3.0 THERMAL EVALUATION

This Section identifies, describes, discusses, and analyzes the principal thermal engineering design of the 3-60B package. Compliance with the performance requirements of 10 CFR 71 (Reference 3-1) is demonstrated.

3.1 DESCRIPTION OF THERMAL DESIGN

Two components contribute to the thermal protection of the cask body. These components are the impact limiters which provide thermal protection to the ends of the cask and the fire shield which protects the side walls between the impact limiters.

3.1.1 Design Features

Figure 3-1 shows the design features of the components contributing to the thermal protection of the cask. These components are identified in the figure with solid red color.

The fire shield is 12 gage stainless steel sheet metal. In order to provide an air gap between the cask outer shell and the fire shield, 5/32″ diameter wires are helically wrapped around the cask outer shell. The fire shield is welded to the cask body at the two ends. Cut-outs are provided in the fire shield in order to wrap around the trunnions and the impact limiter attachment lugs.

The impact limiters are sheet metal enclosures filled with polyurethane foam which acts as insulation barrier to heat flow. The impact limiters are attached to the cask body through the arrangement as shown in Figure 3-1. In order to provide air gaps between the cask ends and the impact limiters, 5/32″ diameter wires are welded to the impact limiter inner plate. The impact limiters provide thermal insulation during the NCT events. However, during the HAC fire event it is assumed that the sheet metal enclosing the polyurethane foam would be damaged during the prior HAC drop and puncture tests (see Section 2.7.8). This will reduce the effectiveness of the foam to provide full thermal insulation. The impact limiters are shown to remain attached to the cask after the HAC tests (see Section 2.7.1.6). Consequently, only the metal casings, separated by the air gap, are the only thermal protection assumed during the HAC fire evaluation.

3.1.2 Content's Decay Heat

The maximum decay heat of the waste component is 500 Watt. The minimum decay heat of zero Watt is used in the evaluation of other limiting case.

3.1.3 Summary Tables of Temperatures

The maximum temperatures in various important components of the cask during the NCT events are summarized in Table 3-1. Table 3-2 summarizes the maximum temperature in these components during the HAC fire test. The time at which these components achieve the maximum temperature is also identified in Table 3-2.

The results summarized in Table 3-1 and 3-2 are discussed in detail in Sections 3.3 and 3.4.

3.1.4 Summary Table of Maximum Pressures

The summary of maximum pressures during the NCT and HAC fire test are provided in Table 3-3. The details of these pressure calculations are provided in Sections 3.3.2 and 3.4.3 for NCT and HAC fire test, respectively.

3.2 MATERIAL PROPERTIES AND COMPONENT SPECIFICATIONS

3.2.1 Material Properties

The material properties of the cask components used in the analysis of the 3-60B package are provided in Tables 3-4 through 3-6. Table 3-4 provides the temperature independent properties of the steel and lead components. Table 3-5 provides the temperature dependent specific heat and thermal conductivity of stainless steel, carbon steel and lead. Table 3-6 provides the temperature dependent density, specific heat and conductivity of air. Material properties have been obtained from standard references (References 3-2 through 3-6) and are identified in Tables 3-4 through 3-6.

3.2.2 Component Specifications

The metallic components that are important for the thermal performance of the package are made of 304L stainless steel. The non-metallic components are specified as follows:

- The seals used in the package are specified to be elastomer, 50-70 Durameter, temperature range -40°F to 300°F.

- Lead is specified to be ASTM B-29 commercial grade. The melting temperature is 622°F.

- Polyurethane foam used in the impact limiters are specified by ES-M-172 (see Appendix 1, Section 8). All the pertinent thermal properties are included in this specification.

3.3 THERMAL EVALUATION FOR NORMAL CONDITIONS OF TRANSPORT

The thermal analyses of the 3-60B package under various loading conditions have been performed using finite element modeling techniques. ANSYS finite element analysis code (Reference 3-7) has been employed to perform the analyses. Since the lid of the cask is attached to the body using 16 bolts, the cask geometry has a cyclic symmetry every 11.25° of the circumference. Therefore, an 11.25° model of the cask is employed. Figure 3-2 shows the finite element model used in various thermal load analyses. Figure 3-3 shows the material property modeling of various components of the cask.

The details of the analyses, including the assumptions, modeling details, boundary conditions, and input and output data are included in EnergySolutions document TH-022 (Reference 3-8).

3.3.1 Heat and Cold

The finite element model described in Section 3.3 is analyzed for the following loading conditions:

- Hot Environment – This load case is based on the requirements of 10 CFR 71.71 (c) (1). The loading includes a 100° F ambient temperature, solar insolation, and maximum internal heat load. This loading is used as one of the extreme initial conditions for the normal conditions of transport (NCT) and hypothetical accident condition (HAC) test evaluation. The temperature distribution in the cask body under this loading condition is shown in Figure 3-4.

- Cold Environment – This load case is based on the requirements of 10 CFR 71.71 (c) (2). The loading includes a -40° F ambient temperature, no solar insolation, and maximum internal heat load. This loading is used as one of the extreme initial conditions for the normal conditions of transport (NCT) and hypothetical accident condition (HAC) test evaluation. The temperature distribution in the cask body under this loading condition is shown in Figure 3-5.

- Normal Hot - This load case is based on the requirements of 10 CFR 71.71 (b). The loading includes a 100° F ambient temperature, no solar insolation, and maximum internal heat load. The temperature distribution in the cask body under this loading condition is shown in Figure 3-6.

- Normal Cold - This load case is based on the requirements of 10 CFR 71.71 (b). The loading includes a -20° F ambient temperature, no solar insolation, and maximum internal heat load. The temperature distribution in the cask body under this loading condition is shown in Figure 3-7.

The thermal analysis shows that under the normal conditions of transport there is no reduction in packaging effectiveness. The heat transfer capability of the components is not reduced under NCT, nor are there changes in material properties that affect structural performance, containment, or shielding.

3.3.2 Maximum Normal Operating Pressure

The maximum internal pressure of the cask is calculated assuming that the gas within the cask, a mixture of air, water vapor, oxygen, and hydrogen, behaves as an ideal gas. Hydrogen and oxygen may be produced in the cask cavity by radiolytic decomposition of water and other materials in the cask contents. The amount of hydrogen and oxygen generated after one year was calculated using RADCALC (Reference 3-9) for the waste forms identified in Section 1, for a maximum activity (30,000 Ci of C0-60), and conservatively assuming 100% gamma absorption.

The hydrogen generation calculation for typical irradiated hardware waste forms loaded underwater depends on the amount of water in the cask cavity after the cask is drained. The grooves in the cask cavity base and drain port have a combined volume of less than 0.02 gallons. If additional water remains on the base to a depth of ½″, the additional water is approximately 2 gallons. To conservatively assess the hydrogen generation for irradiated hardware, the amount of water remaining in the cask is conservatively assumed to be 4 gallons. The other water loaded waste form assessed is swarf. Swarf is assumed to be contained in a high density polyethylene liner (HIC) dewatered to 1% of the liner volume, leaving a water volume of approximately 4 gallons in the cask cavity. RADCALC gives partial pressures for H2 and O2 in the cask cavity at 32°F at the end of one year. The larger of the partial pressures is for swarf, due to the contribution from the polyethylene liner, and are 10.7 and 5.35 psia for hydrogen and oxygen respectively.

To determine the maximum internal pressure in the cask (MNOP) the temperature of the gas mixture within the cask is set equal to the maximum inside surface temperature of the cask. The maximum inside surface temperature of the cask is assumed to be 183°F (T_2) on the 100°F day. Assuming that on loading the cask void is filled with air at atmospheric pressure, P_1, at 70°F, the pressure in the cask at 183°F, P_2, may be calculated by the ideal gas relationship for air, hydrogen, and oxygen:

$$P_2 = \frac{T_2}{T_1} \cdot P_1$$, where T is in degrees absolute

The resulting pressures for air, hydrogen, and oxygen are 17.84, 13.98, and 6.99 psia, respectively.

The vapor pressure contributed by water in the cavity at 183ºF is 8.02 psia (as determined by the Goff-Gratch Equation).

Therefore, the calculated maximum normal operating pressure (in gage pressure) is,

$$MNOP = 17.84 + 13.98 + 6.99 + 8.02 - 14.7 = 32.13 \text{ psig}$$

The value used for MNOP is conservatively set at 35.0 psig.

Evaluation of the flammable gas content in the cask is based on the hydrogen concentration. Hydrogen is the only flammable gas anticipated to be contained in the cask cavity. For the irradiated hardware case assessed above, the hydrogen concentration at the end of one year is 4.6% and thus, is less than the 5% limit. For the swarf case, the hydrogen concentration at the end of one year is greater than 5%, principally due to the polyethylene liner. Thus, for a swarf HIC, or any other package containing substances that could radiolytically generate combustible gases in excess of a 5% concentration, as was determined for irradiated hardware, an evaluation shall be performed that demonstrates that one of the following criteria are met over a period of time that is twice the expected shipping time:

1. The hydrogen generated does not exceed a 5% concentration in the secondary container gas void at STP

2. The secondary container and cask cavity must be inerted with a diluent to assure that oxygen does not exceed a 5% concentration at STP in any portion of the package which could have a hydrogen concentration greater than 5%.

3.3.3 Thermal Stresses

The structural evaluation of the package under the normal conditions of transport loading is performed in Section 2.6.1 of this SAR. All the stresses are within the design allowable values established for 3-60B package.

3.4 HYPOTHETICAL ACCIDENT THERMAL EVALUATION

The thermal analyses of the 3-60B package under HAC fire conditions have been performed using finite element model, described in Section 3.3. A nonlinear thermal transient analysis is performed to obtain the time-history of the temperature in package.

The details of the analyses, including the assumptions, modeling details, boundary conditions, and input and output data are included in EnergySolutions document TH-023 (Reference 3-10).

3.4.1 Initial Conditions

The initial temperature condition, used for the HAC fire test analysis is obtained by running the finite element model with the following boundary conditions:

- Internal heat load – 500 W
- Solar insolation - no
- Heat Transfer to the ambient by radiation – yes
- Heat transfer to the ambient by natural convection – yes
- Ambient air temperature - 100°F

3.4.2 Fire Test Conditions

The fire transient is run with the body temperature resulting from the above initial conditions. The fire transient is run for 30 minutes (1,800 sec) with the following boundary conditions:

- Internal heat load – 500 W
- Solar insolation - no
- Heat Transfer to the ambient by radiation – yes
- Heat transfer to the ambient by forced convection – yes
- Ambient air temperature - 1475°F

The end of fire analysis of the model is performed with the body temperature resulting from the above fire transient to 1801 sec with the following boundary conditions:

- Internal heat load – 500 W
- Solar insolation - no
- Heat Transfer to the ambient by radiation – yes
- Heat transfer to the ambient by natural convection – yes
- Ambient air temperature - 100°F

The cool-down analysis of the model is performed with the body temperature resulting from the above fire transient to 14,000 sec with the following boundary conditions:

- Internal heat load – 500 W
- Solar insolation - yes

- Heat Transfer to the ambient by radiation – yes
- Heat transfer to the ambient by natural convection – yes
- Ambient air temperature - 100°F

Figure 3-8 shows the boundary conditions used during the fire transient analysis.

3.4.3 Maximum Temperatures and Pressure

From the analyses of the finite element model, a time-history data of the temperature in various components of the cask is obtained. The fire shield, outer shell, inner shell, lead, and seal were considered as the critical components of the cask. The temperatures at representative locations in these components are monitored during the entire fire and cool down transient analysis. The nodes that are monitored at these critical components are shown in Figure 3-9.

Figure 3-10 gives the plot of the time-history data at the representative nodes of the cask components. Figure 3-11 gives the same data in cask components that are not directly exposed to the fire. The maximum temperature of various components of the cask during the entire transient analysis is presented in Table 3-2. The temperature profile in the cask during the cool-down period is shown in Figure 3-12.

The maximum internal pressure of the cask is calculated assuming that the gas within the cask, a mixture of air, water vapor, oxygen, and hydrogen, behaves as an ideal gas.

The temperature of the gas mixture within the cask is set equal to the average inside surface temperature of the cask. The average inside surface temperature of the cask under HAC is assumed to be 225°F. Assuming MNOP, P_1, exists inside the cask at 183°F, the pressure in the cask at 225°F, P_2, may be calculated by the ideal gas relationship:

$$P_2 = \frac{T_2}{T_1} \cdot P_1 \text{ , where T is in degrees absolute}$$

$P_2 = 52.95$ psia

The additional vapor pressure contributed by water in the cavity due to the increase in temperature from 183°F to 225°F is 10.88 psia (as determined by the Goff-Gratch Equation).

Therefore, the maximum pressure during the HAC fire,

$P_{max} = 52.95 + 10.88 - 14.7 = 49.13$ psig

The value used for Pmax is conservatively set at 55.0 psig

3.4.4 Maximum Thermal Stresses

The structural evaluation of the package under the HAC fire test conditions is performed in Section 2.7.4 of this SAR. The maximum thermal stresses in the package with the corresponding allowable stresses are compared in Table 2-23. All the stresses are within the design limits established for the 3-60B package.

3.4.5 Accident Conditions for Fissile Packages for Air Transport

Not applicable.

3.5 APPENDIX

3.5.1 List of References

(3-1) Code of Federal Regulations, Title 10, Part 71, Packaging and Transportation of Radioactive Material, January 2007.

(3-2) Heat Transfer, J.P. Holman, McGraw Hill Book Company, New York, Fifth Edition, 1981.

(3-3) Cask Designers Guide, L.B. Shappert, et. al, Oak Ridge National Laboratory, February 1970, ORNL-NSIC-68.

(3-4) CRC Handbook of Chemistry and Physics, Robert C. Weast and Melvin J. Astel, eds., CRC Press, Inc., Boca Raton, Florida, 62nd ed., 1981.

(3-5) ASME Boiler & Pressure Vessel Code, 2001, Section II, Part D, Materials, The American Society of Mechanical Engineers, New York, NY, 2005.

(3-6) Rohsenow and Hartnett, Handbook of Heat Transfer, McGraw Hill Publication, 1973.

(3-7) ANSYS, Rev. 11.0, Computer Software, ANSYS Inc., Canonsburg, PA, 2007.

(3-8) EnergySolutions Document No. TH-022, Rev.1, Steady State Thermal Analyses of the 3-60B Cask Using a 3-D Finite Element Model.

(3-9) RADCALC, Rev. 4.0, Computer Software, DTS-SQA-009, Rev. 0, U.S. Department of Energy, 2005.

(3-10) EnergySolutions Document No. TH-023, Rev.1, Hypothetical Fire Accident Thermal Analyses of the 3-60B Cask.

Table 3-1

Summary of Maximum NCT Temperatures

Component	Maximum Calculated Temp.		Maximum Allowable Temperature (°F)
	Location (Node Nos.)	Value (°F)	
Fire Shield	2268	177.7	185 (1)
Outer Shell	2028	177.6	(2)
Inner Shell	1800	177.8	(2)
Lead	2718	178.9	622
Seals	249	178.6	450

NOTES:

(1) Based on the requirements of 10CFR71.45(g)

(2) Set by stress conditions.

Table 3-2

Summary of Maximum HAC Fire Temperatures

Component	Maximum Calculated Temp.			Maximum Allowable Temperature (°F)
	Location (Node Nos.)	Time (Sec.)	Value (°F)	
Fire Shield	3600	1,800	1,379	N.A
Outer Shell	1897	1,813	263	800
Inner Shell	1790	4,379	227	800
Lead	2366	2,068	233	622
Seals	288	6,209	225	450

Table 3-3

Summary of Maximum Pressures during NCT and HAC Fire Test

Condition	Maximum Pressure (psig)	Reference
NCT	35.0	Section 3.3.2
HAC Fire Test	55.0	Section 3.4.3

Table 3-4

Temperature-Independent Metal Thermal Properties

Material	Property	Reference: Page	Value
Steel	Density	3-2: 536	0.2824 lb/in^3
	ε (Outside)	3-1: 648	0.8
	ε (Inside)	3-3:133	0.15
Lead	Density	3-2: 535	0.4109 lb/in^3
	Spec. Heat	3-2: 535	0.0311 Btu/lb-°F
	Melting Point	3-4: B-29	621.5 °F

Table 3-5

Temperature-Dependent Metal Thermal Properties

Temp. (°F)	**Stainless Steel** (Ref. 3-5)		**Carbon Steel** (Ref.3-5)		**Lead** (Ref.3-6)
	Sp. Heat Btu/lb-°F	**Conductivity** $\times 10^{-3}$ Btu/sec-in-°F	**Sp. Heat** Btu/lb-°F	**Conductivity** $\times 10^{-3}$ Btu/sec-in-°F	**Conductivity** $\times 10^{-3}$ Btu/sec-in-°F
70	0.117	0.199	0.104	0.813	0.465
100	0.117	0.201	0.106	0.803	0.461
150	0.120	0.208	0.109	0.789	0.455
200	0.122	0.215	0.113	0.778	0.448
250	0.125	0.222	0.115	0.762	0.441
300	0.126	0.227	0.118	0.748	0.435
350	0.128	0.234	0.122	0.731	0.428
400	0.129	0.241	0.124	0.715	0.422
450	0.130	0.245	0.126	0.701	0.415
500	0.131	0.252	0.128	0.683	0.409
550	0.132	0.257	0.131	0.667	0.402
600	0.133	0.262	0.133	0.648	0.395
650	0.134	0.269	0.135	0.632	0.389
700	0.135	0.273	0.139	0.616	0.389
750	0.136	0.278	0.142	0.600	0.389
800	0.136	0.282	0.146	0.583	0.389
900	0.138	0.294	0.154	0.551	0.389
1,000	0.139	0.306	0.163	0.519	0.389
1,100	0.141	0.315	0.172	0.484	0.389
1,200	0.141	0.324	0.184	0.451	0.389
1,300	0.143	0.336	0.205	0.417	0.389
1,400	0.144	0.345	0.411	0.380	0.389
1,500	0.145	0.354	0.199	0.363	0.389

Table 3-6

Temperature-Dependent Air Thermal Properties

Temp. (°F)	**Air** (Ref.3-2)		
	Density $\times 10^{-5}$ lb/in^3	**Sp. Heat** Btu/lb-°F	**Conductivity** $\times 10^{-7}$ Btu/sec-in-°F
70	4.3507	0.2402	3.4491
100	4.1117	0.2404	3.5787
150	3.7517	0.2408	3.9028
200	3.4676	0.2414	4.1759
250	3.2361	0.2421	4.4468
300	3.0307	0.2429	4.7037
350	2.8310	0.2438	4.9560
400	2.6730	0.2450	5.2037
450	2.5220	0.2461	5.4491
500	2.3964	0.2474	5.6875
550	2.2778	0.2490	5.9213
600	2.1684	0.2511	6.1435
650	2.0706	0.2527	6.3634
700	1.9803	0.2538	6.5810
750	1.8981	0.2552	6.7894
800	1.8177	0.2568	6.9954
900	1.6898	0.2596	7.4097
1,000	1.5712	0.2628	7.8032
1,100	1.4722	0.2659	8.1759
1,200	1.3848	0.2689	8.5440
1,300	1.3044	0.2717	8.8981
1,400	1.2350	0.2742	9.2847
1,500	1.1707	0.2766	9.7060

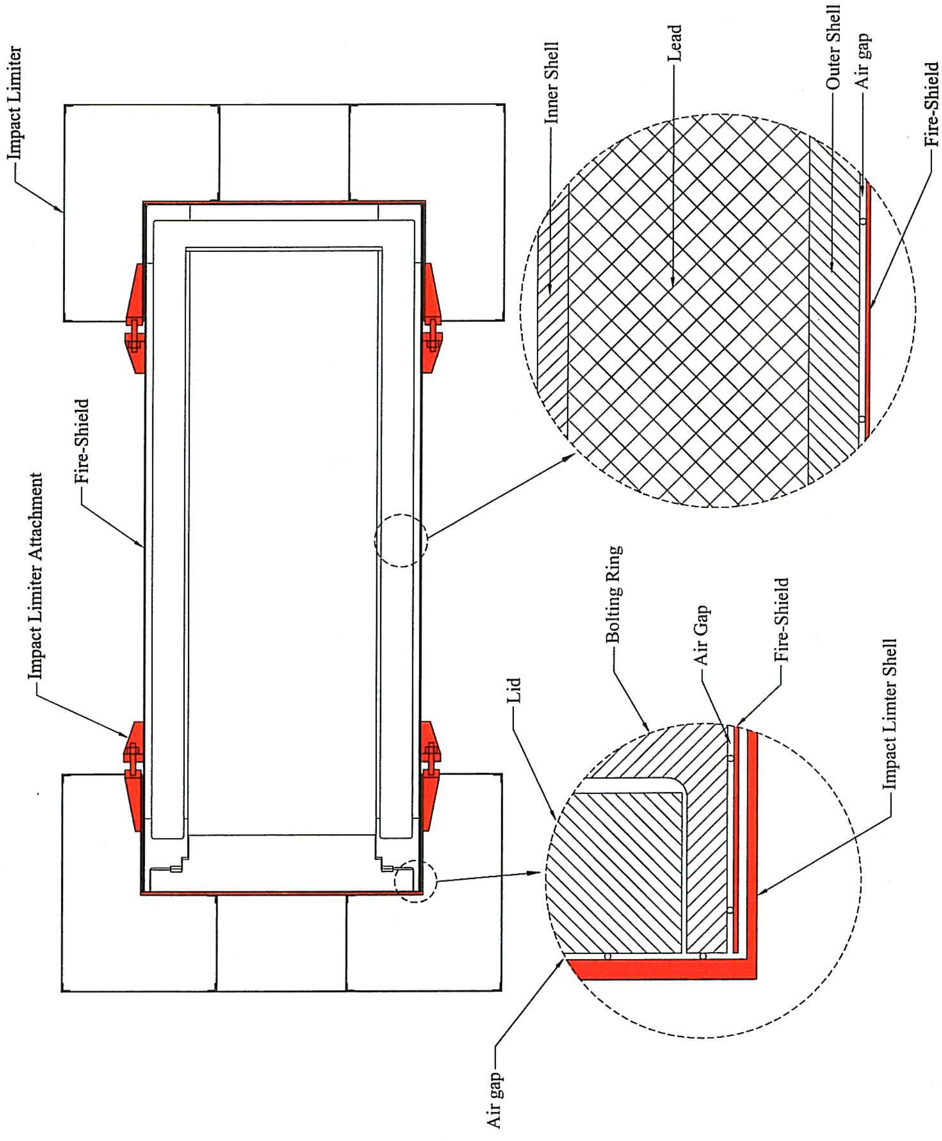

Figure 3-1
3-60B Cask Design Features Important to Thermal Performance

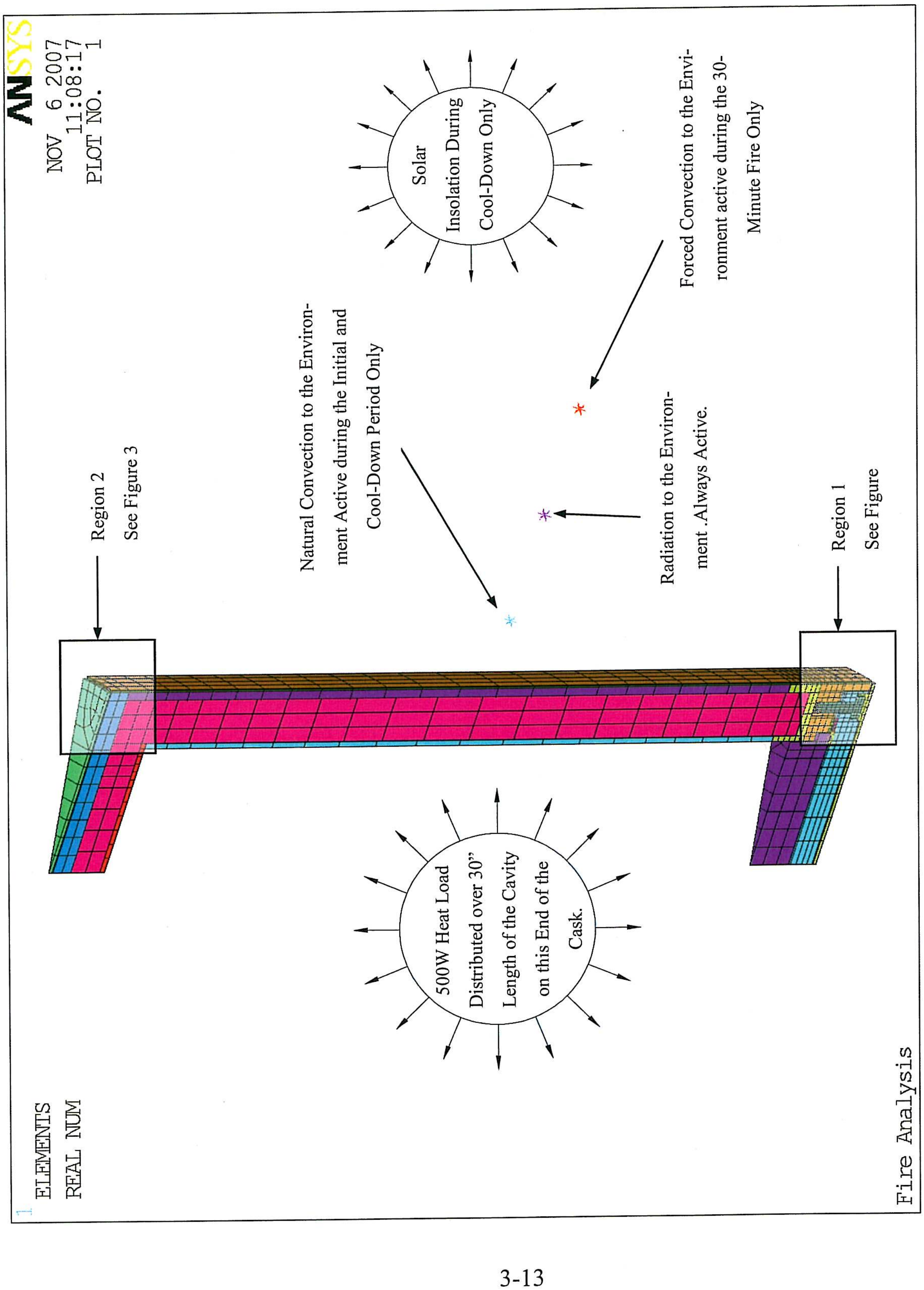

Figure 3-2
Finite Element Model of the 3-60B Cask Used for the Thermal Analyses

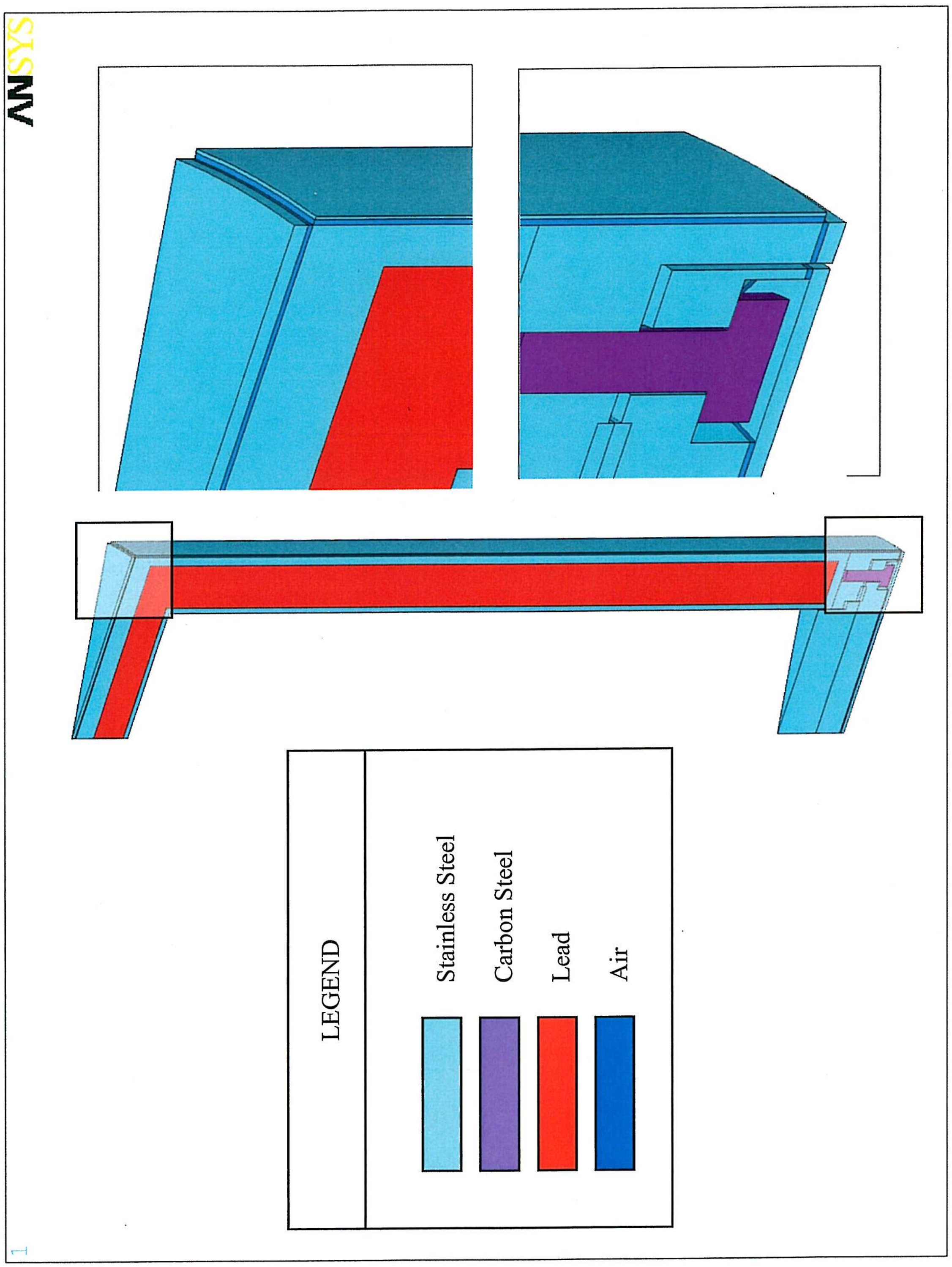

Figure 3-3
Materials Used in the Finite Element Model

Figure 3-4
Temperature Distribution – Hot Environment

Figure 3-5
Temperature Distribution – Cold Environment

Figure 3-6
Temperature Distribution – Normal Hot

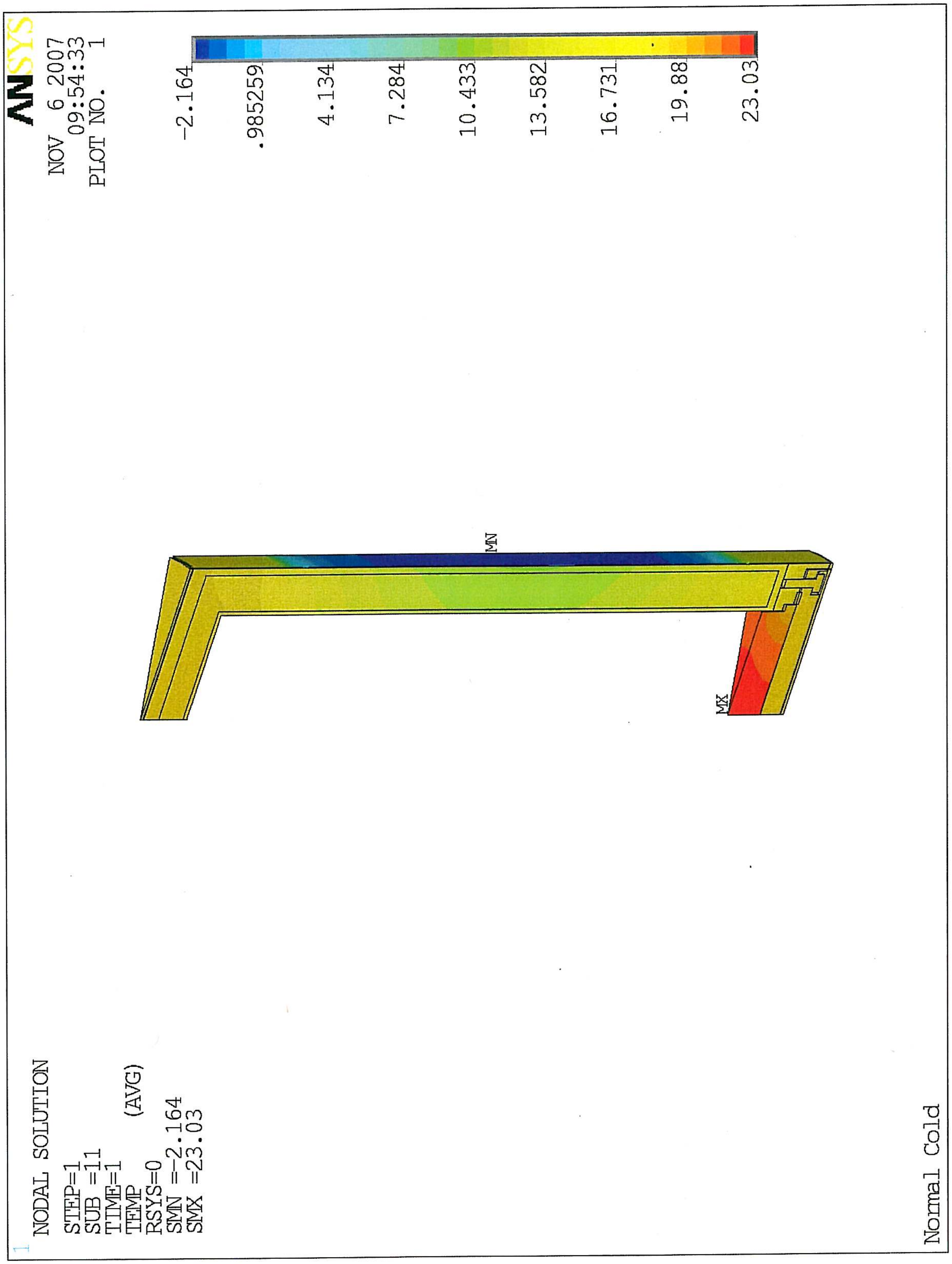

Figure 3-7
Temperature Distribution – Normal Cold

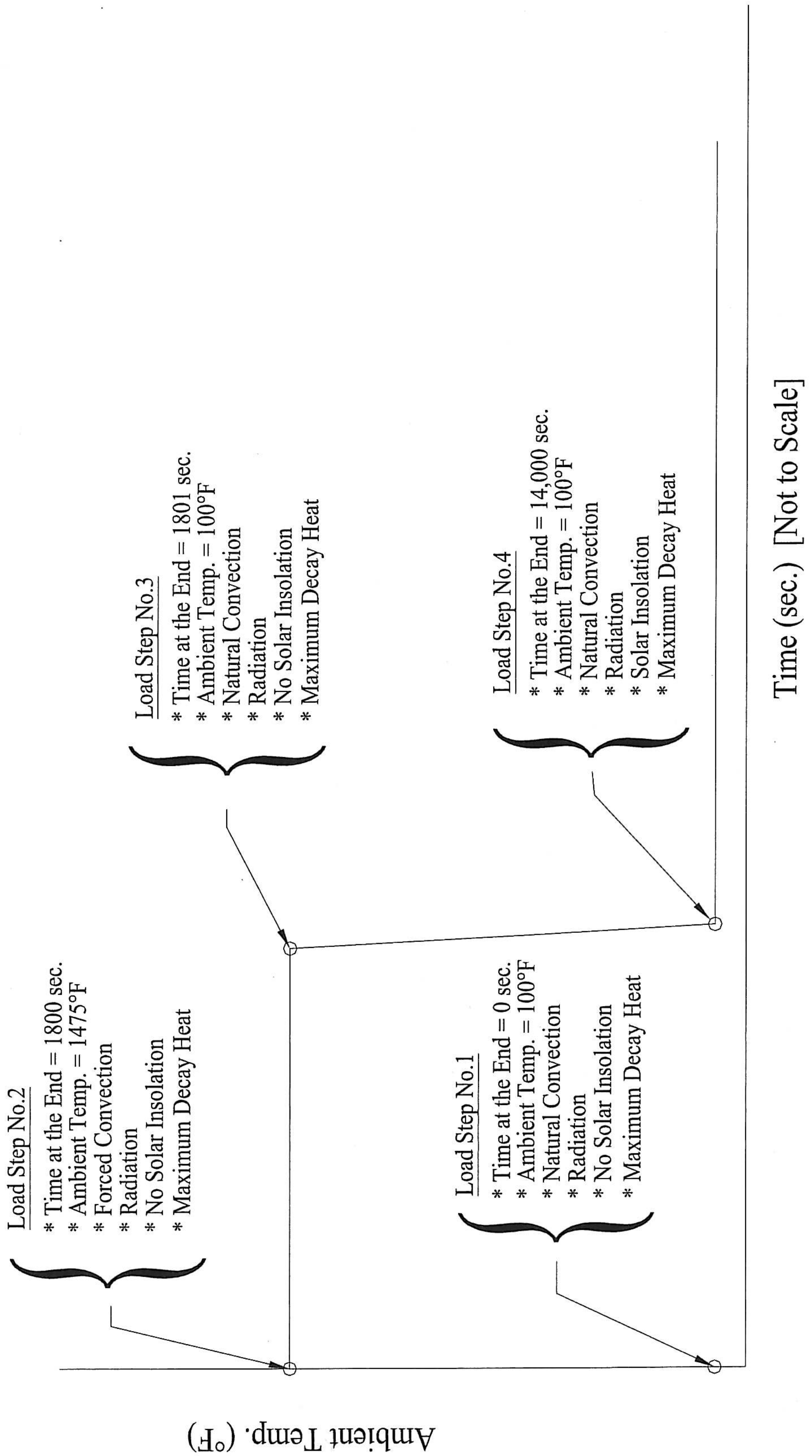

Figure 3-8
HAC Fire Analysis Load Steps and Boundary Conditions

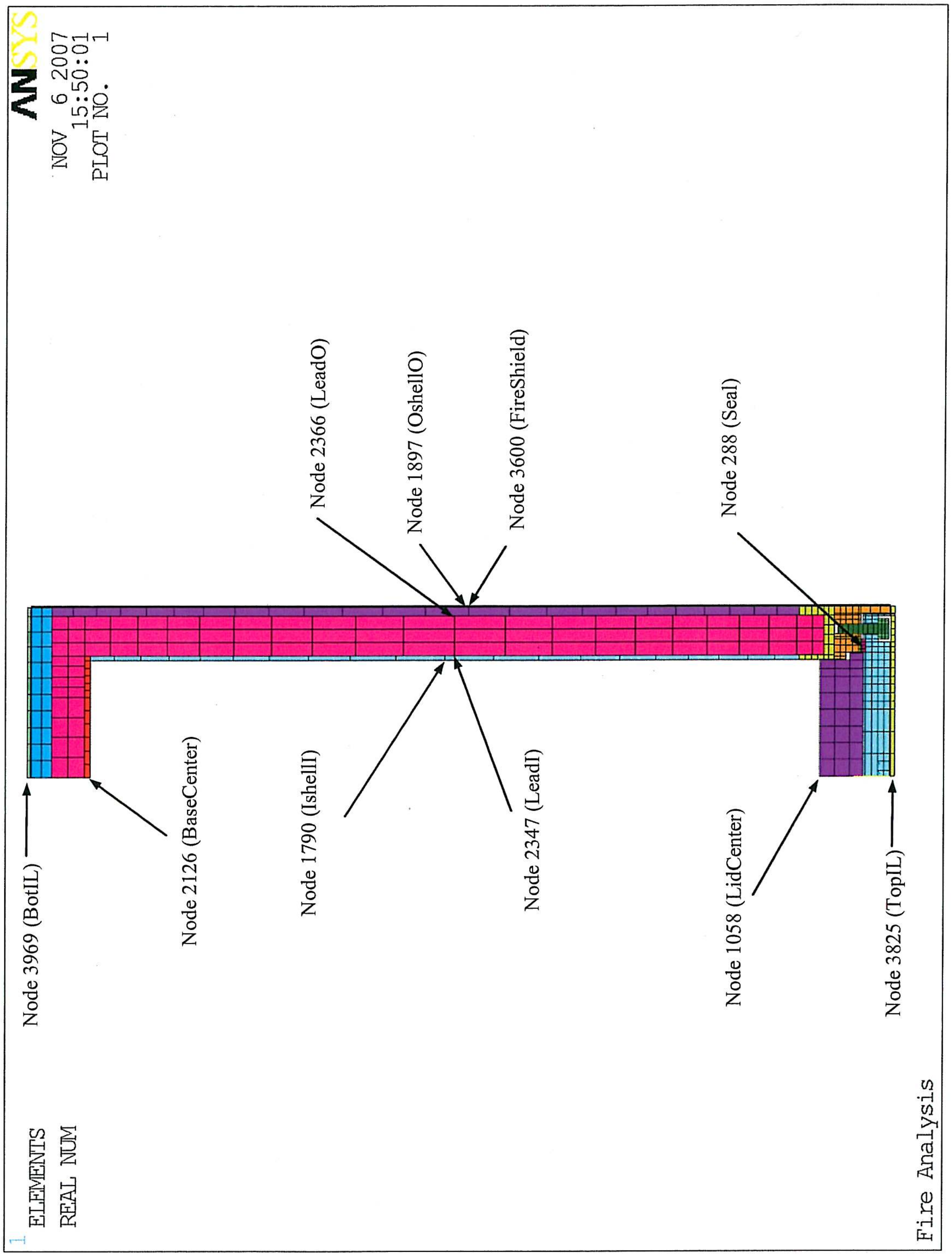

Figure 3-9
Identification of the Nodes where Time-History is Monitored

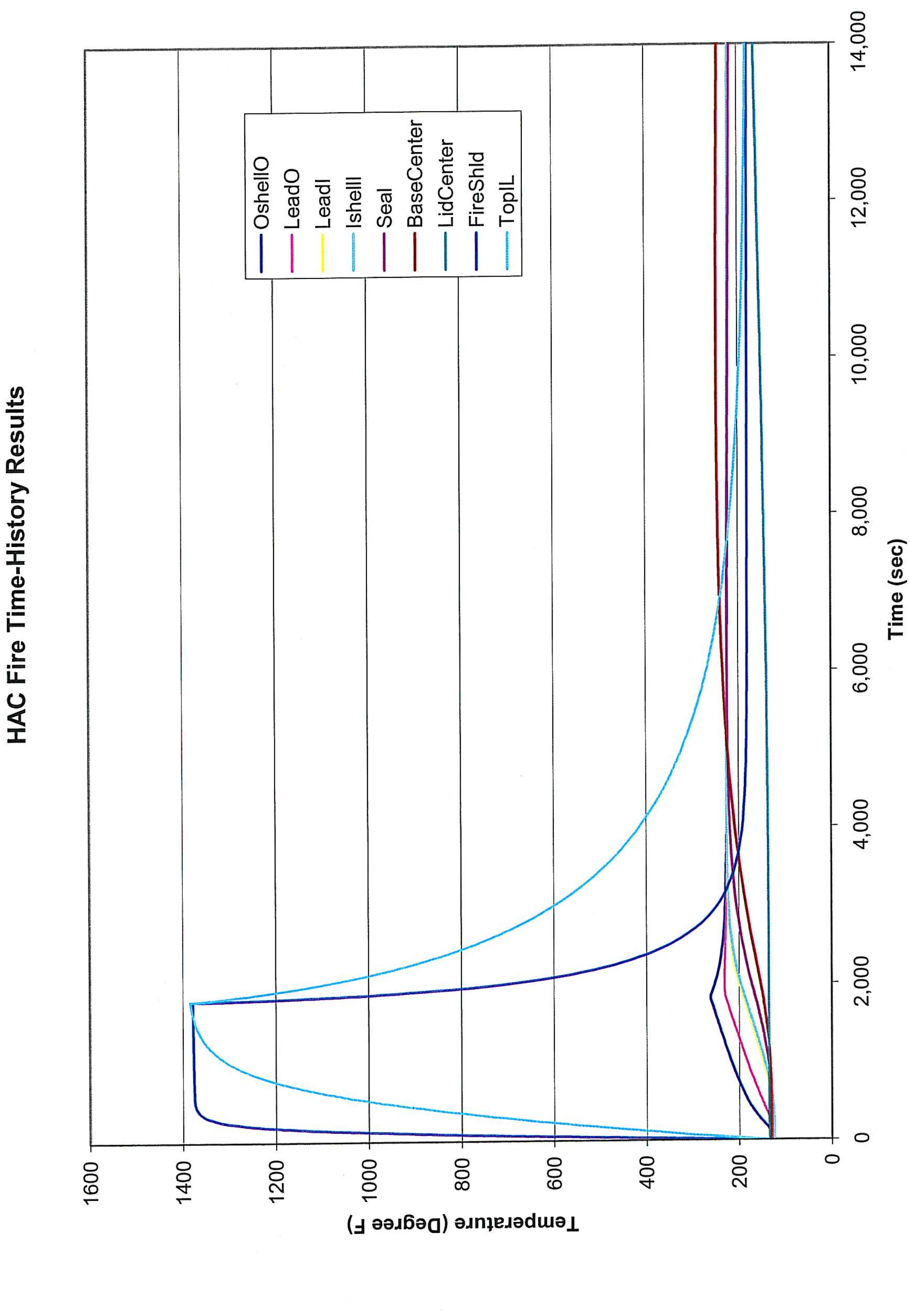

Figure 3-10

Temperature Time-History Plot in Various Components of the Cask

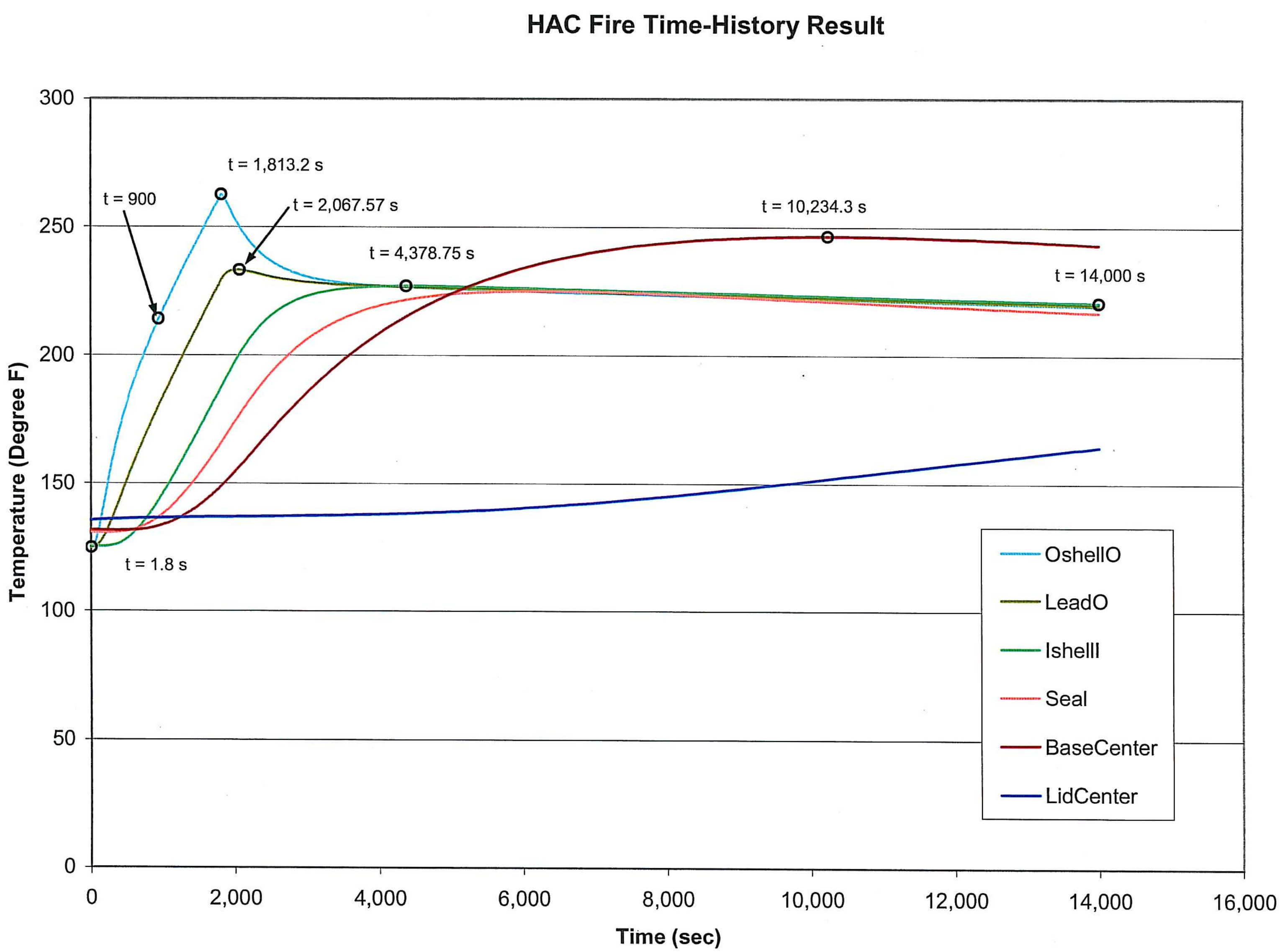

Figure 3-11
Temperature Time-History Plot in Various Components of the Cask (Not Under Direct Contact with the Fire)

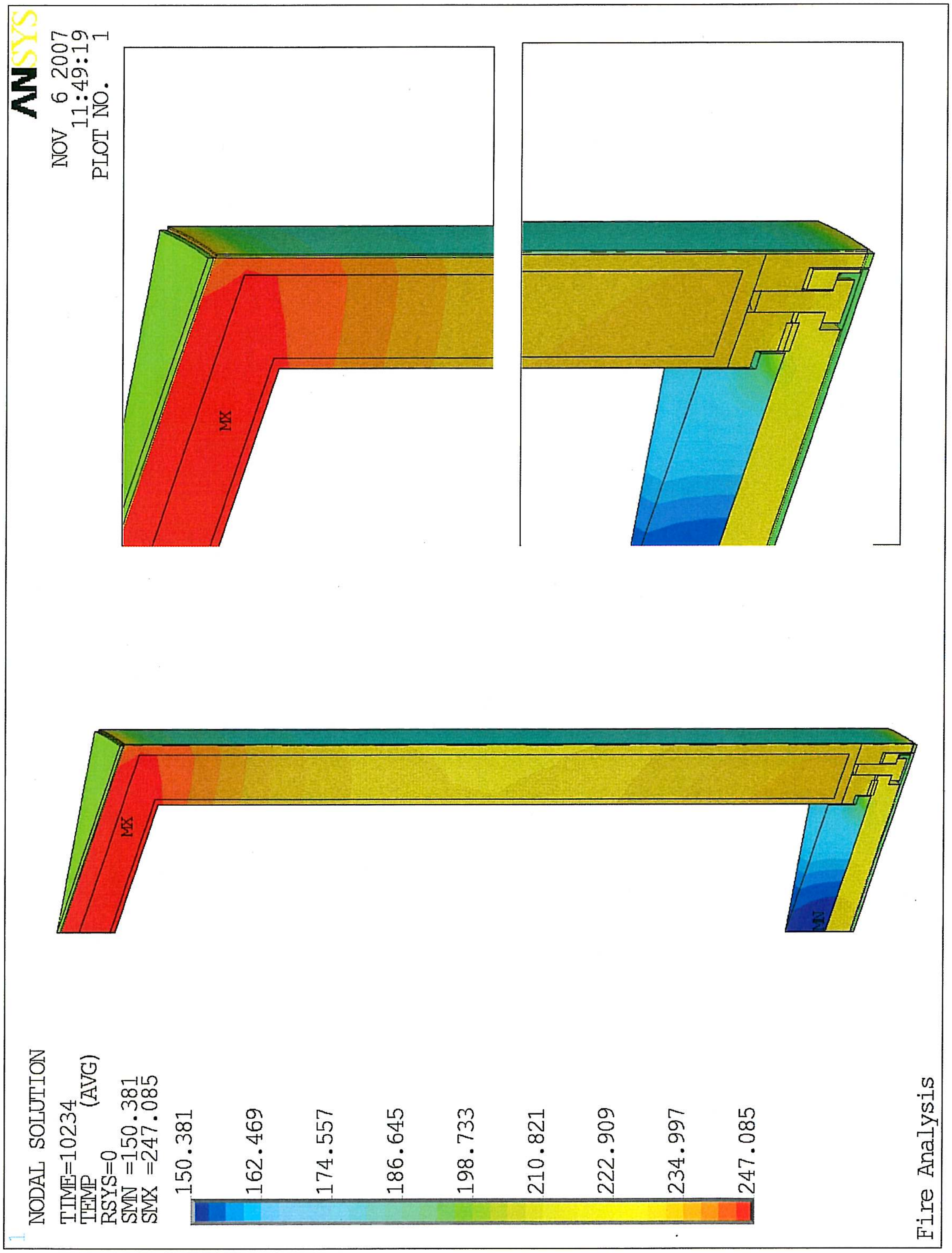

Figure 3-12
Temperature Distribution – 10,234.3 Sec. After the Start of the Fire