologies as used within the calculation presented herein.

3.2 General References

3.2.1 CRC Handbook of Tables for Applied Engineering Science, 2nd Edition, CRC Press

Use: This reference is utilized as the basis for the densities and specific heats of lead at elevated temperatures. Values are taken from Table I-53, Properties of Liquid Metals, of the Handbook.

3.2.2 Energy*Solutions* Drawing No. C-110-D-29003-010, *Cask Assembly General Notes / Parts List 10-160B*, Revision 14 (5 sheets)

Use: This set of drawings is utilized as the basis for the dimensions and materials of the 10-160B cask, as analyzed herein.

4. ASSUMPTIONS

This section presents the assumptions used in the thermal analysis of the 10-160B Transportation Cask.

4.1 Design Configuration

All nominal dimensions pertinent to the ANSYS models utilized are obtained from the Energy*Solutions* 10-160B Transportation Cask drawing package [3.2.2]. Additionally, the design configuration herein includes the following assumptions:

- The 10-160B Transportation Cask is transported in a vertical orientation.
- The 10-160B Transportation Cask's external lifting / rigging / tie-down brackets and associated hardware are not modeled.
- Small and/or minor air gaps and/or other or small voids between the lid and the cask body and/or between the gamma shield and/or the inner and/or the outer steel shells are not modeled.
- The total decay heat load within the cask is 200 Watts, but, the 10-160B Transportation Cask walls are assumed to be subjected to a localized heating via a conservatively sized "hot spot" cavity heat load (refer to Section 5.1 for a detailed description of the "hot spot" heat load with respect to the ANSYS models utilized herein).
- The design basis load conditions are as listed in Table 1.

Table 1 – Design Conditions

Loading	Description	Basis
Waste heat load	200 Watts	Based upon references [3.1.1] and [3.1.2]
Average ambient temperature for a 12-hour day	100°F	Based upon references [3.1.1] and [3.1.2]
Insolation average for a 12-hour day	98.4 Btu / hr / ft^2 (320 $gcal/cm^2$)	Based upon reference [3.1.1]
External surface emissivity during HAC Fire case / 30-minute fire case	0.90	Assumption
External surface emissivity during NCT hot day	0.80	Based upon reference [3.1.2]

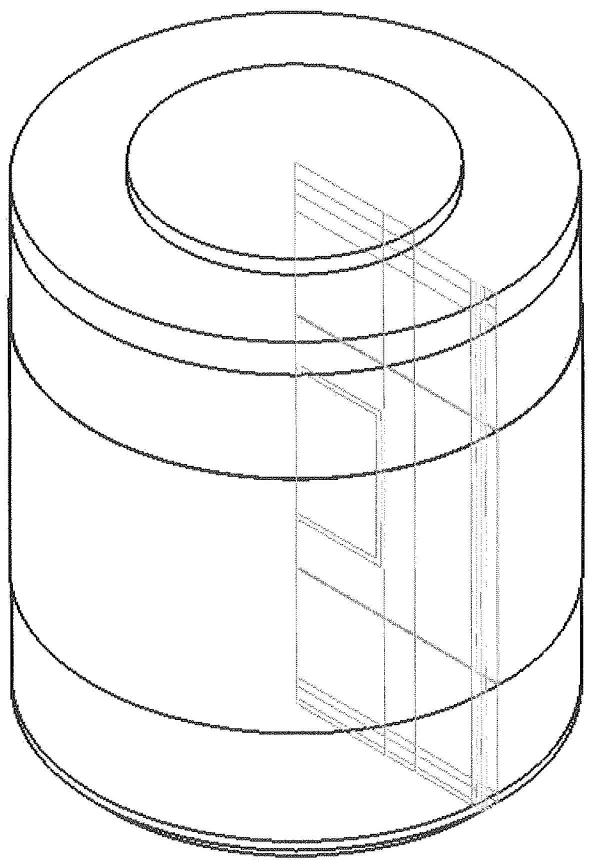

Figure 1 – 10-160B Transportation Cask Simplified Isometric View

4.2 Design Criteria

None.

4.3 Calculation Assumptions

The following assumptions are applicable to the thermal analysis:

1. The geometry of the ANSYS models used herein is based upon the Energy*Solutions* 10-160B Transportation Cask drawings (hereinafter referred to as the drawings) [3.2.2]. However, several simplifying assumptions are made with respect to the upper and lower end fittings and/or the various shell top and bottom plate dimensions. As noted in Section 4.1, the dimensions of the cask match very closely with the drawings; however, small air gaps, such as the gaps between the lid and associated top plates (primary lid) are not included. In addition, the gamma shield is assumed to extend (axially) to the inside bottom surface at the top of the cask cavity. By inspection, these types of simplifications are believed to have insignificant effects on the results of the thermal analysis.

2. For the NCT hot day case, the steady-state values are conservatively calculated by assuming a 12-hour per day ambient temperature of 100°F (in lieu of a 24-hour per day average of 77°F).

3. For the NCT hot day case, the steady-state insolation values are calculated by averaging the 24-hour day values for insolation over a 12-hour solar day (refer to Table 1). This is conservatism because it ignores large thermal inertia / time constant of the 10-160B Transportation Cask. As per Energy*Solutions* calculation number TH-019 [3.1.2] and as listed in Table 1 – Design Conditions, the solar heat load is assumed to be 98.4 Btu/hr/ft^2/°F (320 gcal/cm^2).

   Note: The above assumed heat load is deemed to be a significantly conservative value since the solar heat load can be justified to be based upon a 24-hour average, in lieu of a 12-hour average of constant insolation. In addition, for vertically curved surfaces, the solar heat load can also be justifiably reduced by one half of the horizontal surface heat loads. In short, the solar heat load utilized for the steady-state NCT hot day analysis is believed to be significantly conservative.

4. For the NCT and HAC cases, a conservatively sized "hot spot" sized heat load is modeled herein. As such, the total decay heat load within the cask is 200 Watts, but, the 10-160B Transportation Cask walls are subjected to a localized hot spot of radial and axial heat. Refer to Section 5.1.2.1 for a detailed description of the "hot spot" heat load as utilized herein.

5. The 10-160B Transportation Cask impact limiters are assumed to be in-place and fully intact during the NCT and HAC fire case conditions. The cask surface areas associated with the impact limiter are assumed to be fully insulated from the ambient environment during the NCT and HAC fire conditions.

6. The ambient barometric pressure is assumed to be at sea level conditions.

7. For the NCT hot day case, the natural convection heat transfer coefficient for exterior vertical / curved surfaces is calculated as follows:

$h_f = C * (\text{Delta Temp})^{1/3}$

Where,

h_f = Convection film coefficient

C= 0.19 Assuming units of feet, hours and degrees Fahrenheit, as per reference [3.1.1]

Delta temp = calculated by ANSYS (ambient temperature minus surface temperature)

8. For the HAC fire case initial conditions (steady-state / no solar), the natural convection heat transfer coefficient for exterior vertical / curved surfaces is calculated as follows:

   $h_f = C * (\text{Delta Temp})^{1/3}$

   Where,

   C= 0.19 As per reference [3.1.1]

   Delta temp = calculated by ANSYS (ambient temperature minus surface temperature)

9. For the HAC 30-minute fire, the forced convection heat transfer coefficient for exterior vertical / curved surfaces is calculated accordingly. As per reference [3.1.1], the pool fire gas velocity is taken to be 10 meters/second (32.8 ft/sec), and, the value for the film coefficient is given by:

   $h_f = 10 * W/m^2\ °C$ As per reference [3.1.1]

   Where,
   1W = 9.4804E-4 Btu/sec
   1 m = 39.37-inches
   1 °C = 1.8°F
   Therefore,

   $h_f = 3.398E\text{-}6 * 3600 = 0.0122\ Btu/hr/in^2/°F$ As per reference [3.1.1]

10. For the HAC fire cool-down case, the natural convection heat transfer coefficient for exterior vertical / curved surfaces is calculated as follows:

    $h_f = C * (\text{Delta Temp})^{1/3}$

    Where,

    C= 0.19 Assuming units of feet, hours and degrees Fahrenheit, as per reference [3.1.1]

Delta temp = calculated by ANSYS (ambient temperature minus surface temperature)

11. The calculation assumes that for the NCT hot day case heat transfer from the external surfaces of the 10-160B Transportation Cask is via natural convection and radiation, only. The associated external surface emissivities as used herein are listed in Table 1.

12. The calculation assumes that for the HAC fire case / 30-minute fire the external surfaces of the 10-160B Transportation Cask is via forced convection and radiation, only. The associated external surface emissivities as used herein are listed in Table 1.

13. For the NCT hot day case, the fire shield is assumed to be spaced using radially-wrapped 5/32-inch diameter stainless steel wire, axially spaced 12-inches on center (in lieu of the actual spirally-wrapped wire). As a simplifying ANSYS modeling assumption, the fire shield gap wrapped wire spacer is assumed to be a series of hoops, axially spaced 12-inches on center. In addition, each assumed hoop segment of wire is assumed to contact the outer shell and inner fire shield via a 1/32-inch wide (or tall) region. As such, this is essentially a line-contact conductive heat transfer path at each assumed wire hoop.

14. For the HAC Fire case, the fire shield is assumed to be fully separated from the spirally-wrapped stainless steel wire (see assumption #13, above). This assumption is deemed to be justified since the fire shield will expand and pull away from the under-lying wire support during the HAC fire case. As an ANSYS modeling simplification, the air gap within the fire shield is assumed to be exactly equal to the nominal wire diameter (5/32-inch). However, the HAC fire case also assumes that the fire shield is welded at the top and bottom directly to the outer shell. This top / bottom fire shield-to-outer shell weld is assumed to be sized at the full thickness of the fire shield (0.105-inches).

15. Materials of construction: The 10-160B Transportation Cask is primarily fabricated from a carbon steel inner and outer shell, with a lead gamma shield, and a surrounding painted carbon steel fire shield. The fire shield air gap is maintained utilizing stainless steel spirally-wrapped wire. The lid seal containment integrity is maintained utilizing elastomeric (Butyl rubber or silicon) o-rings. Finally, the fire shield is assumed to be coated with a high temperature resistant paint as needed to obtain the external emissivities as listed in Table 1.

4.4 Dimensions

As noted in Section 4.3, the Drawings (see reference [3.2.2]) provide all of the key 10-160B Transportation Cask dimensions as are used in the thermal analysis.

5. CALCULATION METHODOLOGY

The 10-160B Transportation Cask is analyzed herein for the design basis thermal conditions as defined in the associated 10-160B Transportation Cask Duratek NCT calculation [3.1.2] and the Duratek HAC calculation [3.1.1].

The design basis conditions important to the cask include thermal only conditions and thermal conditions combined with structural load considerations. Combined thermal/structural load combinations require that 10-160B Transportation Cask components under structural loads be maintained below the temperature point established for their allowable stress values. *Note: Establishing material temperature limits for thermal only load conditions are beyond the scope of this calculation. Such material temperature limits are established (elsewhere) to prevent failure of the affected components.*

Through-wall temperature gradients are calculated for the assumed NCT 12-hour maximum temperature (hot) day and the HAC fire case (refer to Table 1). Insolation is included for the hot day and zero insolation is included for the HAC fire analysis. As such, the worst case through-wall gradients and worst case cavity bulk air temperatures are conservatively calculated.

5.1 ANSYS Thermal Model

The thermal analysis of the 10-160B Transportation Cask is carried out using the ANSYS finite element program. The associated ANSYS input files are described in detail, below.

5.1.1 ANSYS Model Geometry

The ANSYS axisymmetric model geometry is based directly upon the Energy*Solutions* 10-160B Transportation Cask drawings [3.2.2]. Simplifying assumptions are included with respect to the cask geometry, where applicable, while still maintaining the fundamental paths and modes of heat transfer available to the cask's major components (refer to the list of assumptions as provided in Section 4). Symmetry is assumed along the axial axis (Y-axis) of the cask. Keypoints are placed at all important material / geometry interfaces. The model is solved for nodal temperatures and/or average element volume temperatures using assumed temperature dependent material properties, bounding cask geometry, and associated classical heat transfer equations.

The ANSYS models used herein for the NCT and HAC cases include areas / elements for all pertinent zones that affect the primary modes of heat transfer, and, appropriate boundary conditions are included to represent the surrounding ambient environment. The basic geometry of the cask models include areas / elements for the bottom plate, the inner structural shell, the gamma shield, the outer shell, the top plate, the lid, etc.. The ANSYS NCT and HAC cask models include surface elements (Surf151) in locations to simulate solar and/or convection and/or cavity heat surface loads, as appropriate. In addition, boundary conditions / surface loads are selected to properly represent the aforementioned "hot spot" heat load. Finally, appropriate nodes are selected at suitable locations to represent the location of the primary and secondary O-ring seals. As such, node #3615 was selected for the primary seal location, and, node #3687 was selected to represent the secondary seal location.

The ANSYS pre-processing module is used to produce the following node, area and element plots for the axisymmetric 10-160B Transportation Cask model (see Figure 2 through Figure 6). ANSYS Plane 55 elements were used for the solid / conduction areas of the model, and, Surf151 elements were used to model the heat flux regions within the cavity, and, the radiation / convection exterior surfaces of the 10-160B Transportation Cask.

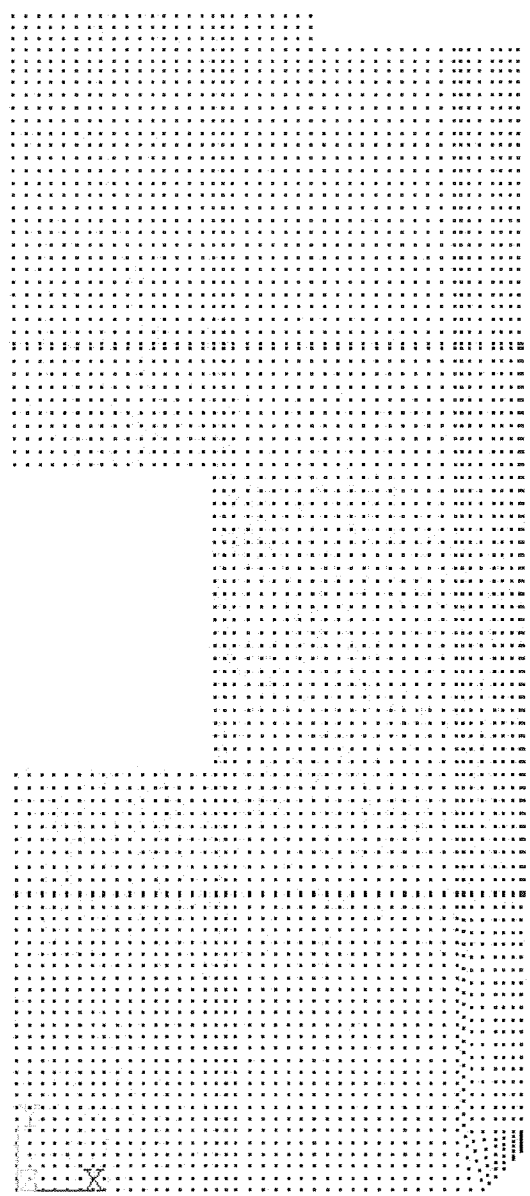

Figure 2 – 10-160B Cask ANSYS NCT and HAC Node Plot

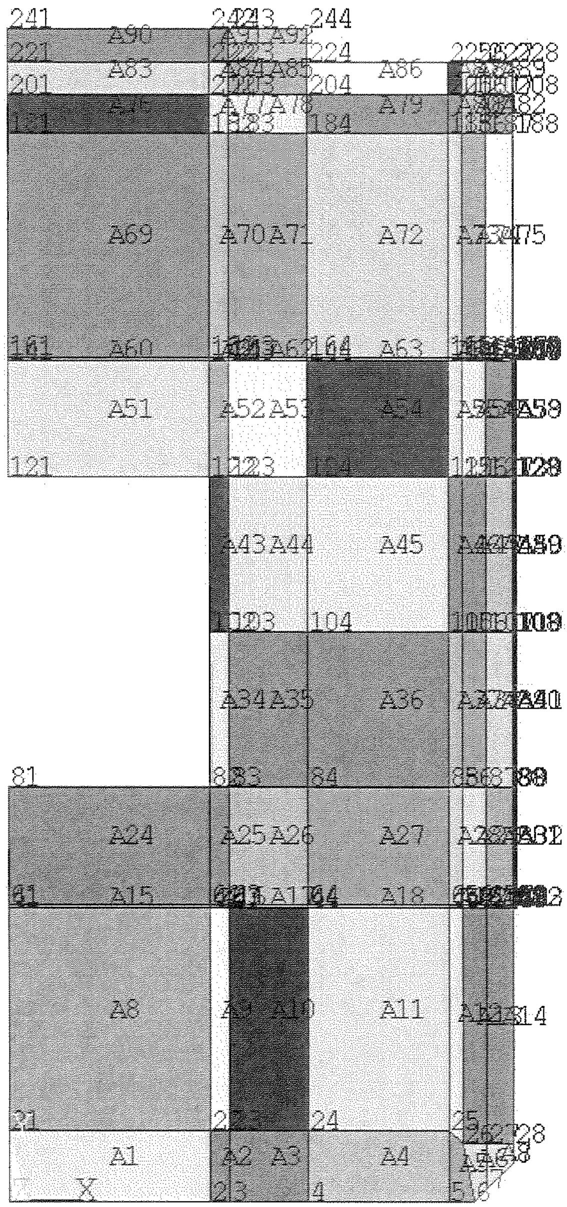

Figure 3 – 10-160B Cask ANSYS NCT and HAC Area Plot

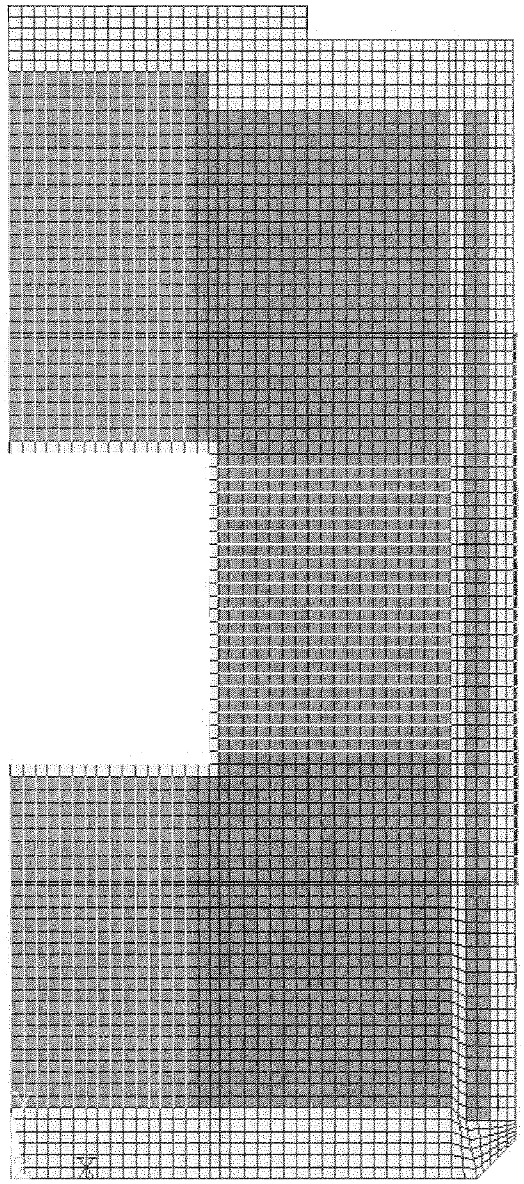

Figure 4 – 10-160B Cask ANSYS NCT and HAC Model Element / Material Plot

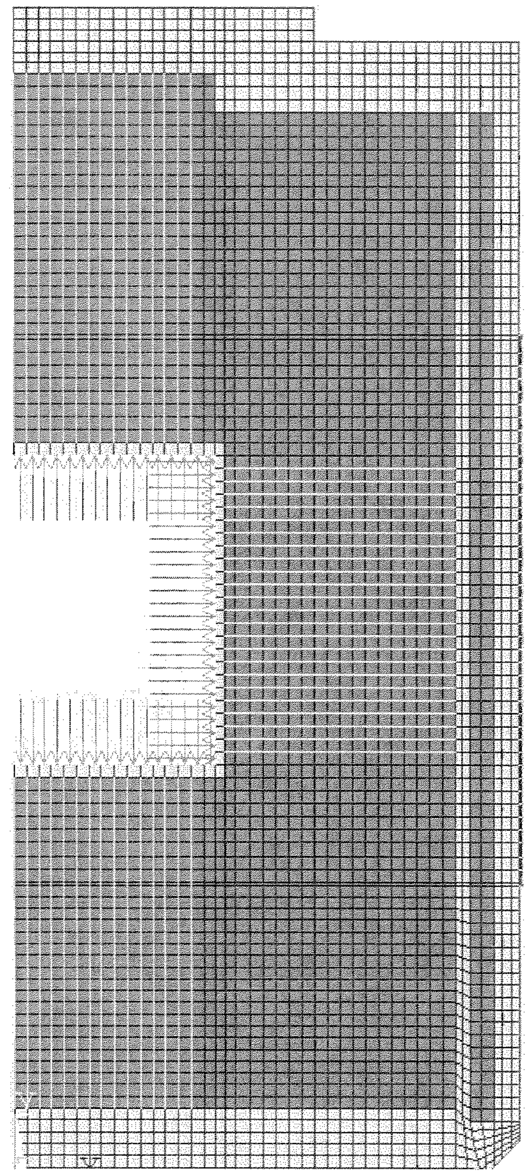

Figure 5 – "Hot spot" Cavity Heat Load (NCT and HAC)

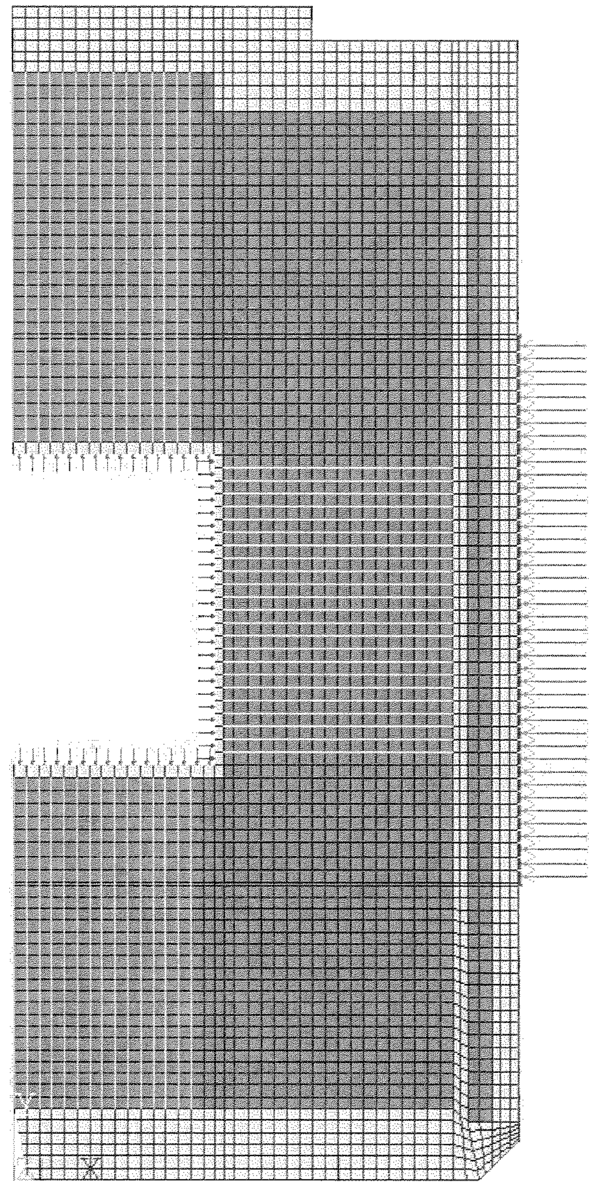

Figure 6 – Solar Heat and Cavity Heat Load (NCT Hot Day, only)

5.1.2 10-160B Transportation Cask Thermal Boundary Conditions

Thermal boundary conditions consist primarily of the following:

- For the NCT and HAC cases, a 200-Watt nominal heat flux smeared evenly within the "hot spot" cavity on all surfaces (radial and axial ends). Refer to the assumptions as listed in Section 4.3.
- For the NCT hot day case, 80% of the 12-hour average solar heat load is applied to the exposed vertical curved (radial) external surfaces of the 10-160B Transportation Cask.
- For NCT and HAC cases, ANSYS thermal / temperature-dependent calculations, Surf151 elements are used to model the natural convection and forced convection (HAC 30-minute fire case, only) film coefficient - combined with radiation heat transfer to an external ambient node.
- Ambient temperature during NCT: 100°F
- Ambient temperature during HAC 30-minute fire: 1475°F
- Ambient temperature during HAC pre-fire and cool-down period: 100°F

5.1.2.1 Waste Liner Heat Load

The 10-160B Transportation Cask "hot spot" heat load is modeled as a small hollow cylindrical carbon steel shell, located at the center of the cask cavity, with dimensions as depicted by Figure 7. For both the NCT and HAC cases, a uniform heat flux is applied to the ANSYS thermal models utilizing the SFE command for hflux with respect to appropriately selected Surf151 elements within the hot spot / hollow cylinder's cavity. The uniform heat flux is calculated as follows:

Heat flux = 200 Watts x 3.412 Btu/hr/Watt / (Cavity Area)

Cavity area = $\pi*R*2*L + 2*\pi*R^2$

Where,

R = 15.5 inches

L = 24 inches

Cavity area = 3847.8 in^2

Therefore, the "hot spot" heat flux is given by:

Heat flux = 200*3.412 / 3847.8 = 0.17739 Btu/hr/ in^2

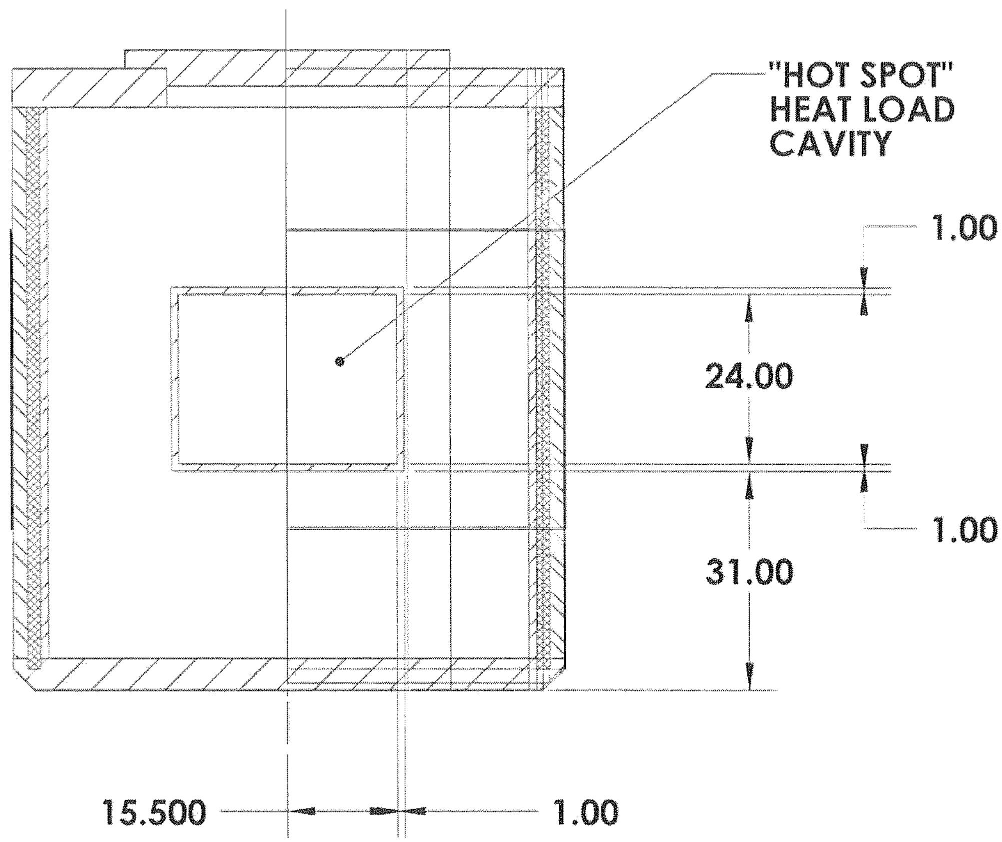

Figure 7 – 10-160B Cask Assumed Centered "Hot Spot" Heat Load

5.2 Real Constants as used with ANSYS (Link 31) Radiation Elements

5.2.1 Axial Radiation Links Between Hot Spot Cavity and Inner Cask Cavity

Simplifying assumptions are made that moderately under-estimate the axial radiation link areas such that only the projected areas between the top of the "hot spot" cavity and the bottom of the cask lid are included. It is noted that 100% of the heat that is transferred initially in the axial direction is eventually be transferred by conduction through the radial shells of the cask, and, via convection and radiation transferred to the ambient environment (note: no conduction is assumed on the exterior shell of the cask).

As per the ANSYS input file, the tributary lengths (based upon Real constants) are calculated as follows:

Real 61 = π*.5^2 = 0.785398 in^2 !Circular area
Real 62 = π*1.5^2-π*0.5^2 = 6.283 in^2 ! Annular ring area, typical
Real 63 = π*2.5^2-π*1.5^2 = 12.566 in^2

Real 64 = π*3.5^2-π*2.5^2 = 18.850 in^2
Real 65 = π*4.5^2-π*3.5^2 = 25.133 in^2
Real 66 = π*5.5^2-π*4.5^2 = 31.416 in^2
Real 67 = π*6.5^2-π*5.5^2 = 37.699 in^2
Real 68 = π*7.5^2-π*6.5^2 = 43.982 in^2
Real 69 = π*8.5^2-π*7.5^2 = 50.265 in^2
Real 70 = π*9.5^2-π*8.5^2 = 56.549 in^2
Real 71 = π*10.5^2-π*9.5^2 = 62.832 in^2
Real 72 = π*11.5^2-π*10.5^2 = 69.115 in^2
Real 73 = π*12.5^2-π*11.5^2 = 75.398 in^2
Real 74 = π*13.5^2-π*12.5^2 = 81.681 in^2
Real 75 = π*14.5^2-π*13.5^2 = 87.965 in^2

5.2.2 Radial Radiation Links (Link31) Between Hot Spot Cavity and Inner Cask Cavity

The areas used for the radial radiation links (Link31 elements) between the inner shell "hot spot" and the cask cavity are calculated as an average tributary (inner radius and outer radius) area. These average areas are then subdivided based upon the nodal tributary lengths associated with each Link31 element. The overall axial length of this radial heat transfer path is limited to the projected area of the "hot spot" inner cylinder and the inner shell of the cask. The tributary areas used are calculated as follows:

Tributary Area = π* Diameter * Axial Length (in^2)
Tributary Area = π* 2 * (Inner Radius + Outer Radius) / 2 * (1-inch)
Tributary Area = π* (16.5 + 34)
Tributary Area = 158.6 in^2

The heat transfer by radiation between two nodes of (type Link31 elements) of the finite element model is governed by the classical heat transfer equations that are available in the ANSYS user manual and/or as is further described within Energy*Solutions* calculation # TH-018 [3.1.1]. In addition, the methodologies employed by ANSYS to determine the effective emissivity of the associated elements are based upon classical heat transfer techniques and are discussed in detail within the ANSYS user manual.

5.2.3 Radial Radiation Links (Link31) Between the Outer Shell and the Fire Shield

The methodologies used for establishing (type Link31) radiation links within the fire shield are essentially the same as those used and discussed in Section 5.2.2, above. However, the links are located between the outer radius of the structural shell and the inner radius of the fire shield shell. Thus, the links are fairly short, and, the average tributary areas are calculated as follows:

Tributary area = π* 2 * (Inner Radius + Outer Radius) / 2 * (1-inch)
Tributary Area = π* (39 + 39.156)
Tributary Area = 246 in^2

5.3 Real Constants as used with ANSYS (Link 32) Conduction Elements

5.3.1 NCT Hot Day Wire Link Areas

The wire link conduction areas are calculated as follows (refer also to the assumptions of 12-inch on-center wire "hoops" in lieu of spirally wrapped wire, as noted in Section 4.3):

Area = 1/32 * π* 2 * R

Where,

R = 39.25 inches

Therefore,

Wire conduction area = 7.7 in^2

5.3.2 HAC Fire Case Fire Shield to Outer Shell Link Areas

For the HAC Fire case, the welds at the top and the bottom of the fire shield are modeled via link conductors. The size of the fire shield-to-outer shell weld conduction areas are calculated as follows (refer to the assumptions as noted in Section 4.3):

Area = 0.105-inches * π* 2 * R

Where,

R = 39.261 inches (note: this radius assumes the fire shield air gap is exactly equal to the wire diameter of 5/32-inch)

Therefore,

Fire shield – to – Outer Shell weld conduction area = 25.9 in^2

5.4 Material Properties

With the exception of the gamma shield (lead) material properties, all other 10-160B Transportation Cask material properties used in the thermal analysis are referenced from Table 2 of Energy*Solutions* calculation number TH-018 [3.1.1]. The densities and specific heats of lead at elevated temperatures are taken directly from Table I-53, Properties of Liquid Metals, of the CRC Handbook of Tables for Applied Engineering Science Handbook, 2nd Edition [3.2.1].

5.5 Load Step Methodology for HAC Fire Transient

The HAC fire case transient analysis consists of the following steps:

- Load step 1: Pre-fire (Steady-state)
  Assumptions for this load step include:

- 100°F ambient
- No solar heat load
- Natural convection on exterior surfaces of the cask
- Time at end of load step: .00001 hrs

- Load step 2: Ramp-up ambient temperature to 1475°F
  Assumptions for this load step include:
  - 1475°F ambient
  - No solar heat load
  - Forced convection on exterior surfaces of the cask
  - Time at end of load step: .001 hours

- Load step 3: 30-minute fire at 1475°F
  Assumptions for this load step include:
  - 1475°F ambient
  - No solar heat load
  - Forced convection on exterior surfaces of the cask
  - Time at end of load step: 0.5 hours

- Load step 4: Ramp-down ambient temperature to 100°F
  Assumptions for this load step include:
  - 100°F ambient
  - No solar heat load
  - Natural convection on exterior surfaces of the cask
  - Time at end of load step: 0.5001 hours

- Load step 5: 48-hours of cool-down
  Assumptions for this load step include:
  - 100°F ambient
  - Solar heat load included
  - Natural convection on exterior surfaces of the cask
  - Time at end of load step: 48.5 hours

5.6 Solution Methodology

A steady-state analysis is performed for the NCT case using the default ANSYS Mechanical / Thermal module solution methodology.

A transient analysis is performed by the HAC case using the default ANSYS Mechanical / Thermal module solution methodology for transient analyses (i.e., ANSYS command "**TRNOPT**" is set to "FULL" for pure thermal transients and ANSYS automatic time stepping is set to "on"). A multi-frame solve methodology was employed to capture each of the five load steps and the resultant output data.

6. CALCULATIONS

6.1 Calculation Results

Table 2 presents the NCT Hot Day 10-160B Transportation Cask maximum cask material temperatures versus cask materials and/or cask structural components. Note: these maximum material temperatures occur at the top and bottom of the cask cavity (as depicted by Figure 8 and Figure 9).

Table 3 presents the HAC Fire Case 10-160B Transportation Cask maximum cask material temperatures versus cask materials and/or cask structural components. Note: the inner and outer steel shell and lead maximum material temperatures occur at an elevation located radially-inward from the exposed fire shield (as depicted by Figure 11). The temperature distribution in the cask body at the end of a 48-hour cool-down period is depicted in Figure 12.

HAC fire case transient plots (temperature versus time, in hours) are presented in Figure 13 through Figure 17. As can be seen from these figures, the cask surface temperatures reach their peak at the end of the 30-minute fire, and, the inner shells of the cask reach their peak temperatures during the cool-down period, thereafter. Table 2 and Table 3 list the component maximum temperatures, based upon the transient plot data, as presented below.

6.1.1 Cask Cavity Air Bulk Average Temperature Results

The cavity bulk air temperatures reflect element averaged values of the results of the ANSYS 2D axisymmetric NCT and HAC analyses. However, it is noted that these numbers reflect the generalized assumptions regarding the size and nature of the "hot spot" heat load (refer to Section 4 and paragraph 5.1.2.1).

6.1.1.1 NCT Hot Day: Bulk Average Air Temperature

Based upon the ANSYS model results for the NCT hot day case, the maximum (steady-state) bulk average temperature of the cask cavity air is 188°F. For reference, the nodal temperature distribution in the cask cavity air for the NCT hot day is depicted in Figure 10.

6.1.1.2 HAC Fire Case: Bulk Average Air Temperature

Based upon the ANSYS model results for the HAC fire case, the maximum bulk average temperature of the cask cavity air is approximately 178°F (occurring at the end of the 48-hour cool-down period).

Table 2 – 10-160B Cask NCT Hot Day Maximum Material / Component Temperatures

Component	Component Material	Maximum Temperature (°F)
Lid (@ axial centerline)	Carbon steel	175
O-ring (primary lid)	Elastomeric	173
O-ring (secondary lid)	Elastomeric	174
Inner shell	Carbon steel	173
Gamma shield	Lead	173
Outer shell	Carbon steel	173
Fire shield	Carbon steel	171
Cavity bulk air	Air	188

Table 3 – 10-160B Cask HAC Fire Case Maximum Material / Component Temperatures

Component	Component Material	Maximum Temperature (°F)	Time (hours)
Lid @ axial centerline	Carbon steel	163.9	19.67
O-ring (primary lid)	Elastomeric	163.9	19.67
O-ring (secondary lid)	Elastomeric	164.5	23.87
Inner shell	Carbon steel	273.8	0.77
Gamma shield	Lead	274.4	0.73
Outer shell	Carbon steel	289.1	0.50
Fire shield	Carbon steel	1368.4	0.50
Cavity bulk air (peak nodal temperature)	Air	273.8	0.77
Cavity air (peak bulk average temperature)	Air	178.2[1]	48.5

[1] Note: the HAC transient cavity bulk air average temperature is less than the steady-state case because the models include slight differences, including external fire shield emissivity differences, and, slight differences in the conduction within the fire shield's air gap region (refer to Section 4.3 and Section 8.1).

Table 4 – Summary of Through-Wall Results

Condition	NCT Hot Day	HAC Fire	
	(°F)	(°F)	(hours)
Maximum temperature difference: inner shell to outer shell	0.2	39.8	0.5001
Maximum temperature difference: outer shell	0.0	20.2	0.5001
Maximum temperature difference: inner shell	0.0	2.3	0.5001
Maximum thru-wall average temperature[2]: inner-to-outer shell @ center of cask	172.6	279.3	0.5334

[2] Maximum average wall temperaturea are based upon the nodal temperatures @ nodes 2816 and 1355.

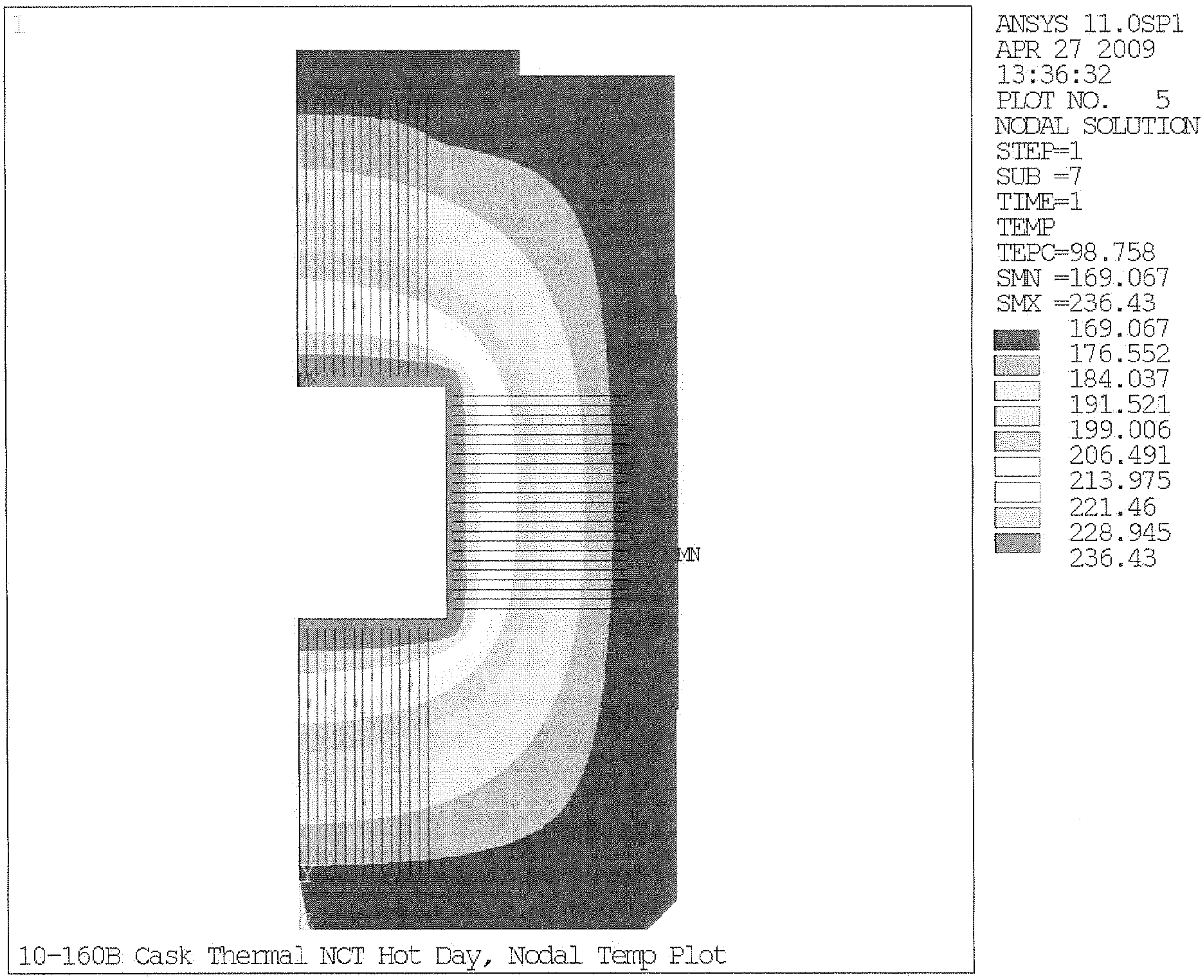

Figure 8 – 10-160B Cask NCT Hot Day (air, lead and steel): Nodal Temps

Figure 9 – 10-160B Cask NCT Hot Day (steel, only): Nodal Temps

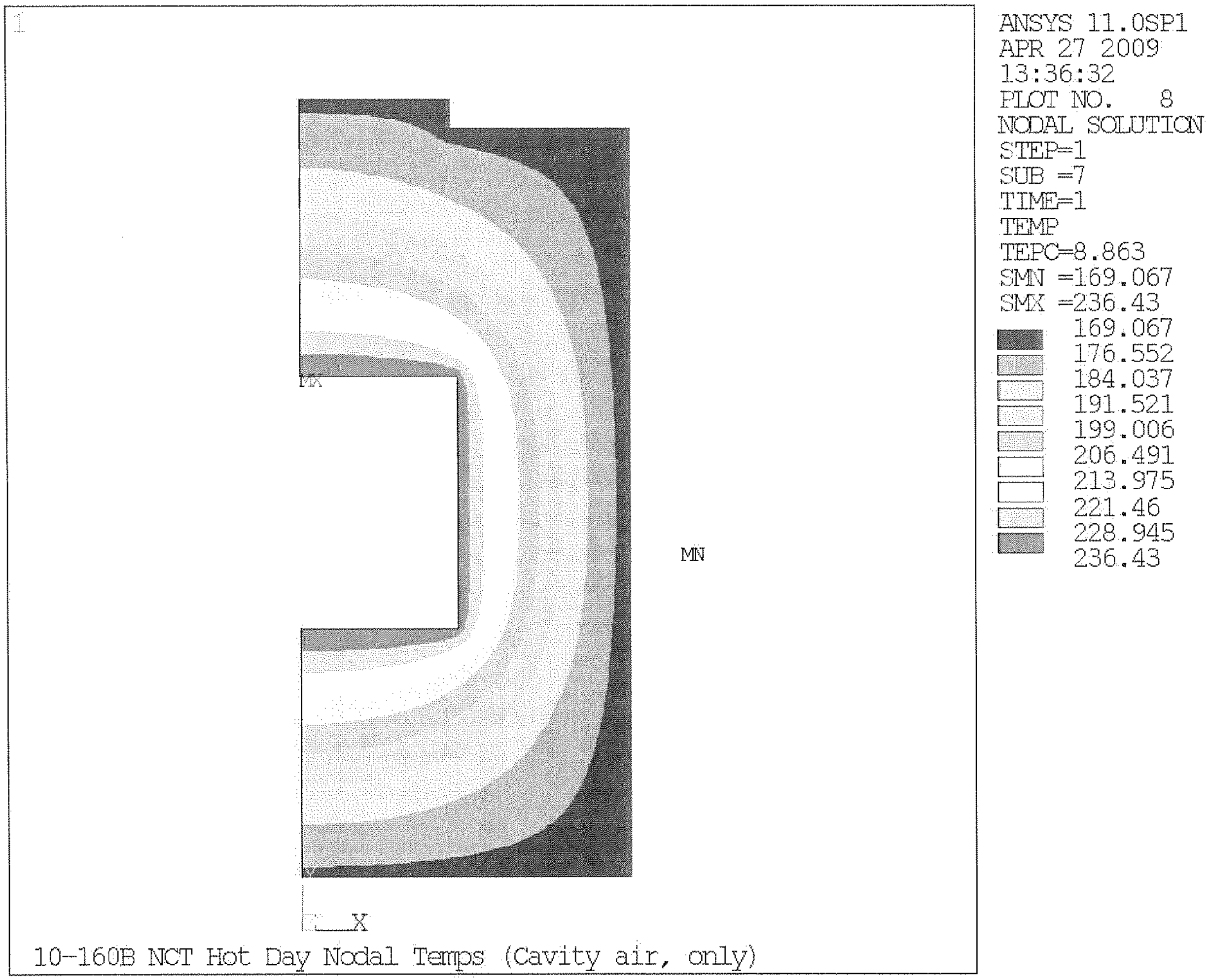

Figure 10 – 10-160B Cask NCT Hot Day (air, only): Nodal Temps

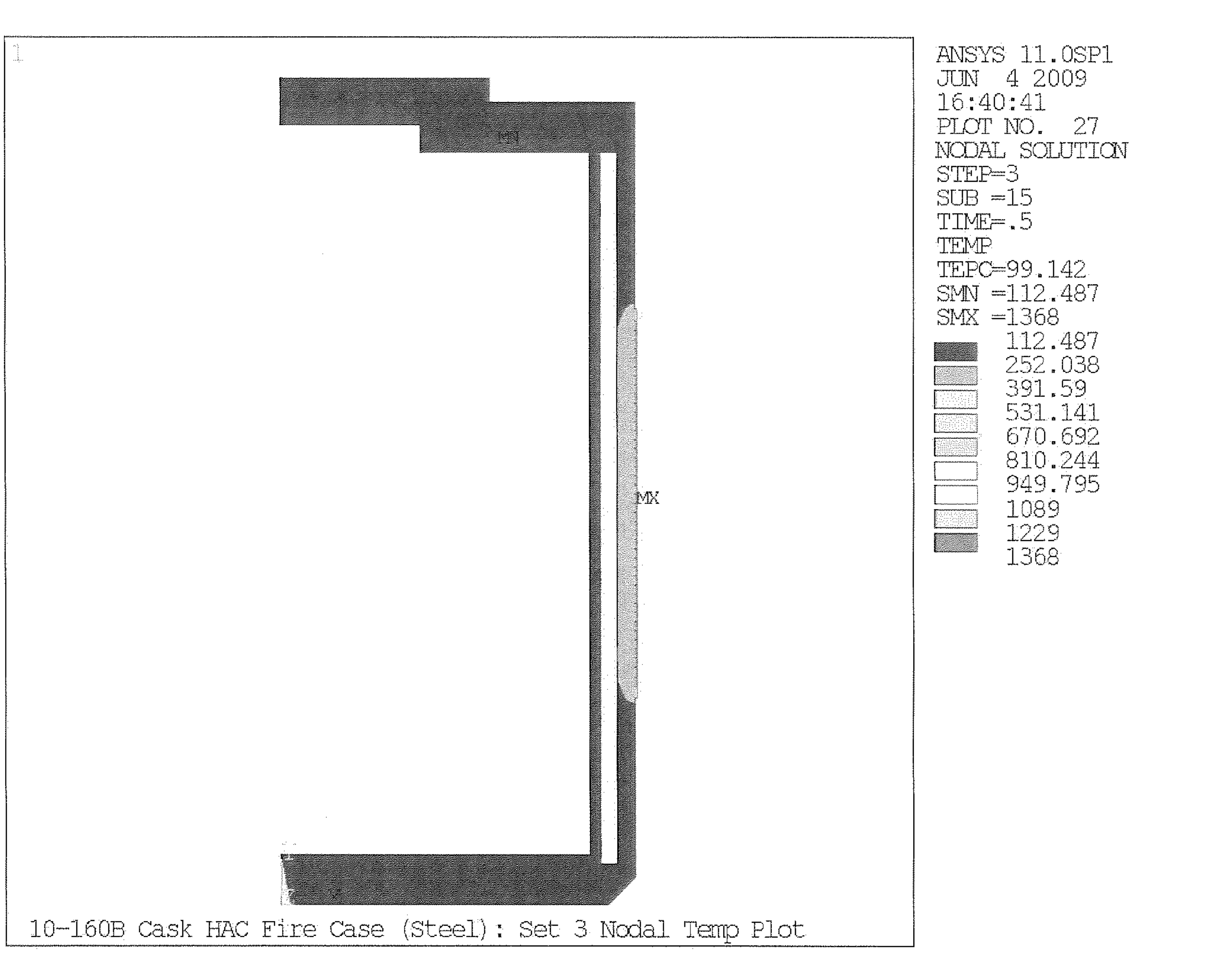

Figure 11 – 10-160B Cask HAC Fire (steel): Nodal temps @ End of 30 Min Fire

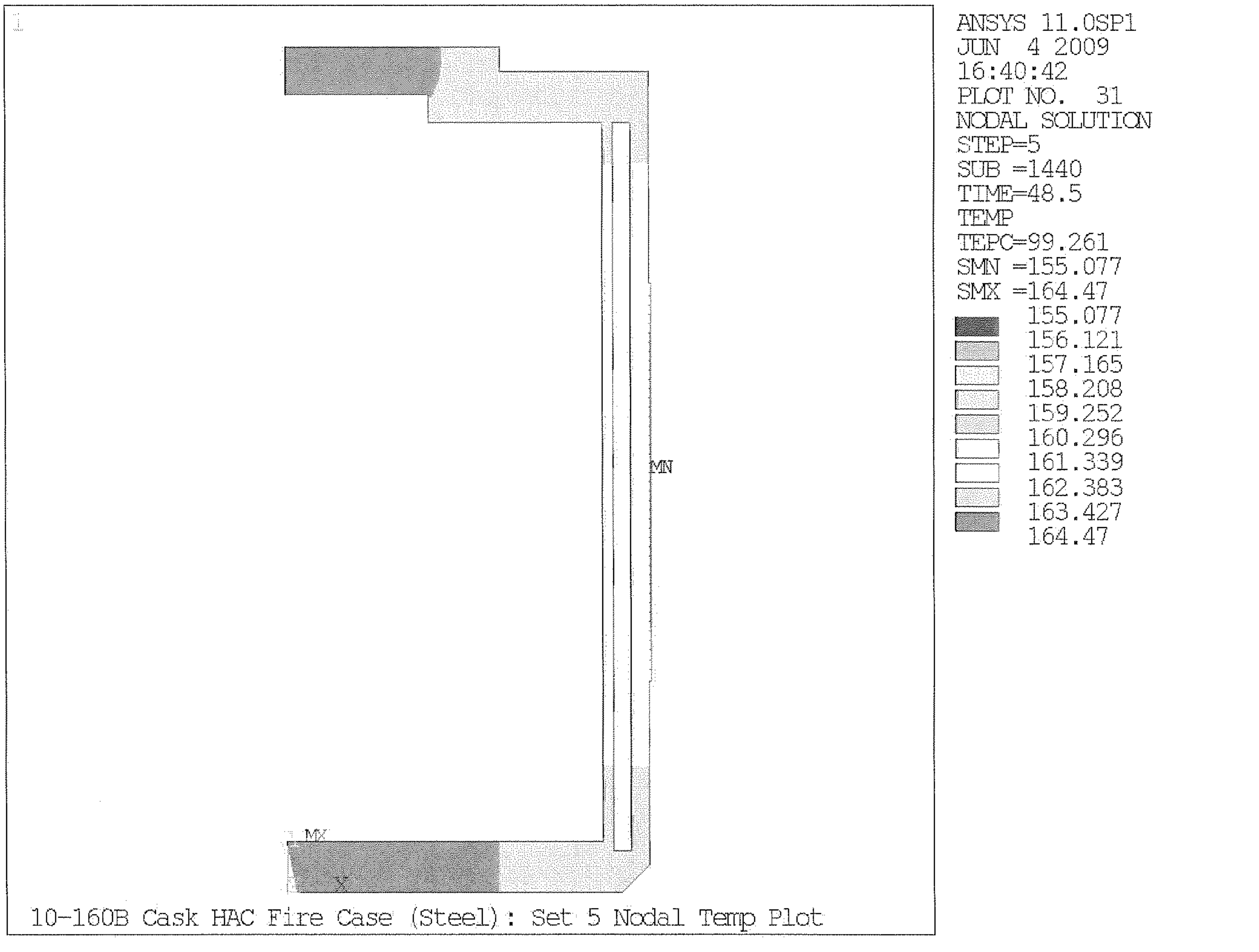

Figure 12 – 10-160B Cask HAC Fire (steel): Nodal temps @ End of 48-Hr Cool-down

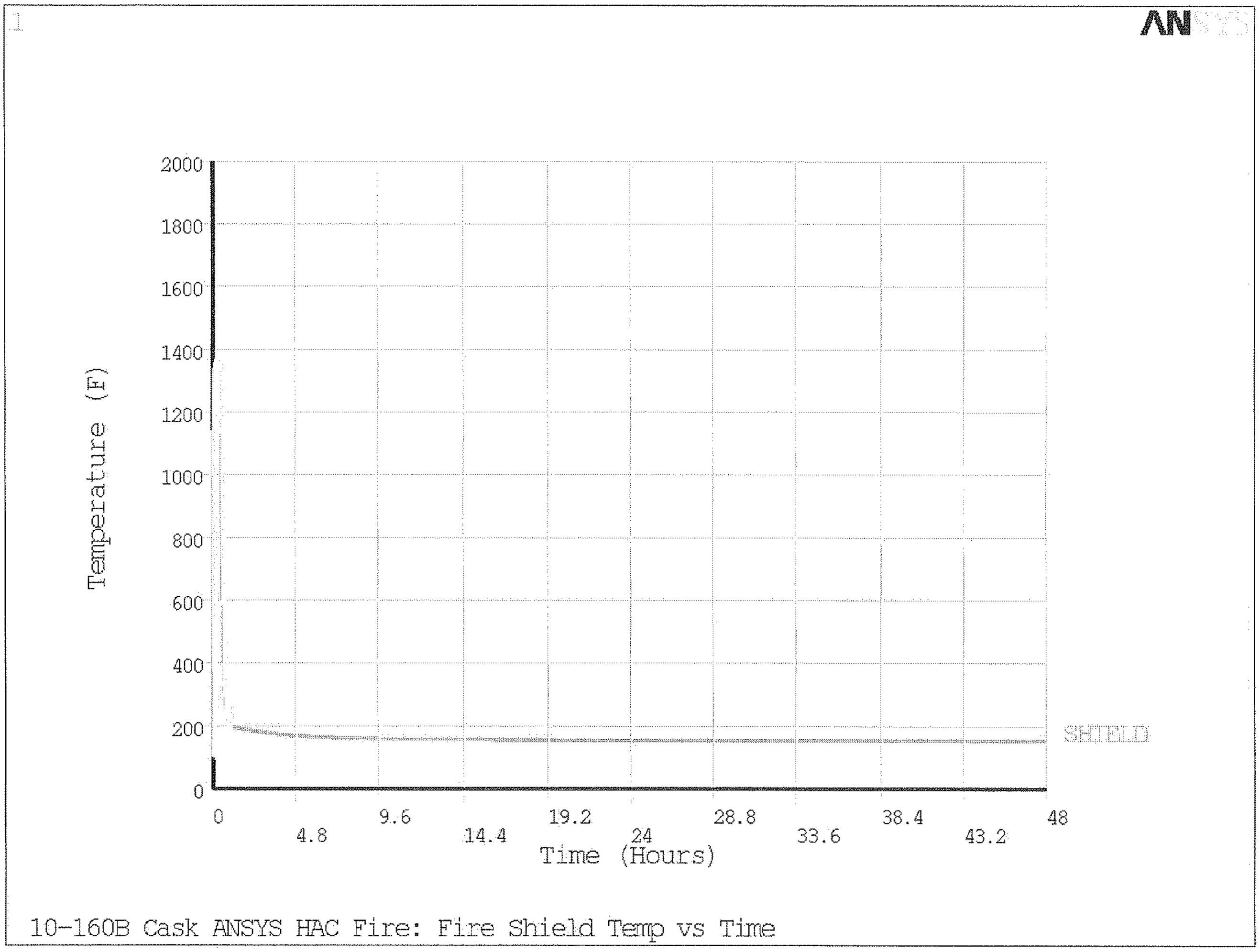

Figure 13 – HAC Fire: Fire Shield Temperature Transient Plot

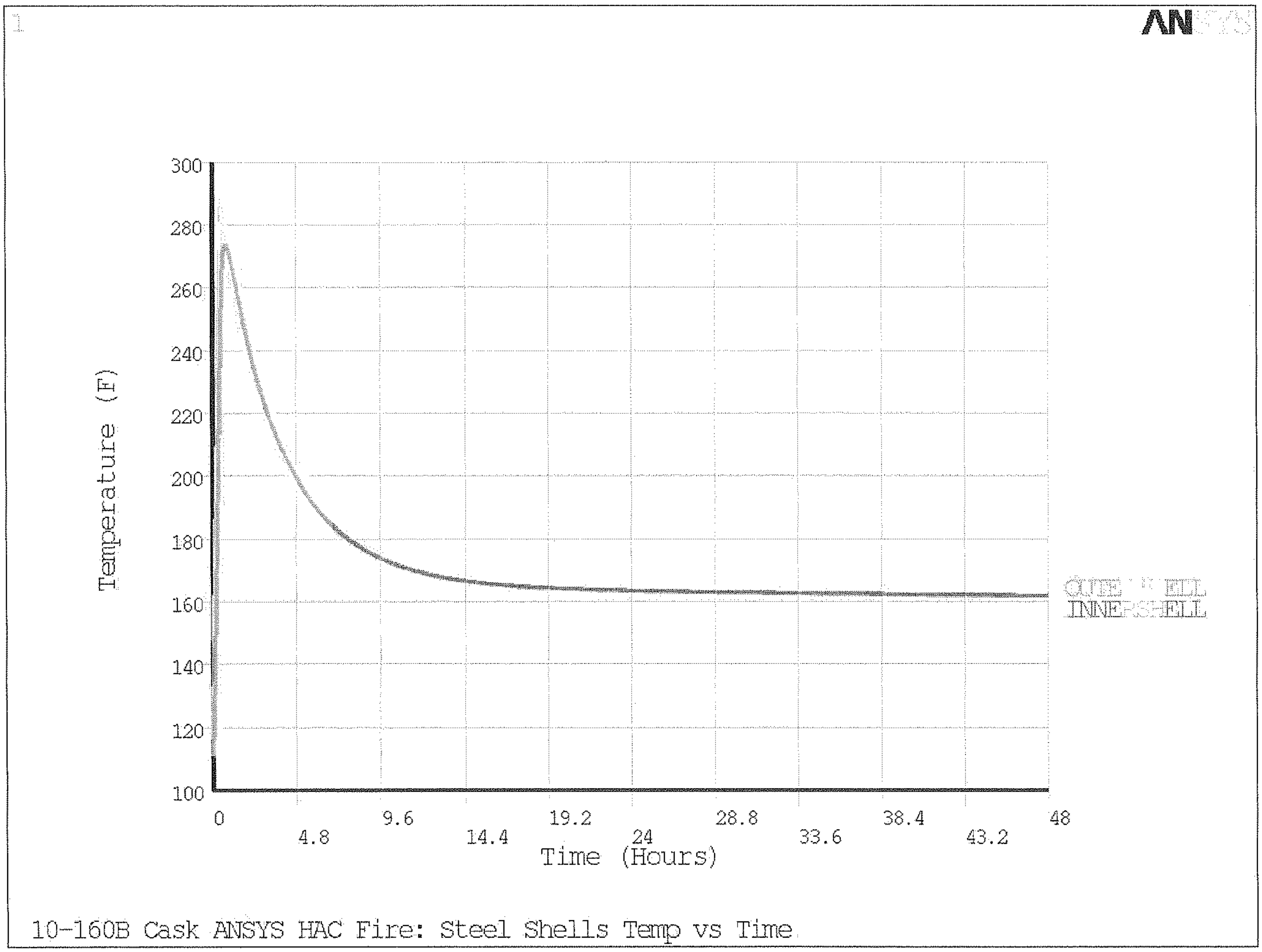

Figure 14 – HAC Fire: Inner and Outer Carbon Steel Shells Temperature Transient Plot

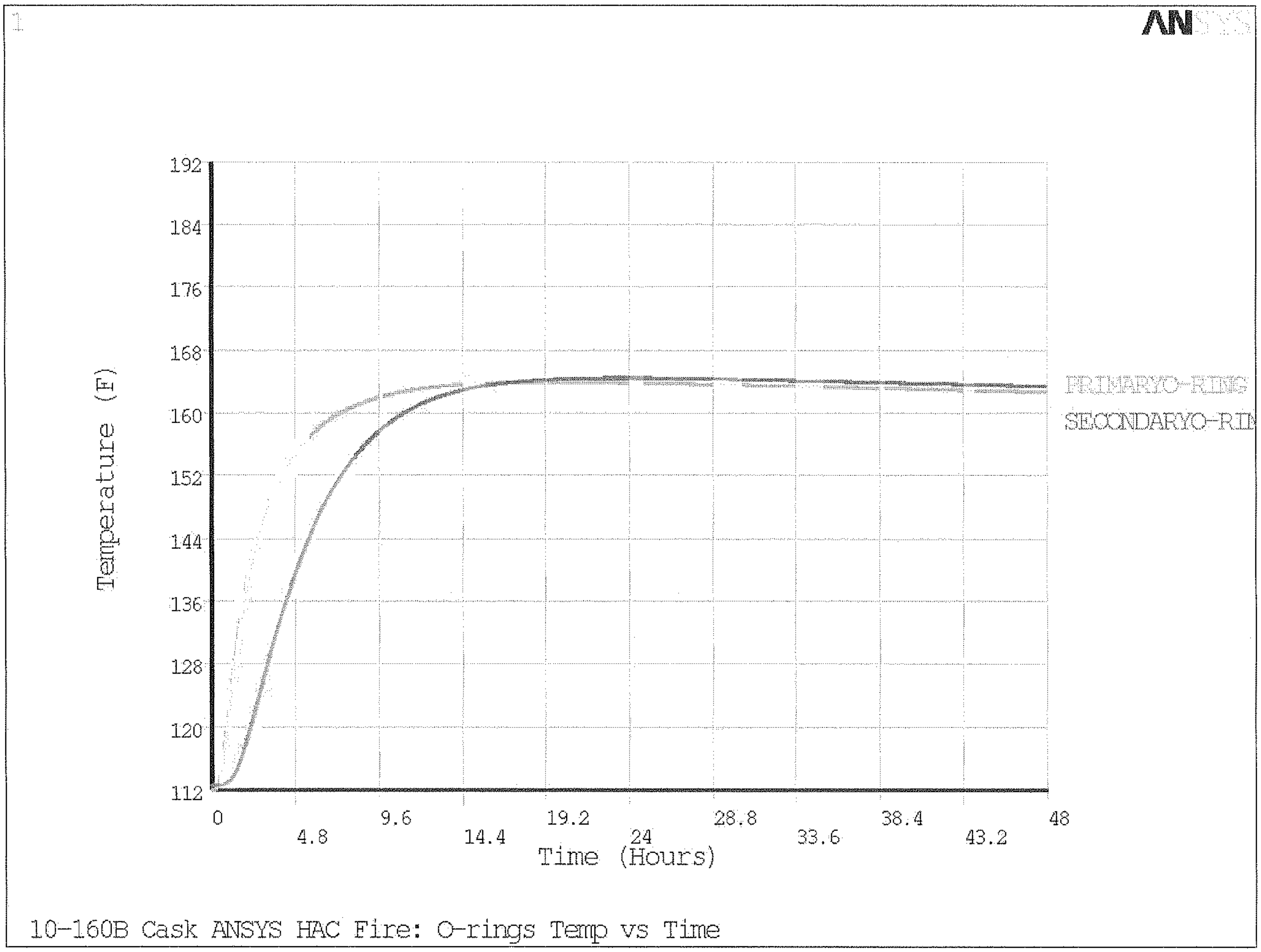

Figure 15 – HAC Fire: O-ring Temperature Transient Plot

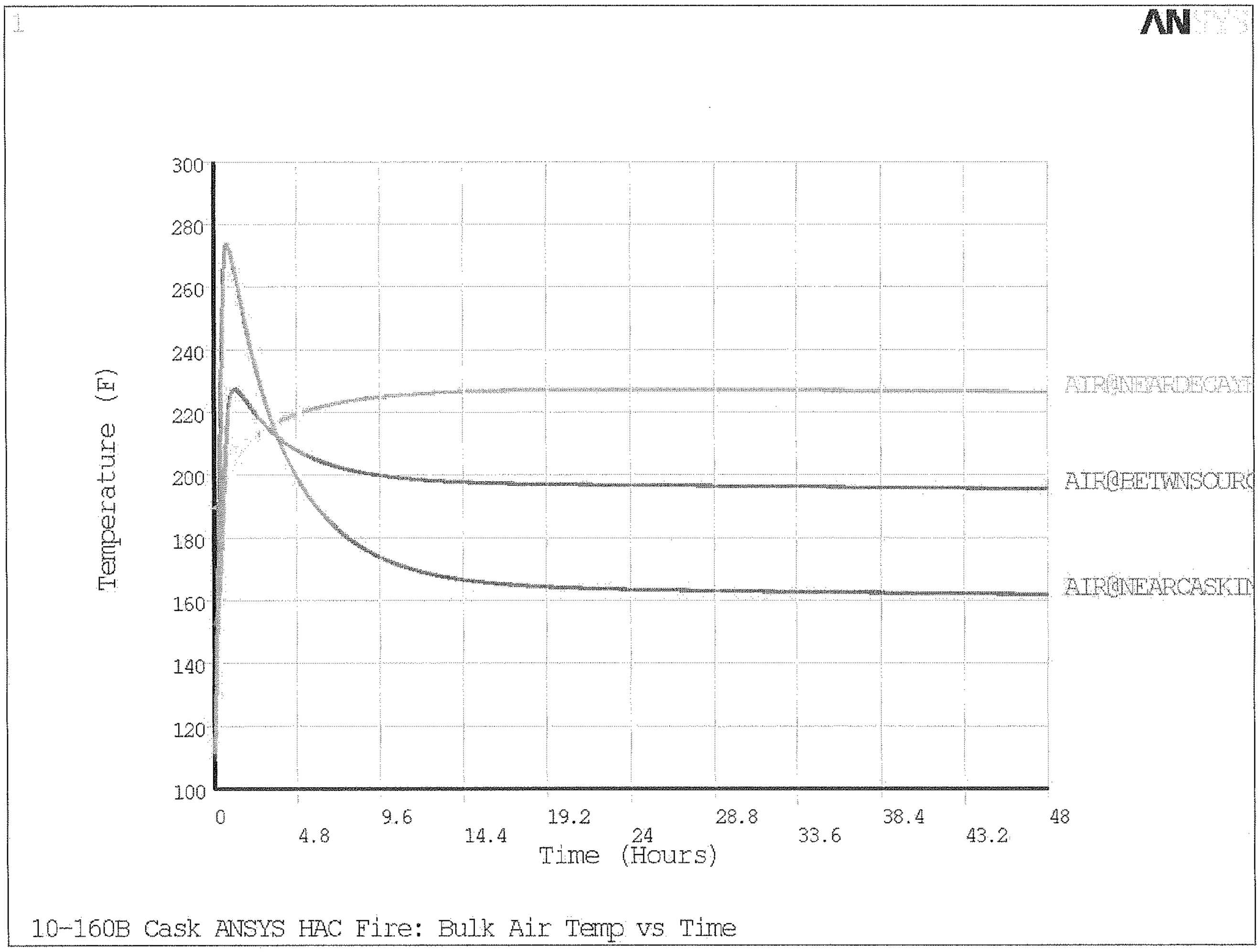

Figure 16 – HAC Fire: Cavity Bulk Air Temperature Transient Plot

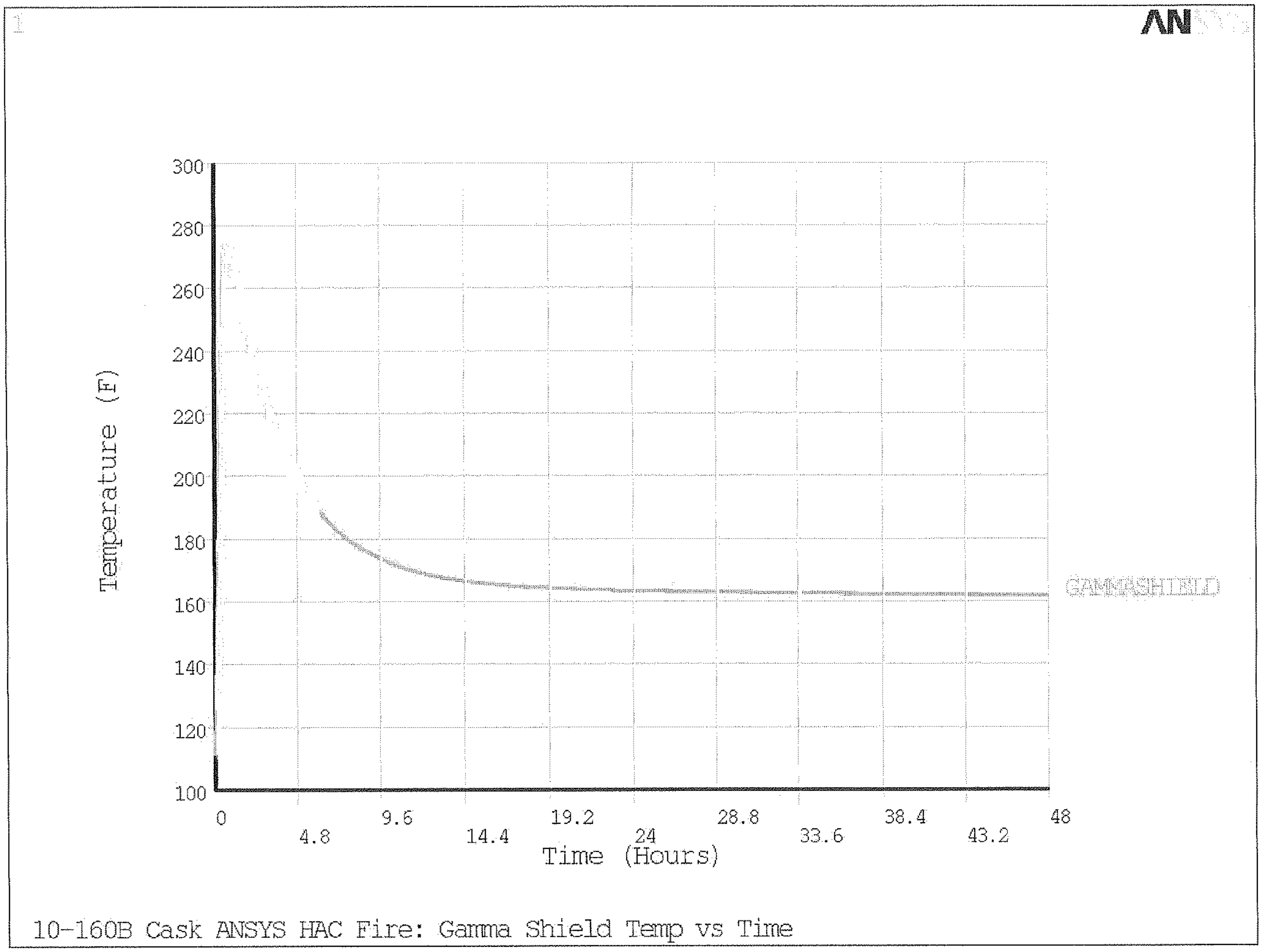

Figure 17 – HAC Fire: Gamma Shield Temperature Transient Plot

7. CONCLUSIONS

7.1 Results

7.1.1 General

Refer to Table 2 for the NCT hot case results and Table 3 for the HAC fire case results.

For the NCT hot condition (as per Table 2), the maximum temperatures of the 10-160B Transportation Cask components do not exceed 175°F. In addition, for the NCT hot case, the maximum bulk average temperature of the air within the cask cavity is 188°.

For the HAC fire case (as per Table 3), with the exception of the fire shield with an external peak temperature of 1368.4°F, the maximum temperatures of the other cask components do not exceed 289.1°F. In addition, for the HAC fire case, the maximum bulk average temperature of the air within the cask cavity is approximately 178°F and the maximum O-ring temperature is 164°F. The peak HAC fire case bulk average cavity air temperature occurs at the end of the 48-hour cool-down period.

Finally, through-wall temperature gradients for the NCT Hot Day and HAC Fire case are provided in Table 4. Per this table, the maximum through-wall temperature (inner shell to outer shell) for the NCT and HAC Fire case are 0.2°F and 39.8°F, respectively.

7.2 Compliance With Requirements

None.

7.3 Range of Validity

The analyses are valid over the range of design conditions as specified in Table 1.

7.4 Summary of Conservatisms

The following bullets summarize the main 10-160B Transportation Cask ANSYS analysis features that conservatively affect the thermal analysis results:

- A conservative solar heat load is assumed;
- A "hot spot" decay heat load is assumed;
- No convection is assumed within the cask cavity and/or within the fire shield air gap;
- For the NCT steady-state hot case, pure natural convection / radiation on all external surfaces is assumed (note: zero wind / no air disturbance is assumed);

7.5 Limitations or Special Instructions

In accordance with the assumptions and/or decay limitations as listed above, no other limitations and/or special instructions are required.

8. ELECTRONIC FILES

8.1 Computer Runs

Table 5 – Computer Runs

Filename	File Date	Computer Code	Cat	Version	Platform	Machine
10_160B_HAC_Fire_06_04_09.out	6/04/2009	ANSYS	2	11	Windows XP x. 64 Edition	26831-D
10_160B_NCT_Hot_04_29_09.out	4/29/2009	ANSYS	2	11	Windows XP x. 64 Edition	26831-D

8.2 Other Electronic Files

Not applicable.

9. ATTACHMENT A - SAMPLE COMPUTER INPUT/OUTPUT

10-160B Transportation Cask – Thermal Analysis for NCT Hot Case

```
/Title, 10-160B Cask Thermal Analysis, 200 W, 100F Hot Day (Vert)
/Prep7
!*
ANTYPE,Static
Toffst,460                    ! offset Degrees F to Degrees R
!
! Define relevant geometry / radii (INCHES)
!
*SET,X0,0
*SET,X1,15.5
*SET,X2,17
*SET,X3,23
*SET,X4,34
*SET,X5,35.125
*SET,X6,36
*SET,X7,37
*SET,X8,39
*SET,X9,39.145+(.156-.145)
*SET,X10,39.25+(.156-.145)
!
*SET,Y0,0
*SET,Y1,1
*SET,Y2,3
*SET,Y3,4.5
*SET,Y4,5.5
*SET,Y5,22.75
*SET,Y6,23
*SET,Y7,32
*SET,Y8,44
*SET,Y9,56
*SET,Y10,65
*SET,Y11,65.25
*SET,Y12,82.5
*SET,Y13,85.5
*SET,Y14,88
*SET,Y15,90.625
!
*set,Pi,acos(-1)
!
! Define load parameters
*set,qtot,200                 ! Heat load (Watts)
*set,qtotb,qtot*3.412         ! Heat load (Btu/hr)
*set,acav,Pi*X1*2*(24)+2*Pi*X1**2 ! Cavity area (in^2)
*set,QIN,qtotb/acav ! heat flux (Btu/hr-in^2)
*set,QSS,0.8*123/144          ! 12-hr max solar (Btu/hr/in^2)
*set,Tamb,100                 ! Ambient temp (deg F)
!
ET,1,PLANE55
KEYOPT,1,1,3                  ! Evaluate film coef. at diff temp
KEYOPT,1,3,1                  ! Axisymmetric option
!
! Surface flux elements
ET,2,Surf151
KEYOPT,2,3,1                  ! Axisymmetric
KEYOPT,2,4,1                  ! No midside node
KEYOPT,2,5,0                  ! No extra node
KEYOPT,2,6,0                  ! Bulk temp from extra node
KEYOPT,2,8,1                  ! Include heat flux
KEYOPT,2,9,0                  ! No radiation
!
! Convection / radiation to ambient
ET,3,Surf151
KEYOPT,3,3,1                  ! Axisymmetric
KEYOPT,3,4,1                  ! No midside node
```

```
KEYOPT,3,5,1                ! Etra node
KEYOPT,3,6,0                ! Bulk temp from extra node
KEYOPT,3,7,1                ! Multiply film coef by abs(Tsurf-Tamb)^n
KEYOPT,3,8,2                ! Evaluate film coef hf at avg film temp (TS +TB)/2
KEYOPT,3,9,1                ! Use radiation form factor / real constant
R,3,1,1.189583E-11! SBC (Btu/hr/in^2/R4)
rmore
rmore,.333
!
! Conduction link
ET,4,LINK32
R,4,7.7
!
! Radiation link (radial)
ET,5,LINK31
KEYOPT,5,3,0                ! Use standard radiation eqn
R,5,Pi*2*(x1+1+x4)/2*(1),1,0.15,1.189583E-11     ! Area, FF, Emis, SBC
R,6,Pi*2*(x8+x9)/2*(1),1,0.15,1.189583E-11       ! Area, FF, Emis, SBC
!
! Radial link (axial)
ET,6,LINK31
KEYOPT,6,3,0                ! Use standard radiation eqn
R,61,Pi*.5**2,1,0.15,1.189583E-11        ! Area, Form Factor, Emis, SBC
R,62,Pi*1.5**2-Pi*0.5**2,1,0.15,1.189583E-11     ! Area, FF, Emis, SBC
R,63,Pi*2.5**2-Pi*1.5**2,1,0.15,1.189583E-11     ! Area, FF, Emis, SBC
R,64,Pi*3.5**2-Pi*2.5**2,1,0.15,1.189583E-11     ! Area, FF, Emis, SBC
R,65,Pi*4.5**2-Pi*3.5**2,1,0.15,1.189583E-11     ! Area, FF, Emis, SBC
R,66,Pi*5.5**2-Pi*4.5**2,1,0.15,1.189583E-11     ! Area, FF, Emis, SBC
R,67,Pi*6.5**2-Pi*5.5**2,1,0.15,1.189583E-11     ! Area, FF, Emis, SBC
R,68,Pi*7.5**2-Pi*6.5**2,1,0.15,1.189583E-11     ! Area, FF, Emis, SBC
R,69,Pi*8.5**2-Pi*7.5**2,1,0.15,1.189583E-11     ! Area, FF, Emis, SBC
R,70,Pi*9.5**2-Pi*8.5**2,1,0.15,1.189583E-11     ! Area, FF, Emis, SBC
R,71,Pi*10.5**2-Pi*9.5**2,1,0.15,1.189583E-11    ! Area, FF, Emis, SBC
R,72,Pi*11.5**2-Pi*10.5**2,1,0.15,1.189583E-11   ! Area, FF, Emis, SBC
R,73,Pi*12.5**2-Pi*11.5**2,1,0.15,1.189583E-11   ! Area, FF, Emis, SBC
R,74,Pi*13.5**2-Pi*12.5**2,1,0.15,1.189583E-11   ! Area, FF, Emis, SBC
R,75,Pi*14.5**2-Pi*13.5**2,1,0.15,1.189583E-11   ! Area, FF, Emis, SBC
!
! Convection / radiation to ambient
ET,7,Surf151
KEYOPT,7,3,1                ! Axisymmetric
KEYOPT,7,4,1                ! No midside node
KEYOPT,7,5,1                ! Extra node
KEYOPT,7,6,0                ! Bulk temp from extra node
KEYOPT,7,7,1                ! Mult film coef by abs(Tsurf-Tamb)^n
KEYOPT,7,8,5                ! Differential temp abs(Tsurf-Tamb)
KEYOPT,7,9,1                ! Use rad form factor / real constant
R,7,1,1.189583E-11! SBC (Btu/hr/in^2/R4)
rmore
rmore,.333
!
!**********************************
! Material properties: carbon steel
!**********************************
MPTemp,1,  70, 100, 200, 300, 400, 500,
MPTemp,7,  600, 700, 800, 900,1000,1100,
MPTemp,13,1200,1300,1400,1500

MPData,kxx,1, 1,35.1/12,34.7/12,33.6/12,32.3/12,30.9/12,29.5/12,
MPData,kxx,1, 7,28.0/12,26.6/12,25.2/12,23.8/12,22.4/12,20.9/12,
MPData,kxx,1,13,19.5/12,18.0/12,16.4/12,15.7/12

MP,DENS,1,.2824

MPdata,C,1, 1,0.104,0.106,0.113,0.118,0.124,0.128
MPdata,C,1, 7,0.133,0.139,0.146,0.154,0.163,0.172
Mpdata,C,1,13,0.184,0.205,0.411,0.199
!
!********************************
! Material properties: lead
```

```
!*********************************
MPData,kxx,2, 1,20.1/12,19.9/12,19.4/12,18.8/12,18.2/12,17.7/12
MPData,kxx,2, 7,17.1/12,16.8/12,16.8/12,16.8/12,16.8/12,16.8/12
MPData,kxx,2,13,16.8/12,16.8/12,16.8/12,16.8/12

MPdata,DENS,2, 1,.411,.411,.411,.411,.411,.411
MPdata,DENS,2, 7,.411,.378,.377,.376,.374,.371
MPdata,DENS,2,13,.367,.364,.364,.364

MPdata,C,2, 1,0.0311,0.0311,0.0311,0.0311,0.0311,0.0311
MPdata,C,2, 7,0.0311,0.0380,0.0370,0.0370,0.0370,0.0370
MPdata,C,2,13,0.0370,0.0370,0.0370,0.0370
!
!*********************************
! Material properties: air
!*********************************
MPData,kxx,3, 1,0.01490/12,.01546/12,.01804/12,.02032/12,.02248/12,.02457/12
MPData,kxx,3, 7,0.02654/12,.02843/12,.03022/12,.03201/12,.03371/12,.03532/12
MPData,kxx,3,13,0.03691/12,.03844/12,.04011/12,.04193/12

MPdata,DENS,3,1,.07518/1728,.07105/1728,.05992/1728,.05237/1728,.04619/1728,.04141/1728
MPdata,DENS,3,7,.03747/1728,.03422/1728,.03141/1728,.02920/1728,.02715/1728,.02544/1728
MPdata,DENS,3,13,.02393/1728,.02254/1728,.02134/1728,.02023/1728

MPdata,C,3, 1,.2402,.2404,.2414,.2429,.2450,.2474
MPdata,C,3, 7,.2511,.2538,.2568,.2596,.2628,.2659
MPdata,C,3,13,.2689,.2717,.2742,.2766
!
!*********************************************************************
! Material properties: External surface elements / natural convection
!*********************************************************************
MPDATA,EMIS,4, 1,0.8,0.8,0.8,0.8,0.8,0.8
MPDATA,EMIS,4, 7,0.8,0.8,0.8,0.8,0.8,0.8
MPDATA,EMIS,4,13,0.8,0.8,0.8,0.8

MPdata,DENS,4,1,.07518/1728,.07105/1728,.05992/1728,.05237/1728,.04619/1728,.04141/1728
MPdata,DENS,4,7,.03747/1728,.03422/1728,.03141/1728,.02920/1728,.02715/1728,.02544/1728
MPdata,DENS,4,13,.02393/1728,.02254/1728,.02134/1728,.02023/1728

MPdata,C,4, 1,.2402,.2404,.2414,.2429,.2450,.2474
MPdata,C,4, 7,.2511,.2538,.2568,.2596,.2628,.2659
MPdata,C,4,13,.2689,.2717,.2742,.2766
!
!*************************************
! Material properties: stainless steel
!*************************************

MPData,kxx,5, 1,8.6/12,8.7/12,9.3/12,9.8/12,10.4/12,10.9/12,
MPData,kxx,5, 7,11.3/12,11.8/12,12.2/12,12.7/12,13.2/12,13.6/12,
MPData,kxx,5,13,14.0/12,14.5/12,14.9/12,15.3/12

MP,DENS,5,.291

MPdata,C,5, 1,0.117,0.117,0.122,0.126,0.129,0.131
MPdata,C,5, 7,0.133,0.135,0.136,0.138,0.139,0.141
Mpdata,C,5,13,0.141,0.143,0.144,0.145
!
!
/com *****************************************************
/com Create geometry / keypoints
/com *****************************************************
!
!
K,1,X0,Y0
K,2,X1,Y0
K,3,X2,Y0
K,4,X3,Y0
K,5,X4,Y0
K,6,X6,Y0
K,7,X7,Y1
```

```
K,8,X8,Y2
!
KGEN,2,1,5,1,,Y4,,20
K,26,X5,Y3
K,27,X7,Y3
K,28,X8,Y3
!
KGEN,2,21,25,1,,(Y5-Y4),,20
K,46,X5,Y5
K,47,X7,Y5
K,48,X8,Y5
K,49,X9,Y5
k,50,X10,Y5
!
KGEN,2,41,50,1,,(Y6-Y5),,20
KGEN,2,61,80,1,,(Y7-Y6),,20
KGEN,2,81,90,1,,(Y8-Y7),,20
KGEN,2,101,110,1,,(Y9-Y8),,20
KGEN,2,121,130,1,,(Y10-Y9),,20
KGEN,2,141,150,1,,(Y11-Y10),,20
KGEN,2,161,169,1,,(Y12-Y11),,20
KGEN,2,181,188,1,,(Y13-Y12),,20
KGEN,2,201,208,1,,(Y14-Y13),,20
KGEN,2,221,224,1,,(Y15-Y14),,20
!
! Define all working areas
!
A,1,2,22,21
A,2,3,23,22
A,3,4,24,23
A,4,5,25,24
A,5,6,26,25
A,6,7,27,26
A,7,8,28,27
!
/PNUM,KP,1
/PNUM,LINE,0
/PNUM,AREA,1
/PNUM,VOLU,0
/PNUM,NODE,0
/PNUM,TABN,0
/PNUM,SVAL,0
/NUMBER,0
/PNUM,ELEM,0
!
A,21,22,42,41
A,22,23,43,42
A,23,24,44,43
A,24,25,45,44
A,25,26,46,45
A,26,27,47,46
A,27,28,48,47
!
A,41,42,62,61
A,42,43,63,62
A,43,44,64,63
A,44,45,65,64
A,45,46,66,65
A,46,47,67,66
A,47,48,68,67
A,48,49,69,68
A,49,50,70,69
!
A,61,62,82,81
A,62,63,83,82
A,63,64,84,83
A,64,65,85,84
A,65,66,86,85
A,66,67,87,86
A,67,68,88,87
```

```
A,68,69,89,88
A,69,70,90,89
!
A,81,82,102,101
A,82,83,103,102
A,83,84,104,103
A,84,85,105,104
A,85,86,106,105
A,86,87,107,106
A,87,88,108,107
A,88,89,109,108
A,89,90,110,109
!
A,101,102,122,121
A,102,103,123,122
A,103,104,124,123
A,104,105,125,124
A,105,106,126,125
A,106,107,127,126
A,107,108,128,127
A,108,109,129,128
A,109,110,130,129
!
A,121,122,142,141
A,122,123,143,142
A,123,124,144,143
A,124,125,145,144
A,125,126,146,145
A,126,127,147,146
A,127,128,148,147
A,128,129,149,148
A,129,130,150,149
!
A,141,142,162,161
A,142,143,163,162
A,143,144,164,163
A,144,145,165,164
A,145,146,166,165
A,146,147,167,166
A,147,148,168,167
A,148,149,169,168
A,149,150,170,169
!
A,161,162,182,181
A,162,163,183,182
A,163,164,184,183
A,164,165,185,184
A,165,166,186,185
A,166,167,187,186
A,167,168,188,187
!
A,181,182,202,201
A,182,183,203,202
A,183,184,204,203
A,184,185,205,204
A,185,186,206,205
A,186,187,207,206
A,187,188,208,207
!
A,201,202,222,221
A,202,203,223,222
A,203,204,224,223
A,204,205,225,224
A,205,206,226,225
A,206,207,227,226
A,207,208,228,227
!
A,221,222,242,241
A,222,223,243,242
A,223,224,244,243
```

```
!
alls
asel,s,loc,x,0,x1
asel,u,loc,y,y0,y8-12
asel,u,loc,y,y8+12,y15
adele,all
alls
!
! CHOP LINES AND MESH AREAS
ALLS
LSEL,S,,,12
LESIZE,ALL,,,6
ALLS
LSEL,S,,,15
LESIZE,ALL,,,6
ALLS
LSEL,S,,,18
LESIZE,ALL,,,6
ALLS
LSEL,S,,,21
LESIZE,ALL,,,6
ALLS
LSEL,S,,,22
LESIZE,ALL,,,3
ALLS
LSEL,S,,,37
LESIZE,ALL,,,3
ALLS
LSEL,S,,,52
LESIZE,ALL,,,3
ALLS
LSEL,S,,,73
LESIZE,ALL,,,3
ALLS
LSEL,S,,,92
LESIZE,ALL,,,3
ALLS
LSEL,S,,,150
LESIZE,ALL,,,1
ALLS
LSEL,S,,,169
LESIZE,ALL,,,3
ALLS
LSEL,S,,,184
LESIZE,ALL,,,3
ALLS
LSEL,S,,,199
LESIZE,ALL,,,3
ALLS
LSEL,S,,,23
LESIZE,ALL,,,19
ALLS
LSEL,S,,,25
LESIZE,ALL,,,19
ALLS
LSEL,S,,,26
LESIZE,ALL,,,19
ALLS
LSEL,S,,,28
LESIZE,ALL,,,19
ALLS
LSEL,S,,,30
LESIZE,ALL,,,19
ALLS
LSEL,S,,,112
LESIZE,ALL,,,12
ALLS
LSEL,S,,,131
LESIZE,ALL,,,9
ALLS
```

```
LSEL,S,,,111
LESIZE,ALL,,,3
ALLS
LSEL,S,,,149
LESIZE,ALL,,,3
ALLS
LSEL,S,,,130
LESIZE,ALL,,,3
ALLS
LSEL,S,,,168
LESIZE,ALL,,,3
ALLS
LSEL,S,,,183
LESIZE,ALL,,,3
ALLS
LSEL,S,,,198
LESIZE,ALL,,,3
ALLS
!
ALLS
LSEL,U,,,12
LSEL,U,,,15
LSEL,U,,,18
LSEL,U,,,21
LSEL,U,,,22
LSEL,U,,,37
LSEL,U,,,52
LSEL,U,,,73
LSEL,U,,,92
LSEL,U,,,112
LSEL,U,,,131
LSEL,U,,,150
LSEL,U,,,169
LSEL,U,,,184
LSEL,U,,,199
lsel,u,,,23
lsel,u,,,25
lsel,u,,,26
lsel,u,,,28
lsel,u,,,30
lsel,u,,,112
lsel,u,,,131
lsel,u,,,111
lsel,u,,,149
lsel,u,,,130
lsel,u,,,168
lsel,u,,,183
lsel,u,,,198
!
LESIZE,ALL,1
ALLS
!
! Create area group = air
alls
asel,s,loc,y,y4,y12
asel,u,loc,x,x4,x10
cm,air_cav_1,area
alls
!
asel,s,loc,y,y12,y13
asel,u,loc,x,x1,x10
cm,air_cav_2,area
alls
!
asel,s,loc,y,y3,y11
asel,u,loc,x,x0,x8-.01
asel,u,loc,x,x9+.01,x10
cm,air_radial,area
alls
!
```

```
cmsel,s,air_cav_1
cmsel,a,air_cav_2
cmsel,a,air_radial,area
cm,air,area
type,1
REAL,1
mat,3
amesh,all
cmsel,u,air,area
cmdele,air_cav_1,area
cmdele,air_cav_2,area
cmdele,air_radial,area
alls
!
!
! Create area group - lead
alls
asel,s,loc,x,x5,x7
asel,u,loc,y,y0,y3-.01
asel,u,loc,y,y12,y15
cm,lead,area
type,1
REAL,1
mat,2
amesh,all
alls
!
! Create area group = steel
alls
asel,s,loc,y,y0,y4
cm,steel_1,area
alls
!
alls
asel,s,loc,x,x4,x10
cmsel,u,lead,area
cmsel,u,air,area
cm,steel_2,area
alls
!
alls
asel,s,loc,y,y12,y15
cmsel,u,air,area
cm,steel_3,area
alls
!
cmsel,s,steel_1,area
cmsel,a,steel_2,area
cmsel,a,steel_3,area
cm,steel,area
type,1
REAL,1
mat,1
amesh,all
cmsel,u,steel,area
cmdele,steel_1,area
cmdele,steel_2,area
cmdele,steel_3,area
alls
!
! Create element component groups / apply mats & elem types
alls
cmsel,s,air
nsla,s,1
esln,s,all
cm,air_elem,elem
alls
!
alls
cmsel,s,lead
```

```
nsla,s,1
esln,s,all
cm,lead_elem,elem
alls
!
alls
cmsel,s,steel
nsla,s,1
esln,s,all
cm,steel_elem,elem
alls
!
! Add wire spacer conduction links
alls
Type,4
Mat,5
REAL,4
E,Node(X8,y5,0),Node(X9,y5,0)
E,Node(X8,y7,0),Node(X9,y7,0)
E,Node(X8,y8,0),Node(X9,y8,0)
E,Node(X8,y9,0),Node(X9,y9,0)
E,Node(X8,y11,0),Node(X9,y11,0)
!
alls
!
! Modify air elements into a steel shell
alls
nsel,s,loc,y,y8-13-.01,y8+13+.01
nsel,u,loc,x,x1+1,x10
esln,s,1,all
emod,all,mat,1
alls
!
! Add radiation links from hot cavity to inner cavity wall
alls
Type,5
Mat,1
Real,5
!
E,Node(x1+1,y8+1,0),Node(x4,y8+1,0)
E,Node(x1+1,y8+2,0),Node(x4,y8+2,0)
E,Node(x1+1,y8+3,0),Node(x4,y8+3,0)
E,Node(x1+1,y8+4,0),Node(x4,y8+4,0)
E,Node(x1+1,y8+5,0),Node(x4,y8+5,0)
E,Node(x1+1,y8+6,0),Node(x4,y8+6,0)
E,Node(x1+1,y8+7,0),Node(x4,y8+7,0)
E,Node(x1+1,y8+8,0),Node(x4,y8+8,0)
E,Node(x1+1,y8+9,0),Node(x4,y8+9,0)
E,Node(x1+1,y8+10,0),Node(x4,y8+10,0)
E,Node(x1+1,y8+11,0),Node(x4,y8+11,0)
!
E,Node(x1+1,y8,0),Node(x4,y8,0)
!
E,Node(x1+1,y8-1,0),Node(x4,y8-1,0)
E,Node(x1+1,y8-2,0),Node(x4,y8-2,0)
E,Node(x1+1,y8-3,0),Node(x4,y8-3,0)
E,Node(x1+1,y8-4,0),Node(x4,y8-4,0)
E,Node(x1+1,y8-5,0),Node(x4,y8-5,0)
E,Node(x1+1,y8-6,0),Node(x4,y8-6,0)
E,Node(x1+1,y8-7,0),Node(x4,y8-7,0)
E,Node(x1+1,y8-8,0),Node(x4,y8-8,0)
E,Node(x1+1,y8-9,0),Node(x4,y8-9,0)
E,Node(x1+1,y8-10,0),Node(x4,y8-10,0)
E,Node(x1+1,y8-11,0),Node(x4,y8-11,0)
!
alls
!
! Add radiation links within fire shield
alls
Type,5
```

```
Mat,1
Real,6
!
E,Node(x8,y9+1,0),Node(x9,y9+1,0)
E,Node(x8,y9+2,0),Node(x9,y9+2,0)
E,Node(x8,y9+3,0),Node(x9,y9+3,0)
E,Node(x8,y9+4,0),Node(x9,y9+4,0)
E,Node(x8,y9+5,0),Node(x9,y9+5,0)
E,Node(x8,y9+6,0),Node(x9,y9+6,0)
E,Node(x8,y9+7,0),Node(x9,y9+7,0)
E,Node(x8,y9+8,0),Node(x9,y9+8,0)
!
E,Node(x8,y9,0),Node(x9,y9,0)
!
E,Node(x8,y8+1,0),Node(x9,y8+1,0)
E,Node(x8,y8+2,0),Node(x9,y8+2,0)
E,Node(x8,y8+3,0),Node(x9,y8+3,0)
E,Node(x8,y8+4,0),Node(x9,y8+4,0)
E,Node(x8,y8+5,0),Node(x9,y8+5,0)
E,Node(x8,y8+6,0),Node(x9,y8+6,0)
E,Node(x8,y8+7,0),Node(x9,y8+7,0)
E,Node(x8,y8+8,0),Node(x9,y8+8,0)
E,Node(x8,y8+9,0),Node(x9,y8+9,0)
E,Node(x8,y8+10,0),Node(x9,y8+10,0)
E,Node(x8,y8+11,0),Node(x9,y8+11,0)
!
E,Node(x8,y8,0),Node(x9,y8,0)
!
E,Node(x8,y8-1,0),Node(x9,y8-1,0)
E,Node(x8,y8-2,0),Node(x9,y8-2,0)
E,Node(x8,y8-3,0),Node(x9,y8-3,0)
E,Node(x8,y8-4,0),Node(x9,y8-4,0)
E,Node(x8,y8-5,0),Node(x9,y8-5,0)
E,Node(x8,y8-6,0),Node(x9,y8-6,0)
E,Node(x8,y8-7,0),Node(x9,y8-7,0)
E,Node(x8,y8-8,0),Node(x9,y8-8,0)
E,Node(x8,y8-9,0),Node(x9,y8-9,0)
E,Node(x8,y8-10,0),Node(x9,y8-10,0)
E,Node(x8,y8-11,0),Node(x9,y8-11,0)
!
E,Node(x8,y7,0),Node(x9,y7,0)
!
E,Node(x8,y7-1,0),Node(x9,y7-1,0)
E,Node(x8,y7-2,0),Node(x9,y7-2,0)
E,Node(x8,y7-3,0),Node(x9,y7-3,0)
E,Node(x8,y7-4,0),Node(x9,y7-4,0)
E,Node(x8,y7-5,0),Node(x9,y7-5,0)
E,Node(x8,y7-6,0),Node(x9,y7-6,0)
E,Node(x8,y7-7,0),Node(x9,y7-7,0)
E,Node(x8,y7-8,0),Node(x9,y7-8,0)
!
alls
!
Type,6
Mat,1
Real,61
E,Node(x0,y8+13,0),Node(x0,y13,0)       !Top rad link
E,Node(x0,y8-13,0),Node(x0,y4,0)        !Bottom rad link
Real,62
E,Node(x0+1,y8+13,0),Node(x0+1,y13,0)          !Top rad link
E,Node(x0+1,y8-13,0),Node(x0+1,y4,0)  !Bottom rad link
Real,63
E,Node(x0+2,y8+13,0),Node(x0+2,y13,0)          !Top rad link
E,Node(x0+2,y8-13,0),Node(x0+2,y4,0)  !Bottom rad link
Real,64
E,Node(x0+3,y8+13,0),Node(x0+3,y13,0)          !Top rad link
E,Node(x0+3,y8-13,0),Node(x0+3,y4,0)  !Bottom rad link
Real,65
E,Node(x0+4,y8+13,0),Node(x0+4,y13,0)          !Top rad link
E,Node(x0+4,y8-13,0),Node(x0+4,y4,0)  !Bottom rad link
```

```
Real,66
E,Node(x0+5,y8+13,0),Node(x0+5,y13,0)          !Top rad link
E,Node(x0+5,y8-13,0),Node(x0+5,y4,0)  !Bottom rad link
Real,67
E,Node(x0+6,y8+13,0),Node(x0+6,y13,0)          !Top rad link
E,Node(x0+6,y8-13,0),Node(x0+6,y4,0)  !Bottom rad link
Real,68
E,Node(x0+7,y8+13,0),Node(x0+7,y13,0)          !Top rad link
E,Node(x0+7,y8-13,0),Node(x0+7,y4,0)  !Bottom rad link
Real,69
E,Node(x0+8,y8+13,0),Node(x0+8,y13,0)          !Top rad link
E,Node(x0+8,y8-13,0),Node(x0+8,y4,0)  !Bottom rad link
Real,70
E,Node(x0+9,y8+13,0),Node(x0+9,y13,0)          !Top rad link
E,Node(x0+9,y8-13,0),Node(x0+9,y4,0)  !Bottom rad link
Real,71
E,Node(x0+10,y8+13,0),Node(x0+10,y13,0)        !Top rad link
E,Node(x0+10,y8-13,0),Node(x0+10,y4,0)         !Bottom rad link
Real,72
E,Node(x0+11,y8+13,0),Node(x0+11,y13,0)        !Top rad link
E,Node(x0+11,y8-13,0),Node(x0+11,y4,0)         !Bottom rad link
Real,73
E,Node(x0+12,y8+13,0),Node(x0+12,y13,0)        !Top rad link
E,Node(x0+12,y8-13,0),Node(x0+12,y4,0)         !Bottom rad link
Real,74
E,Node(x0+13,y8+13,0),Node(x0+13,y13,0)        !Top rad link
E,Node(x0+13,y8-13,0),Node(x0+13,y4,0)         !Bottom rad link
Real,75
E,Node(x0+14,y8+13,0),Node(x0+14,y13,0)        !Top rad link
E,Node(x0+14,y8-13,0),Node(x0+14,y4,0)         !Bottom rad link
!
/com *******************************************************
/com  Add boundary conditions
/com *******************************************************
!
! add extra nodes for surface effects
CSYS,0
WPCSYS,1,0
N,500001,x10+12,y8,0                    ! For side
!
!create surface elements in cavity for heat gen
alls
nsel,s,loc,x,0,x1+.01
nsel,u,loc,y,y8+12+.01,y15
nsel,u,loc,y,y0,y8-12-.01
type,2
REAL,2
mat,1
esurf
esel,s,type,,2
cm,hfluxin,elem
alls
! apply waste liner heat load to cavity
alls
cmsel,s,hfluxin
sfe,all,1,hflux,,QIN     ! cavity heat flux
!
! create surface elements for natural conv./radiation
csys,0
alls
nsel,s,loc,x,x10-.01,x10+20
nsel,u,loc,y,y0,y6-.01
nsel,u,loc,y,y10+.01,y15
type,3
REAL,3
Mat,4
esurf,500001
ALLS
esel,s,type,,3
cm,convside,elem
```

```
sfe,all,1,conv,1,,.19/144 !
!
!
! create surface elements on side for solar
csys,0
alls
nsel,s,loc,x,x10-.01,x10+20
nsel,u,loc,y,y0,y6-.01
nsel,u,loc,y,y10+.01,y15
type,2
REAL,2
Mat,4
esurf
ALLS
esel,s,type,,2
cmsel,u,hfluxin,elem
cm,convside,elem
SFE,all,1,hflux,,QSS              ! Solar load
!
ALLS
TUNIF,100
Finish
save
/sol
tunif,100
! APPLY TEMPERATURE BOUNDARY CONDITIONS
D,500001,TEMP,TAMB
CSYS,0
alls
save
!
AUTOTS,ON
NSUBST,10,20,5
KBC,0
CNVT,TEMP,100,.005
SOLVE
save
FINI
/POST1
! Re-set colors / background to white
/RGB,INDEX,100,100,100, 0
/RGB,INDEX, 80, 80, 80,13
/RGB,INDEX, 60, 60, 60,14
/RGB,INDEX, 0, 0, 0,15
!
! Create various element 2D plots
/nopr
/post1
/GRAPHICS,FULL
/SHOW,JPEG
/UDOC,1,cntr,Left ! Contour legend @ right
/view,1
/foc,1,auto
/dist,1
/lig,1,1
alls
/Title,10-160B Cask Thermal NCT Hot Day, Area Plot
/NUMBER,0
/pnum,area,1
aplot
/Title,10-160B Cask Thermal NCT Hot Day, Keypoint Plot
/NUMBER,2
/pnum,kp,1
kplot
/number,1
/Title,10-160B Cask Thermal NCT Hot Day, Node Plot
nplot
/psf,hflux,,0
/Title,10-160B Cask Thermal NCT Hot Day, Element & Material
/PNUM,ELEM,0
```

```
/pnum,mat,1
eplot
/Title,10-160B Cask Thermal NCT Hot Day, Element / Mat + Surf Loads
/psf,hflux,,2
!
!Plot nodal temps for cask and various components
!
alls
esel,u,type,,2
esel,u,type,,3
nsel,u,,,500001
/Title,10-160B Cask Thermal NCT Hot Day, Nodal Temp Plot
plns,temp
prns,temp
alls
cmsel,s,steel
esel,s,mat,,1
FLST,5,167,2,ORDE,34
FITEM,5,830
FITEM,5,-845
FITEM,5,862
FITEM,5,1026
FITEM,5,1028
FITEM,5,1030
FITEM,5,1032
FITEM,5,1034
FITEM,5,1036
FITEM,5,1038
FITEM,5,1040
FITEM,5,1042
FITEM,5,1044
FITEM,5,1046
FITEM,5,1048
FITEM,5,1266
FITEM,5,1268
FITEM,5,1270
FITEM,5,1272
FITEM,5,1274
FITEM,5,1276
FITEM,5,1278
FITEM,5,1280
FITEM,5,1282
FITEM,5,1284
FITEM,5,1286
FITEM,5,1288
FITEM,5,1506
FITEM,5,-1521
FITEM,5,1650
FITEM,5,3688
FITEM,5,-3710
FITEM,5,3752
FITEM,5,-3837
ESEL,U, , ,P51X
nsle
/Title,10-160B Cask Thermal NCT Hot Day, Nodal Temps (Steel)
esel,u,type,,2
esel,u,type,,3
nsel,u,,,500001
plns,temp
prns,temp
!
/show,,,,
/GROPTS,VIEW,1
!
!*****************************
!Average Air temp calc
!*****************************
!
/com
/com  This macro calculates the volume avg'd temp
```

```
/com  of the currently selected elements.
/com
/post1
alls
!Select air elements
cmsel,s,air
asel,u,loc,x,x8,x10
esla,s
FLST,5,16,2,ORDE,2
FITEM,5,1506
FITEM,5,-1521
ESEL,U, , ,P51X
FLST,5,16,2,ORDE,2
FITEM,5,830
FITEM,5,-845
ESEL,U, , ,P51X
FLST,5,26,2,ORDE,26
FITEM,5,862
FITEM,5,1026
FITEM,5,1028
FITEM,5,1030
FITEM,5,1032
FITEM,5,1034
FITEM,5,1036
FITEM,5,1038
FITEM,5,1040
FITEM,5,1042
FITEM,5,1044
FITEM,5,1046
FITEM,5,1048
FITEM,5,1266
FITEM,5,1268
FITEM,5,1270
FITEM,5,1272
FITEM,5,1274
FITEM,5,1276
FITEM,5,1278
FITEM,5,1280
FITEM,5,1282
FITEM,5,1284
FITEM,5,1286
FITEM,5,1288
FITEM,5,1650
ESEL,U, , ,P51X
cm,tempgrp,elem          ! Store current element group
!vtot=0.0                ! Reset total volume value
!totvxt=0.0              ! Reset total volume times temp. value
etable,tempe,temp        ! fill tempe with average element temp
ssum
etable,volue,volu        ! fill value with element volumes
ssum
smult,vtemp,tempe,volue,1,1   ! mult tempe*value for each element
ssum
*get,vtot,ssum,,item,volue    ! get sum of the volumes
ssum
*get,totvxt,ssum,,item,vtemp  ! get sum of TAVG*VOLUME
ssum
avetemp=totvxt/vtot      ! Calc average temperature
ssum                              ! sum the element table entries
cmsel,s,tempgrp          ! Restore initial element group
cmdel,tempgrp            ! Delete temporary element group
parsave,all,parameters,txt
*stat,avetemp
/Title, 10-160B Cask Element Plot (Cavity air, only)
eplot
save
/Title, 10-160B NCT Hot Day Nodal Temps (Cavity air, only)
esel,u,type,,2
esel,u,type,,3
nsel,u,,,500001
```

```
plns,temp
prns,temp
!
!************************************************
! Next, select the other components for max temps
!************************************************
!
! Top plate
alls
nsel,s,loc,y,y12,y15
FLST,5,48,1,ORDE,4
FITEM,5,2045
FITEM,5,-2060
FITEM,5,2694
FITEM,5,-2725
NSEL,u, , ,P51X
esel,u,mat,,3
esel,u,type,,2
esel,u,type,,3
esln,,1
esln
esel,u,mat,,3
/Title, 10-160B NCT Hot Day Nodal Temps (Top plate / lid)
plns,temp
prns,temp
!
! Primary lid o-ring nodal temps
alls
!nsel,s,loc,x,x5       !Reference where node 3615 is located
!nsel,r,loc,y,y13      !Reference where node 3615 is located
nsel,s,,,3615
esln
/Title, 10-160B NCT Hot Day Nodal Temps (Primary O-ring)
plns,temp
prns,temp
!
! Secondary lid o-ring nodal temps
alls
!nsel,s,loc,x,x2       !Reference where node 3687 is located
!nsel,r,loc,y,y14      !Reference where node 3687 is located
nsel,s,,,3687
esln
/Title, 10-160B NCT Hot Day Nodal Temps (Secondary O-ring)
plns,temp
prns,temp
!
! Gamma shield
alls
nsel,s,loc,x,x6,x7
nsel,u,loc,y,y0,y3-.0001
nsel,u,loc,y,y12+.0001,y15
esln,,1
esel,u,type,,2
esel,u,type,,3
nsel,u,,,500001
/Title, 10-160B NCT Hot Day Nodal Temps (Gamma shield, only)
plns,temp
prns,temp
!
! Outer shell
alls
nsel,s,loc,x,x7,x8
nsel,u,loc,y,y0,y3-.0001
nsel,u,loc,y,y12+.0001,y15
esln,,1
esel,u,mat,,2
esel,u,mat,,3
nsel,u,,,500001
/Title, 10-160B NCT Hot Day Nodal Temps (Outer shell, only)
plns,temp
```

```
prns,temp
!
! Inner shell
alls
nsel,s,loc,x,x4,x5
nsel,u,loc,y,y0,y3-.0001
nsel,u,loc,y,y12+.0001,y15
esln,,1
esel,u,mat,,2
esel,u,mat,,3
nsel,u,,,500001
/Title, 10-160B NCT Hot Day Nodal Temps (Inner shell, only)
plns,temp
prns,temp
!
! Fire shield
alls
nsel,s,loc,x,x9,x10
nsel,u,loc,y,y0,y5-.001
nsel,u,loc,y,y10,y15+.001
esln,,1
esel,u,mat,,2
esel,u,mat,,3
nsel,u,,,500001
/psf,hflux,,0
/Title, 10-160B NCT Hot Day Nodal Temps (Fire shield, only)
plns,temp
prns,temp
!
save
/show,,,,
/GROPTS,VIEW,1
/SHOW, TERM
/graphics,power
/COLOR, DEFAULT
save
```

10-160B Transportation Cask – Thermal Analysis for HAC Fire Case

```
/Title, 10-160B Cask Thermal Analysis, 200 W, Fire Case (Vertical)
/config,nres,5000
/Prep7
!
ANTYPE,Static
Toffst,460                    ! offset Degrees F to Degrees R
!
! Re-set colors / background to white
/RGB,INDEX,100,100,100, 0
/RGB,INDEX, 80, 80, 80,13
/RGB,INDEX, 60, 60, 60,14
/RGB,INDEX, 0, 0, 0,15
!
! Define radii (inches)
!
*SET,X0,0
*SET,X1,15.5
*SET,X2,17
*SET,X3,23
*SET,X4,34
*SET,X5,35.125
*SET,X6,36
*SET,X7,37
*SET,X8,39
*SET,X9,39.145+(.156-.145)
*SET,X10,39.25+(.156-.145)
!
! Define axial heights (inches)
!
*SET,Y0,0
```

```
*SET,Y1,1
*SET,Y2,3
*SET,Y3,4.5
*SET,Y4,5.5
*SET,Y5,22.75
*SET,Y6,23
*SET,Y7,32
*SET,Y8,44
*SET,Y9,56
*SET,Y10,65
*SET,Y11,65.25
*SET,Y12,82.5
*SET,Y13,85.5
*SET,Y14,88
*SET,Y15,90.625
!
*set,Pi,acos(-1)
!
! Define load parameters
*set,qtot,200                 ! Heat load (Watts)
*set,qtotb,qtot*3.412         ! Heat load (Btu/hr)
*set,acav,Pi*X1*2*(24)+2*Pi*X1**2 ! Cavity area (in^2)
*set,QIN,qtotb/acav ! heat flux (Btu/hr-in^2)
*set,QSS,0.8*123/144          ! 12-hr max solar (Btu/hr/in^2)
*set,Tamb,100                 ! Ambient temp (deg F)
!
ET,1,PLANE55
KEYOPT,1,1,3                  ! Evaluate film coef. at diff temp
KEYOPT,1,3,1                  ! Axisymmetric option
!
! Surface flux elements
ET,2,Surf151
KEYOPT,2,3,1                  ! Axisymmetric
KEYOPT,2,4,1                  ! No midside node
KEYOPT,2,5,0                  ! No extra node
KEYOPT,2,6,0                  ! Bulk temp from extra node
KEYOPT,2,8,1                  ! Include heat flux
KEYOPT,2,9,0                  ! No radiation
!
! Natural Ccnvection / radiation to ambient
ET,3,Surf151
KEYOPT,3,3,1                  ! Axisymmetric
KEYOPT,3,4,1                  ! No midside node
KEYOPT,3,5,1                  ! Etra node
KEYOPT,3,6,0                  ! Bulk temp from extra node
KEYOPT,3,7,1                  ! Multiply film coef by abs(Tsurf-Tamb)^n
KEYOPT,3,8,2                  ! Evaluate film coef hf at avg film temp (TS +TB)/2
KEYOPT,3,9,1                  ! Use radiation FF / real constant
R,3,1,1.189583E-11! SBC (Btu/hr/in^2/R4)
rmore
rmore,.333
!
! Conduction link
ET,4,LINK32
R,4,Pi*X10*2*.105   ! Weld thkns at top and bottom of fire shield
!
! Radiation link (radial)
ET,5,LINK31
KEYOPT,5,3,0                  ! Use standard radiation eqn
R,5,Pi*2*(x1+1+x4)/2*(1),1,0.15,1.189583E-11      ! Area, FF, Emis, SBC
!
! Radial link (axial)
ET,6,LINK31
KEYOPT,6,3,0                  ! Use standard radiation eqn
!
R,61,Pi*.5**2,1,0.15,1.189583E-11       ! Area, FF, Emis, SBC
R,62,Pi*1.5**2-Pi*0.5**2,1,1.189583E-11          ! Area, FF, Emis, SBC
R,63,Pi*2.5**2-Pi*1.5**2,1,0.15,1.189583E-11     ! Area, FF, Emis, SBC
R,64,Pi*3.5**2-Pi*2.5**2,1,0.15,1.189583E-11     ! Area, FF, Emis, SBC
R,65,Pi*4.5**2-Pi*3.5**2,1,0.15,1.189583E-11     ! Area, FF, Emis, SBC
```

```
R,66,Pi*5.5**2-Pi*4.5**2,1,0.15,1.189583E-11      ! Area, FF, Emis, SBC
R,67,Pi*6.5**2-Pi*5.5**2,1,0.15,1.189583E-11      ! Area, FF, Emis, SBC
R,68,Pi*7.5**2-Pi*6.5**2,1,0.15,1.189583E-11      ! Area, FF, Emis, SBC
R,69,Pi*8.5**2-Pi*7.5**2,1,0.15,1.189583E-11      ! Area, FF, Emis, SBC
R,70,Pi*9.5**2-Pi*8.5**2,1,0.15,1.189583E-11      ! Area, FF, Emis, SBC
R,71,Pi*10.5**2-Pi*9.5**2,1,0.15,1.189583E-11     ! Area, FF, Emis, SBC
R,72,Pi*11.5**2-Pi*10.5**2,1,0.15,1.189583E-11    ! Area, FF, Emis, SBC
R,73,Pi*12.5**2-Pi*11.5**2,1,0.15,1.189583E-11    ! Area, FF, Emis, SBC
R,74,Pi*13.5**2-Pi*12.5**2,1,0.15,1.189583E-11    ! Area, FF, Emis, SBC
R,75,Pi*14.5**2-Pi*13.5**2,1,0.15,1.189583E-11    ! Area, FF, Emis, SBC
!
! Radiation link (radial within fire shield)
ET,7,LINK31
KEYOPT,7,3,0                        ! Use standard radiation eqn
R,7,Pi*2*(x8+x9)/2*(1),1,0.15,1.189583E-11  ! Area, FF, Emis, SBC
!
! Forced Ccnvection / radiation to ambient
ET,8,Surf151
KEYOPT,8,3,1              ! Axisymmetric
KEYOPT,8,4,1              ! No midside node
KEYOPT,8,5,1              ! Etra node
KEYOPT,8,6,0              ! Bulk temp from extra node
KEYOPT,8,7,1              ! Apply film coefficient directly
KEYOPT,8,8,2              ! Evaluate film coef hf at avg film temp (TS +TB)/2
KEYOPT,8,9,1              ! Use radiation FF / real constant
R,8,1,1.189583E-11! SBC (Btu/hr/in^2/R4)
rmore
rmore,.333
!
!**********************************
! Material properties: carbon steel
!**********************************
MPTemp,1,  70, 100, 200, 300, 400, 500,
MPTemp,7,  600, 700, 800, 900,1000,1100,
MPTemp,13,1200,1300,1400,1500

MPData,kxx,1, 1,35.1/12,34.7/12,33.6/12,32.3/12,30.9/12,29.5/12,
MPData,kxx,1, 7,28.0/12,26.6/12,25.2/12,23.8/12,22.4/12,20.9/12,
MPData,kxx,1,13,19.5/12,18.0/12,16.4/12,15.7/12

MP,DENS,1,.2824

MPdata,C,1, 1,0.104,0.106,0.113,0.118,0.124,0.128
MPdata,C,1, 7,0.133,0.139,0.146,0.154,0.163,0.172
Mpdata,C,1,13,0.184,0.205,0.411,0.199
!
!*******************************
! Material properties: lead
!*******************************
MPData,kxx,2, 1,20.1/12,19.9/12,19.4/12,18.8/12,18.2/12,17.7/12
MPData,kxx,2, 7,17.1/12,16.8/12,16.8/12,16.8/12,16.8/12,16.8/12
MPData,kxx,2,13,16.8/12,16.8/12,16.8/12,16.8/12

MPdata,DENS,2, 1,.411,.411,.411,.411,.411,.411
MPdata,DENS,2, 7,.411,.378,.377,.376,.374,.371
MPdata,DENS,2,13,.367,.364,.364,.364

MPdata,C,2, 1,0.0311,0.0311,0.0311,0.0311,0.0311,0.0311
MPdata,C,2, 7,0.0311,0.0380,0.0370,0.0370,0.0370,0.0370
MPdata,C,2,13,0.0370,0.0370,0.0370,0.0370
!
!********************************
! Material properties: air
!********************************
MPData,kxx,3, 1,0.01490/12,.01546/12,.01804/12,.02032/12,.02248/12,.02457/12
MPData,kxx,3, 7,0.02654/12,.02843/12,.03022/12,.03201/12,.03371/12,.03532/12
MPData,kxx,3,13,0.03691/12,.03844/12,.04011/12,.04193/12

MPdata,DENS,3,1,.07518/1728,.07105/1728,.05992/1728,.05237/1728,.04619/1728,.04141/1728
MPdata,DENS,3,7,.03747/1728,.03422/1728,.03141/1728,.02920/1728,.02715/1728,.02544/1728
```

```
MPdata,DENS,3,13,.02393/1728,.02254/1728,.02134/1728,.02023/1728

MPdata,C,3, 1,.2402,.2404,.2414,.2429,.2450,.2474
MPdata,C,3, 7,.2511,.2538,.2568,.2596,.2628,.2659
MPdata,C,3,13,.2689,.2717,.2742,.2766
!
!*********************************************************************
! Material properties: External surface elements / natural convection
!*********************************************************************
MPDATA,EMIS,4, 1,0.9,0.9,0.9,0.9,0.9,0.9
MPDATA,EMIS,4, 7,0.9,0.9,0.9,0.9,0.9,0.9
MPDATA,EMIS,4,13,0.9,0.9,0.9,0.9

MPdata,DENS,4,1,.07518/1728,.07105/1728,.05992/1728,.05237/1728,.04619/1728,.04141/1728
MPdata,DENS,4,7,.03747/1728,.03422/1728,.03141/1728,.02920/1728,.02715/1728,.02544/1728
MPdata,DENS,4,13,.02393/1728,.02254/1728,.02134/1728,.02023/1728

!*************************************
! Material properties: stainless steel
!*************************************

MPData,kxx,5, 1,8.6/12,8.7/12,9.3/12,9.8/12,10.4/12,10.9/12,
MPData,kxx,5, 7,11.3/12,11.8/12,12.2/12,12.7/12,13.2/12,13.6/12,
MPData,kxx,5,13,14.0/12,14.5/12,14.9/12,15.3/12

MP,DENS,5,.291

MPdata,C,5, 1,0.117,0.117,0.122,0.126,0.129,0.131
MPdata,C,5, 7,0.133,0.135,0.136,0.138,0.139,0.141
Mpdata,C,5,13,0.141,0.143,0.144,0.145
!
/com *****************************************************
/com Create geometry / keypoints
/com *****************************************************
!
!*********************************************************************
! Material properties: External surface elements / forced convection
!*********************************************************************
MPDATA,EMIS,6, 1,0.9,0.9,0.9,0.9,0.9,0.9
MPDATA,EMIS,6, 7,0.9,0.9,0.9,0.9,0.9,0.9
MPDATA,EMIS,6,13,0.9,0.9,0.9,0.9

MPdata,DENS,6,1,.07518/1728,.07105/1728,.05992/1728,.05237/1728,.04619/1728,.04141/1728
MPdata,DENS,6,7,.03747/1728,.03422/1728,.03141/1728,.02920/1728,.02715/1728,.02544/1728
MPdata,DENS,6,13,.02393/1728,.02254/1728,.02134/1728,.02023/1728
!
K,1,X0,Y0
K,2,X1,Y0
K,3,X2,Y0
K,4,X3,Y0
K,5,X4,Y0
K,6,X6,Y0
K,7,X7,Y1
K,8,X8,Y2
!
KGEN,2,1,5,1,,Y4,,20
K,26,X5,Y3
K,27,X7,Y3
K,28,X8,Y3
!
KGEN,2,21,25,1,,(Y5-Y4),,20
K,46,X5,Y5
K,47,X7,Y5
K,48,X8,Y5
K,49,X9,Y5
k,50,X10,Y5
!
KGEN,2,41,50,1,,(Y6-Y5),,20
KGEN,2,61,80,1,,(Y7-Y6),,20
KGEN,2,81,90,1,,(Y8-Y7),,20
```

```
KGEN,2,101,110,1,,(Y9-Y8),,20
KGEN,2,121,130,1,,(Y10-Y9),,20
KGEN,2,141,150,1,,(Y11-Y10),,20
KGEN,2,161,169,1,,(Y12-Y11),,20
KGEN,2,181,188,1,,(Y13-Y12),,20
KGEN,2,201,208,1,,(Y14-Y13),,20
KGEN,2,221,224,1,,(Y15-Y14),,20
!
! Define all working areas
!
A,1,2,22,21
A,2,3,23,22
A,3,4,24,23
A,4,5,25,24
A,5,6,26,25
A,6,7,27,26
A,7,8,28,27
!
A,21,22,42,41
A,22,23,43,42
A,23,24,44,43
A,24,25,45,44
A,25,26,46,45
A,26,27,47,46
A,27,28,48,47
!
A,41,42,62,61
A,42,43,63,62
A,43,44,64,63
A,44,45,65,64
A,45,46,66,65
A,46,47,67,66
A,47,48,68,67
A,48,49,69,68
A,49,50,70,69
!
A,61,62,82,81
A,62,63,83,82
A,63,64,84,83
A,64,65,85,84
A,65,66,86,85
A,66,67,87,86
A,67,68,88,87
A,68,69,89,88
A,69,70,90,89
!
A,81,82,102,101
A,82,83,103,102
A,83,84,104,103
A,84,85,105,104
A,85,86,106,105
A,86,87,107,106
A,87,88,108,107
A,88,89,109,108
A,89,90,110,109
!
A,101,102,122,121
A,102,103,123,122
A,103,104,124,123
A,104,105,125,124
A,105,106,126,125
A,106,107,127,126
A,107,108,128,127
A,108,109,129,128
A,109,110,130,129
!
A,121,122,142,141
A,122,123,143,142
A,123,124,144,143
A,124,125,145,144
```

```
A,125,126,146,145
A,126,127,147,146
A,127,128,148,147
A,128,129,149,148
A,129,130,150,149
!
A,141,142,162,161
A,142,143,163,162
A,143,144,164,163
A,144,145,165,164
A,145,146,166,165
A,146,147,167,166
A,147,148,168,167
A,148,149,169,168
A,149,150,170,169
!
A,161,162,182,181
A,162,163,183,182
A,163,164,184,183
A,164,165,185,184
A,165,166,186,185
A,166,167,187,186
A,167,168,188,187
!
A,181,182,202,201
A,182,183,203,202
A,183,184,204,203
A,184,185,205,204
A,185,186,206,205
A,186,187,207,206
A,187,188,208,207
!
A,201,202,222,221
A,202,203,223,222
A,203,204,224,223
A,204,205,225,224
A,205,206,226,225
A,206,207,227,226
A,207,208,228,227
!
A,221,222,242,241
A,222,223,243,242
A,223,224,244,243
!A,224,225,245,244
!
alls
asel,s,loc,x,0,x1
asel,u,loc,y,y0,y8-12
asel,u,loc,y,y8+12,y15
adele,all
alls
!
! CHOP LINES AND MESH AREAS
ALLS
LSEL,S,,,12
LESIZE,ALL,,,6
ALLS
LSEL,S,,,15
LESIZE,ALL,,,6
ALLS
LSEL,S,,,18
LESIZE,ALL,,,6
ALLS
LSEL,S,,,21
LESIZE,ALL,,,6
ALLS
LSEL,S,,,22
LESIZE,ALL,,,3
ALLS
LSEL,S,,,37
```

```
LESIZE,ALL,,,3
ALLS
LSEL,S,,,52
LESIZE,ALL,,,3
ALLS
LSEL,S,,,73
LESIZE,ALL,,,3
ALLS
LSEL,S,,,92
LESIZE,ALL,,,3
ALLS
LSEL,S,,,150
LESIZE,ALL,,,1
ALLS
LSEL,S,,,169
LESIZE,ALL,,,3
ALLS
LSEL,S,,,184
LESIZE,ALL,,,3
ALLS
LSEL,S,,,199
LESIZE,ALL,,,3
ALLS
LSEL,S,,,23
LESIZE,ALL,,,19
ALLS
LSEL,S,,,25
LESIZE,ALL,,,19
ALLS
LSEL,S,,,26
LESIZE,ALL,,,19
ALLS
LSEL,S,,,28
LESIZE,ALL,,,19
ALLS
LSEL,S,,,30
LESIZE,ALL,,,19
ALLS
LSEL,S,,,112
LESIZE,ALL,,,12
ALLS
LSEL,S,,,131
LESIZE,ALL,,,9
ALLS
LSEL,S,,,111
LESIZE,ALL,,,3
ALLS
LSEL,S,,,149
LESIZE,ALL,,,3
ALLS
LSEL,S,,,130
LESIZE,ALL,,,3
ALLS
LSEL,S,,,168
LESIZE,ALL,,,3
ALLS
LSEL,S,,,183
LESIZE,ALL,,,3
ALLS
LSEL,S,,,198
LESIZE,ALL,,,3
ALLS
!
ALLS
LSEL,U,,,12
LSEL,U,,,15
LSEL,U,,,18
LSEL,U,,,21
LSEL,U,,,22
LSEL,U,,,37
```

```
LSEL,U,,,52
LSEL,U,,,73
LSEL,U,,,92
LSEL,U,,,112
LSEL,U,,,131
LSEL,U,,,150
LSEL,U,,,169
LSEL,U,,,184
LSEL,U,,,199
lsel,u,,,23
lsel,u,,,25
lsel,u,,,26
lsel,u,,,28
lsel,u,,,30
lsel,u,,,112
lsel,u,,,131
lsel,u,,,111
lsel,u,,,149
lsel,u,,,130
lsel,u,,,168
lsel,u,,,183
lsel,u,,,198
!
LESIZE,ALL,1
ALLS
!
! Create area group = air
alls
asel,s,loc,y,y4,y12
asel,u,loc,x,x4,x10
cm,air_cav_1,area
alls
!
asel,s,loc,y,y12,y13
asel,u,loc,x,x1,x10
cm,air_cav_2,area
alls
!
asel,s,loc,y,y3,y11
asel,u,loc,x,x0,x8-.01
asel,u,loc,x,x9+.01,x10
cm,air_radial,area
alls
!
cmsel,s,air_cav_1
cmsel,a,air_cav_2
cmsel,a,air_radial,area
cm,air,area
type,1
REAL,1
mat,3
amesh,all
cmsel,u,air,area
cmdele,air_cav_1,area
cmdele,air_cav_2,area
cmdele,air_radial,area
alls
!
!
! Create area group - lead
alls
asel,s,loc,x,x5,x7
asel,u,loc,y,y0,y3-.01
asel,u,loc,y,y12,y15
cm,lead,area
type,1
REAL,1
mat,2
amesh,all
alls
```

```
!
! Create area group = steel
alls
asel,s,loc,y,y0,y4
cm,steel_1,area
alls
!
alls
asel,s,loc,x,x4,x10
cmsel,u,lead,area
cmsel,u,air,area
cm,steel_2,area
alls
!
alls
asel,s,loc,y,y12,y15
cmsel,u,air,area
cm,steel_3,area
alls
!
cmsel,s,steel_1,area
cmsel,a,steel_2,area
cmsel,a,steel_3,area
cm,steel,area
type,1
REAL,1
mat,1
amesh,all
cmsel,u,steel,area
cmdele,steel_1,area
cmdele,steel_2,area
cmdele,steel_3,area
alls
!
! Create element component groups / apply mats & elem types
alls
cmsel,s,air
nsla,s,1
esln,s,all
cm,air_elem,elem
alls
!
alls
cmsel,s,lead
nsla,s,1
esln,s,all
cm,lead_elem,elem
alls
!
alls
cmsel,s,steel
nsla,s,1
esln,s,all
cm,steel_elem,elem
alls
!
! Add weld conduction links @ top / bottom of fire shield
alls
Type,4
Mat,5
REAL,4
E,Node(X8,y5,0),Node(X9,y5,0)
!E,Node(X8,y7,0),Node(X9,y7,0)
!E,Node(X8,y8,0),Node(X9,y8,0)
!E,Node(X8,y9,0),Node(X9,y9,0)
E,Node(X8,y11,0),Node(X9,y11,0)
!
alls
!
! Modify air elements into a steel shell
```

```
alls
nsel,s,loc,y,y8-13-.01,y8+13+.01
nsel,u,loc,x,x1+1,x10
esln,s,1,all
emod,all,mat,1
alls
!
! Add radiation links from hot cavity to inner cavity wall
alls
Type,5
Mat,1
Real,5
!
E,Node(x1+1,y8+1,0),Node(x4,y8+1,0)
E,Node(x1+1,y8+2,0),Node(x4,y8+2,0)
E,Node(x1+1,y8+3,0),Node(x4,y8+3,0)
E,Node(x1+1,y8+4,0),Node(x4,y8+4,0)
E,Node(x1+1,y8+5,0),Node(x4,y8+5,0)
E,Node(x1+1,y8+6,0),Node(x4,y8+6,0)
E,Node(x1+1,y8+7,0),Node(x4,y8+7,0)
E,Node(x1+1,y8+8,0),Node(x4,y8+8,0)
E,Node(x1+1,y8+9,0),Node(x4,y8+9,0)
E,Node(x1+1,y8+10,0),Node(x4,y8+10,0)
E,Node(x1+1,y8+11,0),Node(x4,y8+11,0)
!
E,Node(x1+1,y8,0),Node(x4,y8,0)
!
E,Node(x1+1,y8-1,0),Node(x4,y8-1,0)
E,Node(x1+1,y8-2,0),Node(x4,y8-2,0)
E,Node(x1+1,y8-3,0),Node(x4,y8-3,0)
E,Node(x1+1,y8-4,0),Node(x4,y8-4,0)
E,Node(x1+1,y8-5,0),Node(x4,y8-5,0)
E,Node(x1+1,y8-6,0),Node(x4,y8-6,0)
E,Node(x1+1,y8-7,0),Node(x4,y8-7,0)
E,Node(x1+1,y8-8,0),Node(x4,y8-8,0)
E,Node(x1+1,y8-9,0),Node(x4,y8-9,0)
E,Node(x1+1,y8-10,0),Node(x4,y8-10,0)
E,Node(x1+1,y8-11,0),Node(x4,y8-11,0)
!
alls
!
! Add radiation links within fire shield
alls
Type,7
Mat,1
Real,7
!
E,Node(x8,y9+1,0),Node(x9,y9+1,0)
E,Node(x8,y9+2,0),Node(x9,y9+2,0)
E,Node(x8,y9+3,0),Node(x9,y9+3,0)
E,Node(x8,y9+4,0),Node(x9,y9+4,0)
E,Node(x8,y9+5,0),Node(x9,y9+5,0)
E,Node(x8,y9+6,0),Node(x9,y9+6,0)
E,Node(x8,y9+7,0),Node(x9,y9+7,0)
E,Node(x8,y9+8,0),Node(x9,y9+8,0)
!
E,Node(x8,y9,0),Node(x9,y9,0)
!
E,Node(x8,y8+1,0),Node(x9,y8+1,0)
E,Node(x8,y8+2,0),Node(x9,y8+2,0)
E,Node(x8,y8+3,0),Node(x9,y8+3,0)
E,Node(x8,y8+4,0),Node(x9,y8+4,0)
E,Node(x8,y8+5,0),Node(x9,y8+5,0)
E,Node(x8,y8+6,0),Node(x9,y8+6,0)
E,Node(x8,y8+7,0),Node(x9,y8+7,0)
E,Node(x8,y8+8,0),Node(x9,y8+8,0)
E,Node(x8,y8+9,0),Node(x9,y8+9,0)
E,Node(x8,y8+10,0),Node(x9,y8+10,0)
E,Node(x8,y8+11,0),Node(x9,y8+11,0)
!
```

```
E,Node(x8,y8,0),Node(x9,y8,0)
!
E,Node(x8,y8-1,0),Node(x9,y8-1,0)
E,Node(x8,y8-2,0),Node(x9,y8-2,0)
E,Node(x8,y8-3,0),Node(x9,y8-3,0)
E,Node(x8,y8-4,0),Node(x9,y8-4,0)
E,Node(x8,y8-5,0),Node(x9,y8-5,0)
E,Node(x8,y8-6,0),Node(x9,y8-6,0)
E,Node(x8,y8-7,0),Node(x9,y8-7,0)
E,Node(x8,y8-8,0),Node(x9,y8-8,0)
E,Node(x8,y8-9,0),Node(x9,y8-9,0)
E,Node(x8,y8-10,0),Node(x9,y8-10,0)
E,Node(x8,y8-11,0),Node(x9,y8-11,0)
!
E,Node(x8,y7,0),Node(x9,y7,0)
!
E,Node(x8,y7-1,0),Node(x9,y7-1,0)
E,Node(x8,y7-2,0),Node(x9,y7-2,0)
E,Node(x8,y7-3,0),Node(x9,y7-3,0)
E,Node(x8,y7-4,0),Node(x9,y7-4,0)
E,Node(x8,y7-5,0),Node(x9,y7-5,0)
E,Node(x8,y7-6,0),Node(x9,y7-6,0)
E,Node(x8,y7-7,0),Node(x9,y7-7,0)
E,Node(x8,y7-8,0),Node(x9,y7-8,0)
!
alls
!
Type,6
Mat,1
Real,61
E,Node(x0,y8+13,0),Node(x0,y13,0)       !Top rad link
E,Node(x0,y8-13,0),Node(x0,y4,0)        !Bottom rad link
Real,62
E,Node(x0+1,y8+13,0),Node(x0+1,y13,0)           !Top rad link
E,Node(x0+1,y8-13,0),Node(x0+1,y4,0)  !Bottom rad link
Real,63
E,Node(x0+2,y8+13,0),Node(x0+2,y13,0)           !Top rad link
E,Node(x0+2,y8-13,0),Node(x0+2,y4,0)  !Bottom rad link
Real,64
E,Node(x0+3,y8+13,0),Node(x0+3,y13,0)           !Top rad link
E,Node(x0+3,y8-13,0),Node(x0+3,y4,0)  !Bottom rad link
Real,65
E,Node(x0+4,y8+13,0),Node(x0+4,y13,0)           !Top rad link
E,Node(x0+4,y8-13,0),Node(x0+4,y4,0)  !Bottom rad link
Real,66
E,Node(x0+5,y8+13,0),Node(x0+5,y13,0)           !Top rad link
E,Node(x0+5,y8-13,0),Node(x0+5,y4,0)  !Bottom rad link
Real,67
E,Node(x0+6,y8+13,0),Node(x0+6,y13,0)           !Top rad link
E,Node(x0+6,y8-13,0),Node(x0+6,y4,0)  !Bottom rad link
Real,68
E,Node(x0+7,y8+13,0),Node(x0+7,y13,0)           !Top rad link
E,Node(x0+7,y8-13,0),Node(x0+7,y4,0)  !Bottom rad link
Real,69
E,Node(x0+8,y8+13,0),Node(x0+8,y13,0)           !Top rad link
E,Node(x0+8,y8-13,0),Node(x0+8,y4,0)  !Bottom rad link
Real,70
E,Node(x0+9,y8+13,0),Node(x0+9,y13,0)           !Top rad link
E,Node(x0+9,y8-13,0),Node(x0+9,y4,0)  !Bottom rad link
Real,71
E,Node(x0+10,y8+13,0),Node(x0+10,y13,0)         !Top rad link
E,Node(x0+10,y8-13,0),Node(x0+10,y4,0)          !Bottom rad link
Real,72
E,Node(x0+11,y8+13,0),Node(x0+11,y13,0)         !Top rad link
E,Node(x0+11,y8-13,0),Node(x0+11,y4,0)          !Bottom rad link
Real,73
E,Node(x0+12,y8+13,0),Node(x0+12,y13,0)         !Top rad link
E,Node(x0+12,y8-13,0),Node(x0+12,y4,0)          !Bottom rad link
Real,74
E,Node(x0+13,y8+13,0),Node(x0+13,y13,0)         !Top rad link
```

```
E,Node(x0+13,y8-13,0),Node(x0+13,y4,0)          !Bottom rad link
Real,75
E,Node(x0+14,y8+13,0),Node(x0+14,y13,0)         !Top rad link
E,Node(x0+14,y8-13,0),Node(x0+14,y4,0)          !Bottom rad link
!
/com  ******************************************************
/com  Add boundary conditions
/com  ******************************************************
!
! add extra nodes for surface effects
CSYS,0
WPCSYS,1,0
N,500001,x10+12,y8,0                    ! For side
!
!create surface elements in cavity for heat gen
alls
nsel,s,loc,x,0,x1+.01
nsel,u,loc,y,y8+12+.01,y15
nsel,u,loc,y,y0,y8-12-.01
type,2
REAL,2
mat,1
esurf
esel,s,type,,2
cm,hfluxin,elem
alls
! apply waste liner heat load to cavity
alls
cmsel,s,hfluxin
sfe,all,1,hflux,,QIN    ! cavity heat flux
!
! create surface elements on side for solar
csys,0
alls
nsel,s,loc,x,x10-.01,x10+20
nsel,u,loc,y,y0,y6-.01
nsel,u,loc,y,y10+.01,y15
type,2
REAL,2
Mat,4
esurf
ALLS
esel,s,type,,2
cmsel,u,hfluxin,elem
cm,convside_solar,elem
SFE,all,1,hflux,,QSS            ! Solar load (for cool-down, only)
ekill,all
!
! create surface elements for conv./radiation
csys,0
alls
nsel,s,loc,x,x10-.01,x10+20
nsel,u,loc,y,y0,y6-.01
nsel,u,loc,y,y10+.01,y15
type,3
REAL,3
Mat,4
esurf,500001
ALLS
esel,s,type,,3
cm,convside_natural,elem
sfe,all,1,conv,1,.19/144,.19/144
!
! create surface elements for conv./radiation
csys,0
alls
nsel,s,loc,x,x10-.01,x10+20
nsel,u,loc,y,y0,y6-.01
nsel,u,loc,y,y10+.01,y15
type,8
```

```
REAL,8
Mat,6
esurf,500001
ALLS
esel,s,type,,8
cm,convside_forced,elem
sfe,all,1,conv,1,0.01223,0.01223
ekill,all
!
ALLS
TUNIF,100
Finish
save
!
!********************************
!Solution phase TRANS = ANtype,4
!********************************
/solu
/rescontrol,define,all,1,5  !Write .RNNN per set. Max of 5 REST per LS.
antype,trans
trnopt,full
OUTRES,NSOL,1
autots,on
deltim,.00001,.000001,.0001,off
timint,off
nsubs,10,20,2
neqit,100
!
! Begin steady-state
alls
cmsel,s,convside_forced
cmsel,a,convside_solar
ekill,all
alls
cmsel,s,convside_natural
ealive,all
alls
D,500001,TEMP,100
time,.0001
kbc,1
solve
!
! START OF 30 Minute Fire
alls
cmsel,s,convside_natural
cmsel,a,convside_solar
ekill,all
alls
cmsel,s,convside_forced
ealive,all
alls
D,500001,TEMP,1475          !Set ambient at 10CFR71 flame temp
TIMINT,ON                   !Time integration effects on
DELTIME,1/30,,,off  !Specify time step sizes
Time,.001            !Time at end of step 2 (ramp-up to fire temp)
KBC,0
solve
!
! END OF 30 Minute Fire
alls
cmsel,s,convside_natural
cmsel,a,convside_solar
ekill,all
alls
cmsel,s,convside_forced
ealive,all
alls
D,500001,TEMP,1475          !Set ambient at 10CFR71 flame temp
Time,0.5             !Time at end of step 3 (30-minute fire)
solve
```

```
!
! BEGINNING OF COOLDOWN
alls
cmsel,s,convside_natural
cmsel,a,convside_solar
ealive,all
alls
cmsel,s,convside_forced
ekill,all
alls
D,500001,TEMP,100             !Set ambient TO 100
Time,0.5001                   !Time at end of step 4 (ramp-down)
solve
!
! 48-hour cool-down
alls
cmsel,s,convside_natural
cmsel,a,convside_solar
ealive,all
alls
cmsel,s,convside_forced
ekill,all
alls
D,500001,TEMP,100             !Re-set to ambient temp
TIME,48.5                     !Time at end of step 5
solve
SAVE
FINISH
save
!
! Create various element 2D plots
/nopr
/post1
/GRAPHICS,FULL
/SHOW,JPEG
!
/POST26                       !Time-history postprocessor
alls
!NSOL,2,NODE(X10,Y8+6,0),TEMP,,SHIELD @ MIDSPAN
NSOL,3,NODE(X10,Y8,0),TEMP,,SHIELD
!NSOL,4,NODE(X8,Y8+6,0),TEMP,,OUTER SHELL @ MIDSPAN
NSOL,5,NODE(X8,Y8,0),TEMP,,OUTER SHELL
NSOL,6,NODE(X4,Y8,0),TEMP,,INNER SHELL
/axlabel,y,Temperature (F)
/axlabel,x,Time (Hours)
/xrange,0,48
/Title, 10-160B Cask ANSYS HAC Fire: Fire Shield Temp vs Time
PLVAR,2,3
EXTREM,2,3
!
/Title, 10-160B Cask ANSYS HAC Fire: Steel Shells Temp vs Time
PLVAR,4,5,6
EXTREM,4,6
!
*get,Shield_temp,vari,3,extrem,vmax
*get,Shield_time,vari,3,extrem,tmax

/nopr

/output,extreme_temps,txt,,append
/com  Fire shield
*vwrite,Shield_temp,Shield_time
(12F12.2)

/output
/gopr

*get,Outer_temp,vari,5,extrem,vmax
*get,Outer_time,vari,5,extrem,tmax
*get,Inner_temp,vari,6,extrem,vmax
```

```
*get,Inner_time,vari,6,extrem,tmax

/nopr

/output,extreme_temps,txt,,append
/com  Outer shell
*vwrite,Outer_temp,Outer_time
(12F12.2)

/output,extreme_temps,txt,,append
/com  Inner shell
*vwrite,Inner_temp,Inner_time
(12F12.2)
/output
/gopr
!
alls
NSOL,2,NODE(X1,Y8,0),TEMP,,AIR @ NEAR DECAY HEAT SOURCE
NSOL,3,NODE(X3,Y8,0),TEMP,,AIR @ BETWN SOURCE AND INNER SHELL
NSOL,4,NODE(X4,Y8,0),TEMP,,AIR @ NEAR CASK INNER SHELL
NSOL,5,NODE((X6+(X7-X6)/2),Y8,0),TEMP,,GAMMA SHIELD

/Title, 10-160B Cask ANSYS HAC Fire: Bulk Air Temp vs Time
PLVAR,2,3,4
/Title, 10-160B Cask ANSYS HAC Fire: Gamma Shield Temp vs Time
PLVAR,5
EXTREM,5
EXTREM,4
EXTREM,3
EXTREM,2

*get,Air_temp,vari,4,extrem,vmax
*get,Air_time,vari,4,extrem,tmax
*get,Gamma_temp,vari,5,extrem,vmax
*get,Gamma_time,vari,5,extrem,tmax

/nopr

/output,extreme_temps,txt,,append
/com  Air in cavity
*vwrite,Air_temp,Air_time
(12F12.2)

/output,extreme_temps,txt,,append
/com  Gamma shield
*vwrite,Gamma_temp,Gamma_time
(12F12.2)

/output
/gopr

alls
NSOL,2,NODE(X5,Y13,0),TEMP,,PRIMARY O-RING
NSOL,3,NODE(X2,Y14,0),TEMP,,SECONDARY O-RING

/Title, 10-160B Cask ANSYS HAC Fire: O-rings Temp vs Time
PLVAR,2,3
EXTREM,2,3

*get,Primary_temp,vari,2,extrem,vmax
*get,Primary_time,vari,2,extrem,tmax
*get,Secondary_temp,vari,3,extrem,vmax
*get,Secondary_time,vari,3,extrem,tmax

/nopr

/output,extreme_temps,txt,,append
/com  Primary O-ring
*vwrite,Primary_temp,Primary_time
(12F12.2)
```

```
/output,extreme_temps,txt,,append
/com  Secondary O-ring
*vwrite,Secondary_temp,Secondary_time
(12F12.2)

/output
/gopr
!
alls
NSOL,2,NODE(0,Y14,0),TEMP,,LID @ CENTERLINE

*get,Lid_temp,vari,2,extrem,vmax
*get,Lid_time,vari,2,extrem,tmax

/nopr

/output,extreme_temps,txt,,append
/com  Lid
*vwrite,Lid_temp,Lid_time
(12F12.2)

/output
/gopr

/Title, 10-160B Cask ANSYS HAC Fire: Lid Centerline Temp vs Time
PLVAR,2
EXTREM,2

!**************************************
! Shell differential temperature calcs
!**************************************
alls
nsol,2,1211,temp,,IS_I
nsol,3,2828,temp,,Lead_I
nsol,4,2829,temp,,Lead_M
nsol,5,2816,temp,,Lead_O
nsol,6,1355,temp,,OS_O
add,7,3,2,,IS_Diff,,,1,-1
add,8,6,5,,OS_Diff,,,1,-1

/nopr

/output,shell_TDs,txt,,
/com  Inner shell differential
EXTREM,IS_diff,,1,
!*vwrite,IS_Diff
!(12F12.2)

/output,shell_TDs,txt,,append
/com  Outer shell differential
EXTREM,OS_diff,,1,
!*vwrite,OS_Diff
!(12F12.2)

/output
/gopr

alls
nsol,2,1211,temp,,IS_I
nsol,3,2828,temp,,Lead_I
nsol,4,2829,temp,,Lead_M
nsol,5,2816,temp,,Lead_O
nsol,6,1355,temp,,OS_O
add,7,6,2,,Wall_Diff,,,1,-1
add,8,5,6,,Wall_Avg,,,0.5,0.5

/nopr

/output,shell_TDs,txt,,append
```

```
/com  Wall differential
EXTREM,Wall_Diff,,1,
!*vwrite,Wall_Diff
!(12F12.2)

/output,shell_TDs,txt,,append
/com  Wall average
EXTREM,Wall_Avg,,1,
!*vwrite,Wall_Avg
!(12F12.2)

/output
/gopr
!
/post1
alls
/view,1
/foc,1,auto
/dist,1
/lig,1,1
/Title, 10-160B Cask ANSYS Thermal Analysis Area Plot
/number,0
/pnum,area,1
aplot
/Title, 10-160B Cask ANSYS Thermal Analysis Keypoint Plot
/number,2
/pnum,kp,1
kplot
/Title, 10-160B Cask ANSYS Thermal Analysis Nodal Plot
/number,1
/pnum,node,0
nplot
/Title, 10-160B Cask ANSYS Thermal Analysis Elem / Mat Plot
/NUMBER,1
/PNUM,MAT,1
/psf,hflux,,0
eplot
/psf,hflux,,2
/Title, 10-160B Cask ANSYS Thermal: Elem Plot + Surf Loads
eplot
!
alls
set,1
/psf,hflux,,0
/Title, 10-160B Cask HAC Fire Case - Set 1 Nodal Temp Plot
esel,u,mat,,3
nsel,u,,,500001
esln,,1
PLNS,TEMP                    !Temp contour plot
prns,temp
/Title, 10-160B Cask HAC Fire Case - Set 1 Thermal Flux Plot
PLVECT,TF                    !Thermal flux plot
set,2
/Title, 10-160B Cask HAC Fire Case - Set 2 Nodal Temp Plot
esel,u,mat,,2
esel,u,mat,,3
nsel,u,,,500001
esln,,1
PLNS,TEMP                    !Temp contour plot
prns,temp
/Title, 10-160B Cask HAC Fire Case - Set 2 Thermal Flux Plot
PLVECT,TF                    !Thermal flux plot
set,3
/Title, 10-160B Cask HAC Fire Case - Set 3 Nodal Temp Plot
esel,u,mat,,2
esel,u,mat,,3
nsel,u,,,500001
esln,,1
PLNS,TEMP                    !Temp contour plot
prns,temp
```

```
/Title, 10-160B Cask HAC Fire Case - Set 3 Thermal Flux Plot
PLVECT,TF                    !Thermal flux plot
set,4
/Title, 10-160B Cask HAC Fire Case - Set 4 Nodal Temp Plot
esel,u,mat,,2
esel,u,mat,,3
nsel,u,,,500001
esln,,1
PLNS,TEMP                    !Temp contour plot
prns,temp
/Title, 10-160B Cask HAC Fire Case - Set 4 Thermal Flux Plot
PLVECT,TF                    !Thermal flux plot
set,5
/Title, 10-160B Cask HAC Fire Case - Set 5 Nodal Temp Plot
esel,u,mat,,2
esel,u,mat,,3
nsel,u,,,500001
esln,,1
PLNS,TEMP                    !Temp contour plot
prns,temp
/Title, 10-160B Cask HAC Fire Case - Set 5 Thermal Flux Plot
PLVECT,TF                    !Thermal flux plot
!
! Repeat plots for Steel, only
alls
esel,u,mat,,2
esel,u,mat,,3
nsel,u,,,500001
esln,,1
plns,temp
prns,temp
alls
cmsel,s,steel
esel,s,mat,,1
FLST,5,167,2,ORDE,34
FITEM,5,830
FITEM,5,-845
FITEM,5,862
FITEM,5,1026
FITEM,5,1028
FITEM,5,1030
FITEM,5,1032
FITEM,5,1034
FITEM,5,1036
FITEM,5,1038
FITEM,5,1040
FITEM,5,1042
FITEM,5,1044
FITEM,5,1046
FITEM,5,1048
FITEM,5,1266
FITEM,5,1268
FITEM,5,1270
FITEM,5,1272
FITEM,5,1274
FITEM,5,1276
FITEM,5,1278
FITEM,5,1280
FITEM,5,1282
FITEM,5,1284
FITEM,5,1286
FITEM,5,1288
FITEM,5,1506
FITEM,5,-1521
FITEM,5,1650
FITEM,5,3688
FITEM,5,-3710
FITEM,5,3752
FITEM,5,-3837
ESEL,U, , ,P51X
```

```
nsle
!
set,1
/psf,hflux,,0
/Title, 10-160B Cask HAC Fire Case (steel): Set 1 Nodal Temp Plot
esel,u,mat,,2
esel,u,mat,,3
nsel,u,,,500001
esln,,1
esel,u,type,,5
esel,u,type,,6
FLST,5,2480,1,ORDE,44
FITEM,5,18
FITEM,5,-340
FITEM,5,343
FITEM,5,-380
FITEM,5,387
FITEM,5,-500
FITEM,5,531
FITEM,5,-745
FITEM,5,747
FITEM,5,-756
FITEM,5,761
FITEM,5,-985
FITEM,5,995
FITEM,5,-1084
FITEM,5,1103
FITEM,5,-1210
FITEM,5,1223
FITEM,5,-1342
FITEM,5,1367
FITEM,5,-1474
FITEM,5,1487
FITEM,5,-1606
FITEM,5,1631
FITEM,5,-1871
FITEM,5,1881
FITEM,5,-1970
FITEM,5,1989
FITEM,5,-2013
FITEM,5,2015
FITEM,5,-2024
FITEM,5,2028
FITEM,5,-2332
FITEM,5,2334
FITEM,5,-2350
FITEM,5,2352
FITEM,5,-2368
FITEM,5,2370
FITEM,5,-2386
FITEM,5,2392
FITEM,5,-2476
FITEM,5,2505
FITEM,5,-2674
FITEM,5,2694
FITEM,5,-2725
NSEL,U, , ,P51X

PLNS,TEMP                    !Temp contour plot
prns,temp
/Title, 10-160B Cask HAC Fire Case - Set 1 Thermal Flux Plot
/psf,hflux,,2
PLVECT,TF                    !Thermal flux plot
set,2
/psf,hflux,,0
/Title, 10-160B Cask HAC Fire Case (Steel): Set 2 Nodal Temp Plot
esel,u,mat,,2
esel,u,mat,,3
nsel,u,,,500001
esln,,1
```

```
esel,u,type,,5
esel,u,type,,6
FLST,5,2480,1,ORDE,44
FITEM,5,18
FITEM,5,-340
FITEM,5,343
FITEM,5,-380
FITEM,5,387
FITEM,5,-500
FITEM,5,531
FITEM,5,-745
FITEM,5,747
FITEM,5,-756
FITEM,5,761
FITEM,5,-985
FITEM,5,995
FITEM,5,-1084
FITEM,5,1103
FITEM,5,-1210
FITEM,5,1223
FITEM,5,-1342
FITEM,5,1367
FITEM,5,-1474
FITEM,5,1487
FITEM,5,-1606
FITEM,5,1631
FITEM,5,-1871
FITEM,5,1881
FITEM,5,-1970
FITEM,5,1989
FITEM,5,-2013
FITEM,5,2015
FITEM,5,-2024
FITEM,5,2028
FITEM,5,-2332
FITEM,5,2334
FITEM,5,-2350
FITEM,5,2352
FITEM,5,-2368
FITEM,5,2370
FITEM,5,-2386
FITEM,5,2392
FITEM,5,-2476
FITEM,5,2505
FITEM,5,-2674
FITEM,5,2694
FITEM,5,-2725
NSEL,U, , ,P51X

PLNS,TEMP                     !Temp contour plot
prns,temp
/Title, 10-160B Cask HAC Fire Case - Set 2 Thermal Flux Plot
/psf,hflux,,2
PLVECT,TF                     !Thermal flux plot
set,3
/psf,hflux,,0
/Title, 10-160B Cask HAC Fire Case (Steel): Set 3 Nodal Temp Plot
esel,u,mat,,2
esel,u,mat,,3
nsel,u,,,500001
esln,,1
esel,u,type,,5
esel,u,type,,6
FLST,5,2480,1,ORDE,44
FITEM,5,18
FITEM,5,-340
FITEM,5,343
FITEM,5,-380
FITEM,5,387
FITEM,5,-500
```

```
FITEM,5,531
FITEM,5,-745
FITEM,5,747
FITEM,5,-756
FITEM,5,761
FITEM,5,-985
FITEM,5,995
FITEM,5,-1084
FITEM,5,1103
FITEM,5,-1210
FITEM,5,1223
FITEM,5,-1342
FITEM,5,1367
FITEM,5,-1474
FITEM,5,1487
FITEM,5,-1606
FITEM,5,1631
FITEM,5,-1871
FITEM,5,1881
FITEM,5,-1970
FITEM,5,1989
FITEM,5,-2013
FITEM,5,2015
FITEM,5,-2024
FITEM,5,2028
FITEM,5,-2332
FITEM,5,2334
FITEM,5,-2350
FITEM,5,2352
FITEM,5,-2368
FITEM,5,2370
FITEM,5,-2386
FITEM,5,2392
FITEM,5,-2476
FITEM,5,2505
FITEM,5,-2674
FITEM,5,2694
FITEM,5,-2725
NSEL,U, , ,P51X

PLNS,TEMP                    !Temp contour plot
prns,temp
/Title, 10-160B Cask HAC Fire Case - Set 3 Thermal Flux Plot
/psf,hflux,,2
PLVECT,TF                    !Thermal flux plot
set,4
/psf,hflux,,0
/Title, 10-160B Cask HAC Fire Case (Steel): Set 4 Nodal Temp Plot
esel,u,mat,,2
esel,u,mat,,3
nsel,u,,,500001
esln,,1
esel,u,type,,5
esel,u,type,,6
FLST,5,2480,1,ORDE,44
FITEM,5,18
FITEM,5,-340
FITEM,5,343
FITEM,5,-380
FITEM,5,387
FITEM,5,-500
FITEM,5,531
FITEM,5,-745
FITEM,5,747
FITEM,5,-756
FITEM,5,761
FITEM,5,-985
FITEM,5,995
FITEM,5,-1084
FITEM,5,1103
```

```
FITEM,5,-1210
FITEM,5,1223
FITEM,5,-1342
FITEM,5,1367
FITEM,5,-1474
FITEM,5,1487
FITEM,5,-1606
FITEM,5,1631
FITEM,5,-1871
FITEM,5,1881
FITEM,5,-1970
FITEM,5,1989
FITEM,5,-2013
FITEM,5,2015
FITEM,5,-2024
FITEM,5,2028
FITEM,5,-2332
FITEM,5,2334
FITEM,5,-2350
FITEM,5,2352
FITEM,5,-2368
FITEM,5,2370
FITEM,5,-2386
FITEM,5,2392
FITEM,5,-2476
FITEM,5,2505
FITEM,5,-2674
FITEM,5,2694
FITEM,5,-2725
NSEL,U, , ,P51X

PLNS,TEMP                    !Temp contour plot
prns,temp
/Title, 10-160B Cask HAC Fire Case - Set 4 Thermal Flux Plot
/psf,hflux,,2
PLVECT,TF                    !Thermal flux plot
set,5
/psf,hflux,,0
/Title, 10-160B Cask HAC Fire Case (Steel): Set 5 Nodal Temp Plot
esel,u,mat,,2
esel,u,mat,,3
nsel,u,,,500001
esln,,1
esel,u,type,,5
esel,u,type,,6
FLST,5,2480,1,ORDE,44
FITEM,5,18
FITEM,5,-340
FITEM,5,343
FITEM,5,-380
FITEM,5,387
FITEM,5,-500
FITEM,5,531
FITEM,5,-745
FITEM,5,747
FITEM,5,-756
FITEM,5,761
FITEM,5,-985
FITEM,5,995
FITEM,5,-1084
FITEM,5,1103
FITEM,5,-1210
FITEM,5,1223
FITEM,5,-1342
FITEM,5,1367
FITEM,5,-1474
FITEM,5,1487
FITEM,5,-1606
FITEM,5,1631
FITEM,5,-1871
```

```
FITEM,5,1881
FITEM,5,-1970
FITEM,5,1989
FITEM,5,-2013
FITEM,5,2015
FITEM,5,-2024
FITEM,5,2028
FITEM,5,-2332
FITEM,5,2334
FITEM,5,-2350
FITEM,5,2352
FITEM,5,-2368
FITEM,5,2370
FITEM,5,-2386
FITEM,5,2392
FITEM,5,-2476
FITEM,5,2505
FITEM,5,-2674
FITEM,5,2694
FITEM,5,-2725
NSEL,U, , ,P51X

PLNS,TEMP                    !Temp contour plot
prns,temp
/Title, 10-160B Cask HAC Fire Case - Set 5 Thermal Flux Plot
/psf,hflux,,2
PLVECT,TF                    !Thermal flux plot
alls
!
!******************************************
!Calculate the bulk average air temp
!******************************************
!
/com
/com  This macro calculates the volume avg'd temps of the
/com  currently selected elements.
/com
/post1                                          !              !
!Select air elements
cmsel,s,air
asel,u,loc,x,x8,x10
esla,s
FLST,5,16,2,ORDE,2
FITEM,5,1506
FITEM,5,-1521
ESEL,U, , ,P51X
FLST,5,16,2,ORDE,2
FITEM,5,830
FITEM,5,-845
ESEL,U, , ,P51X
FLST,5,26,2,ORDE,26
FITEM,5,862
FITEM,5,1026
FITEM,5,1028
FITEM,5,1030
FITEM,5,1032
FITEM,5,1034
FITEM,5,1036
FITEM,5,1038
FITEM,5,1040
FITEM,5,1042
FITEM,5,1044
FITEM,5,1046
FITEM,5,1048
FITEM,5,1266
FITEM,5,1268
FITEM,5,1270
FITEM,5,1272
FITEM,5,1274
FITEM,5,1276
```

```
FITEM,5,1278
FITEM,5,1280
FITEM,5,1282
FITEM,5,1284
FITEM,5,1286
FITEM,5,1288
FITEM,5,1650
ESEL,U, , ,P51X
!
set,3                    !
cm,tempgrp,elem        ! Store current element group
etable,tempe,temp      ! fill tempe with average element temp
ssum
etable,volue,volu      ! fill volue with element volumes
ssum
smult,vtemp,tempe,volue,1,1     ! multiply tempe*volue for each element
ssum
*get,vtot,ssum,,item,volue      ! get sum of the volumes
ssum
*get,totvxt,ssum,,item,vtemp    ! get sum of TAVG*VOLUME
ssum
avetemp_3=totvxt/vtot   ! Calculate average temperature
ssum                             ! sum the element table entries
cmsel,s,tempgrp        ! Restore initial element group
cmdel,tempgrp          ! Delete temporary element group
parsave,all,parameters,txt
*stat,avetemp_3
/Title, 10-160B Cask HAC Fire Elements:  Cavity air, only (set, 3)
eplot
save
/Title, 10-160B Cask HAC Fire Nodal Temps:  Cavity air, only (set, 3)
plns,temp                        ! Plot nodal air temp
prns,temp
set,4                    !
cm,tempgrp,elem        ! Store current element group
etable,tempe,temp      ! fill tempe with average element temp
ssum
etable,volue,volu      ! fill volue with element volumes
ssum
smult,vtemp,tempe,volue,1,1     ! multiply tempe*volue for each element
ssum
*get,vtot,ssum,,item,volue      ! get sum of the volumes
ssum
*get,totvxt,ssum,,item,vtemp    ! get sum of TAVG*VOLUME
ssum
avetemp_4=totvxt/vtot   ! Calculate average temperature
ssum                             ! sum the element table entries
cmsel,s,tempgrp        ! Restore initial element group
cmdel,tempgrp          ! Delete temporary element group
parsave,all,parameters,txt
*stat,avetemp_4
/Title, 10-160B Cask HAC Fire Elements:  Cavity air, only (set, 4)
eplot
save
/Title, 10-160B Cask HAC Fire Nodal Temps:  Cavity air, only (set, 4)
plns,temp                        ! Plot nodal air temp
prns,temp
!
set,5
cm,tempgrp,elem        ! Store current element group
etable,tempe,temp      ! fill tempe with average element temp
ssum
etable,volue,volu      ! fill volue with element volumes
ssum
smult,vtemp,tempe,volue,1,1     ! multiply tempe*volue for each element
ssum
*get,vtot,ssum,,item,volue      ! get sum of the volumes
ssum
*get,totvxt,ssum,,item,vtemp    ! get sum of TAVG*VOLUME
ssum
```

```
avetemp_5=totvxt/vtot   ! Calculate average temperature
ssum                            ! sum the element table entries
cmsel,s,tempgrp        ! Restore initial element group
cmdel,tempgrp          ! Delete temporary element group
parsave,all,parameters,txt
*stat,avetemp_5
/Title, 10-160B Cask HAC Fire Elements:  Cavity air, only (set, 5)
eplot
save
/Title, 10-160B Cask HAC Fire Nodal Temps:  Cavity air, only (set, 5)
plns,temp                       ! Plot nodal air temp
prns,temp
!
!************************************************
! Next, select the other components for max temps
!************************************************
!
set,3
! Top plate
alls
nsel,s,loc,y,y12,y15
FLST,5,48,1,ORDE,4
FITEM,5,2045
FITEM,5,-2060
FITEM,5,2694
FITEM,5,-2725
NSEL,u, , ,P51X
esel,u,mat,,3
esel,u,type,,2
esel,u,type,,3
esln,,1
esln
esel,u,mat,,3
/Title, 10-160B HAC fire Nodal Temps (Top plate / lid - set3)
plns,temp
prns,temp
!
! Primary lid o-ring nodal temps
alls
!nsel,s,loc,x,x5       !Reference where node 3615 is located
!nsel,r,loc,y,y13      !Reference where node 3615 is located
nsel,s,,,3615
esln
/Title, 10-160B HAC fire Nodal Temps (Primary O-ring - set3)
plns,temp
prns,temp
!
! Secondary lid o-ring nodal temps
alls
!nsel,s,loc,x,x2       !Reference where node 3687 is located
!nsel,r,loc,y,y14      !Reference where node 3687 is located
nsel,s,,,3687
esln
/Title, 10-160B HAC fire Nodal Temps (Secondary O-ring - set3)
plns,temp
prns,temp
!
! Gamma shield
alls
nsel,s,loc,x,x6,x7
nsel,u,loc,y,y0,y3-.0001
nsel,u,loc,y,y12+.0001,y15
nsel,u,,,500001
esel,u,type,,2
esel,u,type,,3
esln,,1
/Title, 10-160B HAC fire Nodal Temps (Gamma shield - set3)
plns,temp
prns,temp
!
```

```
! Outer shell
alls
nsel,s,loc,x,x7,x8
nsel,u,loc,y,y0,y3-.0001
nsel,u,loc,y,y12+.0001,y15
esel,u,mat,,2
esel,u,mat,,3
nsel,u,,,500001
esln,,1
/Title, 10-160B HAC fire Nodal Temps (Outer shell - set3)
plns,temp
prns,temp
!
! Inner shell
alls
nsel,s,loc,x,x4,x5
nsel,u,loc,y,y0,y3-.0001
nsel,u,loc,y,y12+.0001,y15
esel,u,mat,,2
esel,u,mat,,3
nsel,u,,,500001
esln,,1
/Title, 10-160B HAC fire Nodal Temps (Inner shell - set3)
plns,temp
prns,temp
!
set,5
! Top plate
alls
nsel,s,loc,y,y12,y15
FLST,5,48,1,ORDE,4
FITEM,5,2045
FITEM,5,-2060
FITEM,5,2694
FITEM,5,-2725
NSEL,u, , ,P51X
esel,u,mat,,3
esel,u,type,,2
esel,u,type,,3
esln,,1
esln
esel,u,mat,,3
/Title, 10-160B HAC fire Nodal Temps (Top plate / lid - set5)
plns,temp
prns,temp
!
! Primary lid o-ring nodal temps
alls
!nsel,s,loc,x,x5        !Reference where node 3615 is located
!nsel,r,loc,y,y13       !Reference where node 3615 is located
nsel,s,,,3615
esln
/Title, 10-160B HAC fire Nodal Temps (Primary O-ring - set5)
plns,temp
prns,temp
!
! Secondary lid o-ring nodal temps
alls
!nsel,s,loc,x,x2        !Reference where node 3687 is located
!nsel,r,loc,y,y14       !Reference where node 3687 is located
nsel,s,,,3687
esln
/Title, 10-160B HAC fire Nodal Temps (Secondary O-ring - set5)
plns,temp
prns,temp
!
! Gamma shield
alls
nsel,s,loc,x,x6,x7
nsel,u,loc,y,y0,y3-.0001
```

```
nsel,u,loc,y,y12+.0001,y15
nsel,u,,,500001
esel,u,type,,2
esel,u,type,,3
esln,,1
/Title, 10-160B HAC fire Nodal Temps (Gamma shield - set5)
plns,temp
prns,temp
!
! Outer shell
alls
nsel,s,loc,x,x7,x8
nsel,u,loc,y,y0,y3-.0001
nsel,u,loc,y,y12+.0001,y15
esel,u,mat,,2
esel,u,mat,,3
nsel,u,,,500001
esln,,1
/Title, 10-160B HAC fire Nodal Temps (Outer shell - set5)
plns,temp
prns,temp
!
! Inner shell
alls
nsel,s,loc,x,x4,x5
nsel,u,loc,y,y0,y3-.0001
nsel,u,loc,y,y12+.0001,y15
esel,u,mat,,2
esel,u,mat,,3
nsel,u,,,500001
esln,,1
/Title, 10-160B HAC fire Nodal Temps (Inner shell - set5)
plns,temp
prns,temp
!
FINISH
/show,,,,
/GROPTS,VIEW,1
/EOF
```

Attachment 4
DVD with analysis files