Attachment 1
Calculation Package CSG-01-1000
10-160B Transportation Cask Thermal Analysis

ENERGYSOLUTIONS **Spent Fuel Division**	**CALCULATION PACKAGE**	Calc. Pkg No. CSG-01.1000 File No.: CSG-01.1000 Revision: 1

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

4-29-09

Verified by: Steve Sisley

4-29-09

Approved by Engineering Manager: Steve Sisley

4-29-09

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	Steve 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	Steve 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 Sisley

4-29-09

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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	0.7347	Based upon reference [3.1.2]
External surface emissivity during NCT hot day	0.80	Based upon reference [3.1.2]

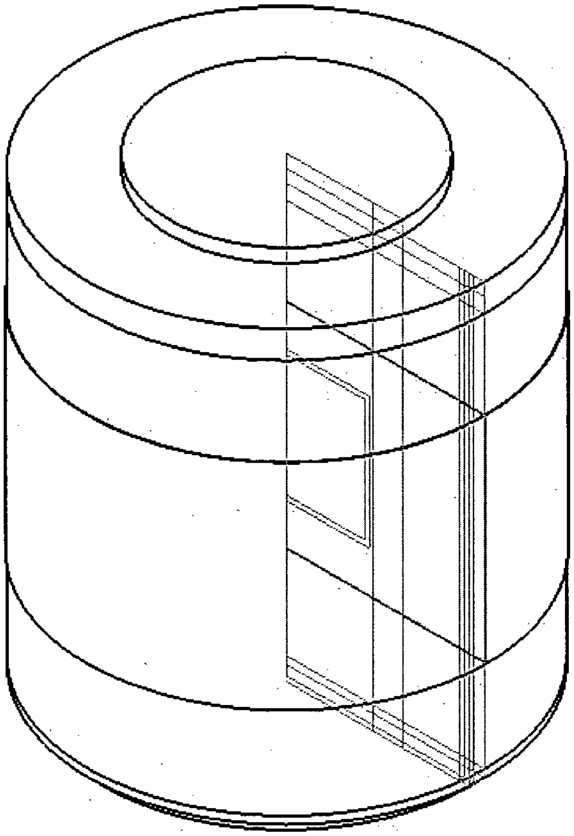


Figure 1 – 10-160B Transportation Cask Simplified Isometric View

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:

   $h_f = 10 * \text{W/m}^2\ ^\circ\text{C}$ As per reference [3.1.1]

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

   $h_f = 3.398\text{E-}6 * 3600 = 0.0122\ \text{Btu/hr/in}^2/^\circ\text{F}$ 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, Figure 3, and Figure 4). 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.

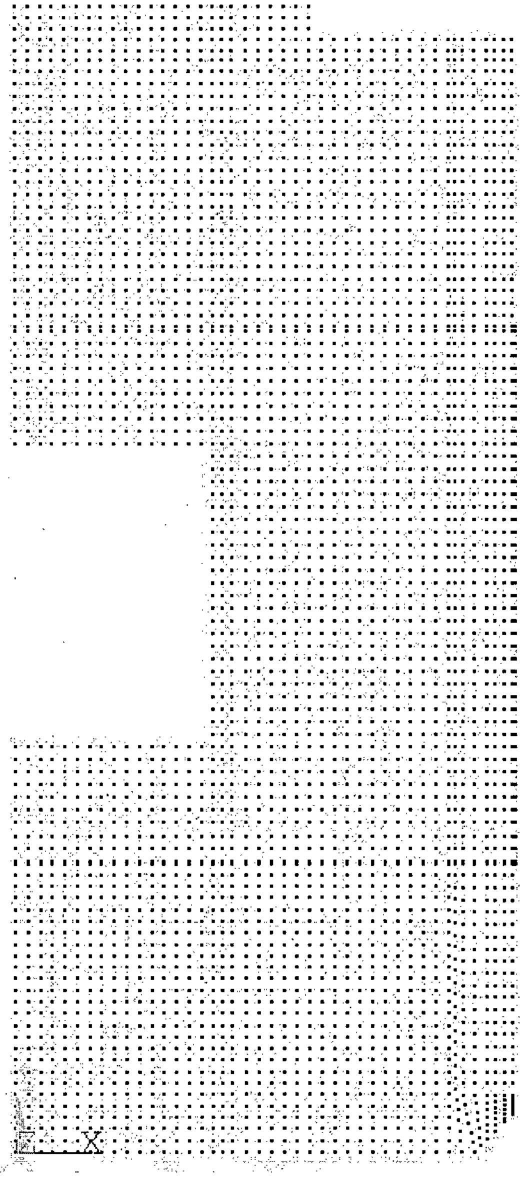


Figure 2 – 10-160B Cask ANSYS NCT and HAC Node Plot

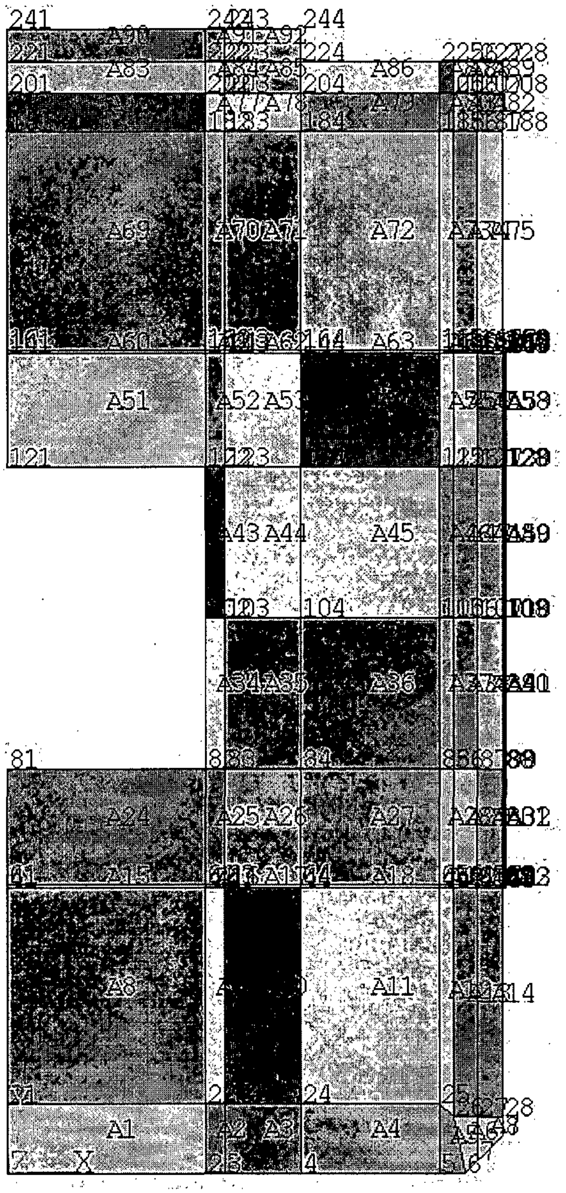


Figure 3 – 10-160B Cask ANSYS NCT and HAC Area Plot

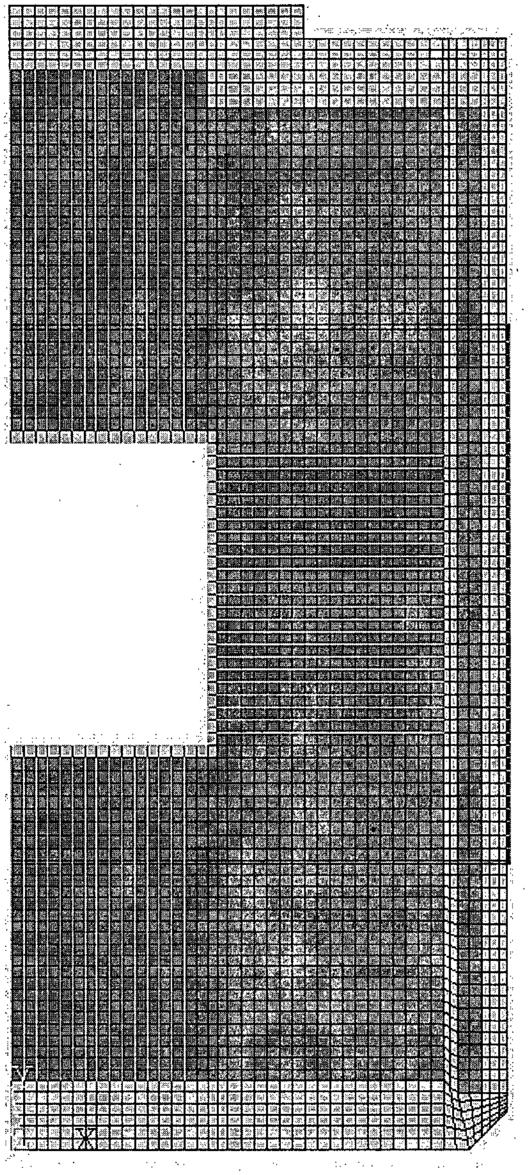


Figure 4 – 10-160B Cask ANSYS NCT and HAC Model Element / Material Plot

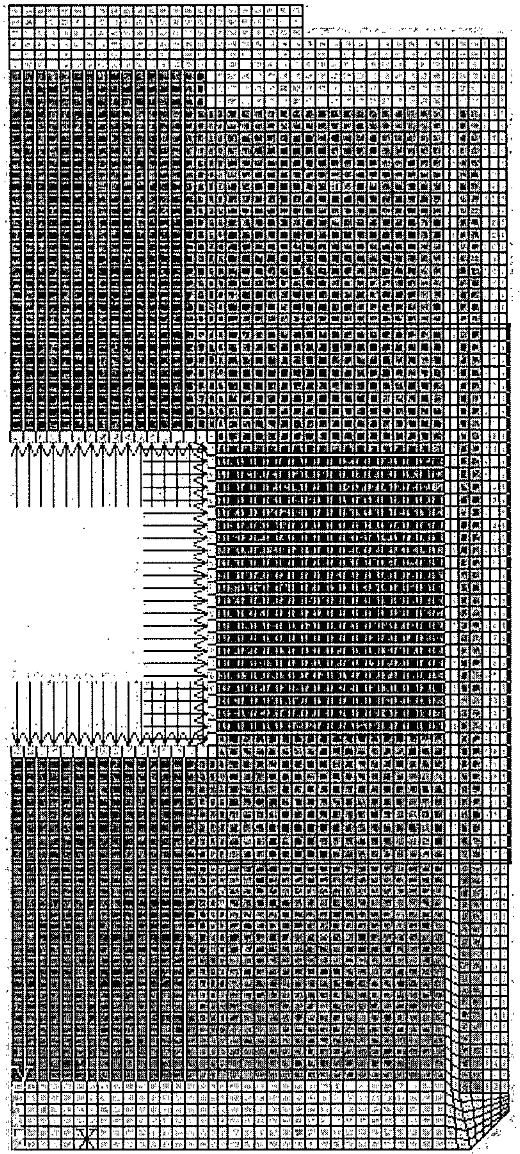


Figure 5 – "Hot spot" Cavity Heat Load (NCT and HAC)

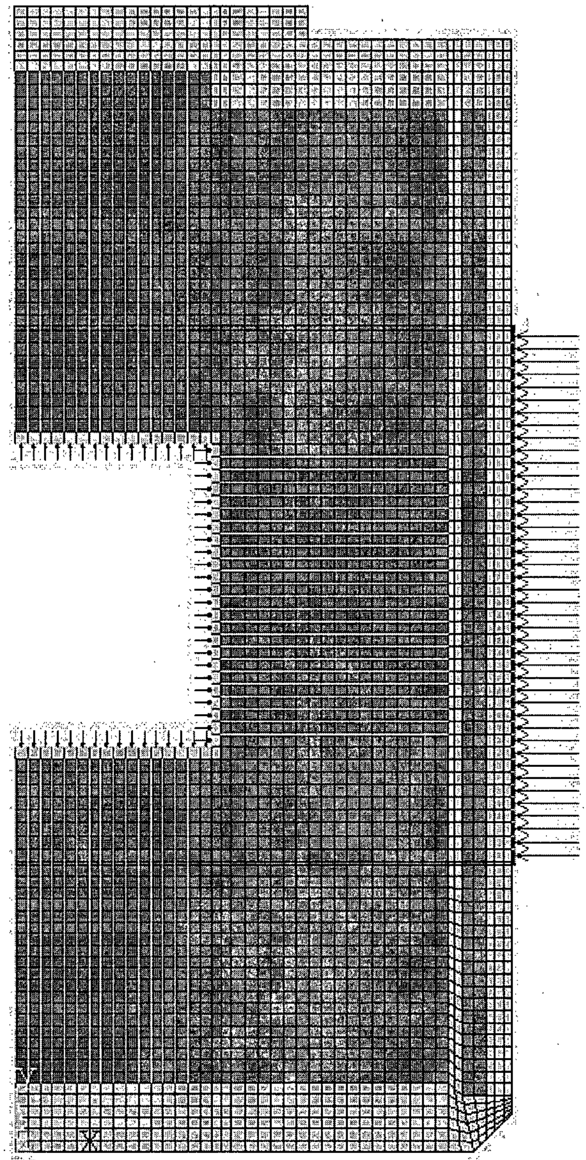


Figure 6 – Solar Heat and Cavity Heat Load (NCT Hot Day, only)

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

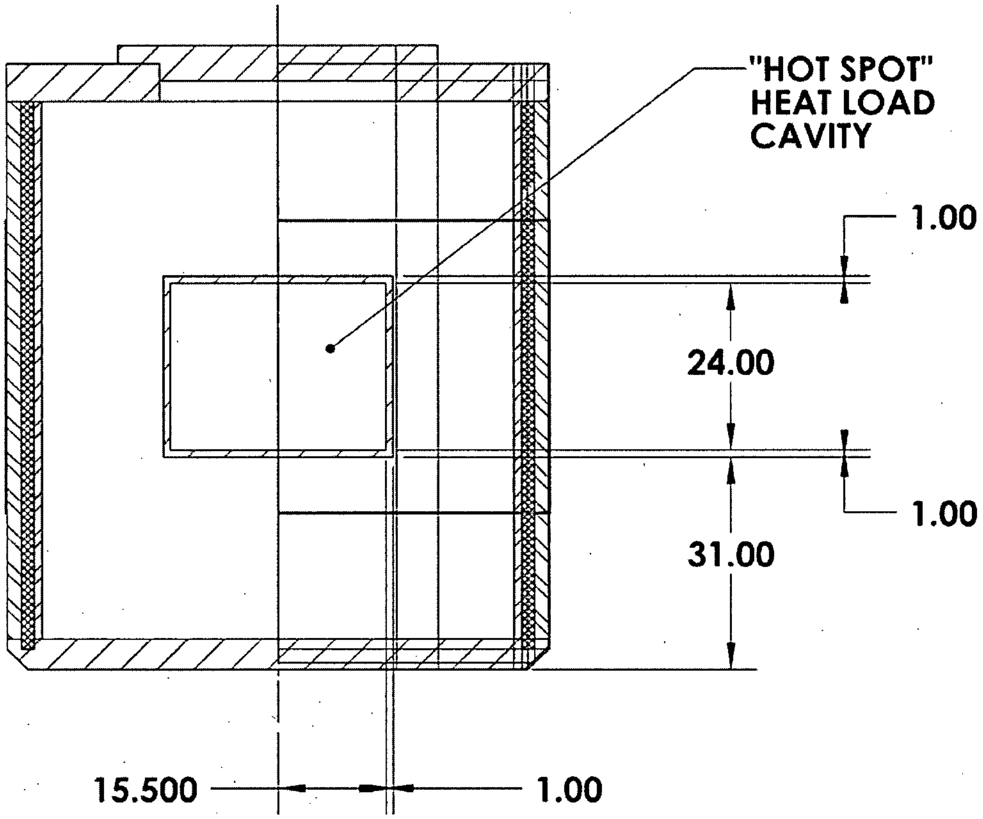


Figure 7 – 10-160B Cask Assumed Centered "Hot Spot" Heat Load

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 = $1/32 * \pi * 2 * R$

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 181°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	165.8	48.50
O-ring (primary lid)	Elastomeric	165.8	48.50
O-ring (secondary lid)	Elastomeric	166.4	48.50
Inner shell	Carbon steel	270.8	0.77
Gamma shield	Lead	271.5	0.73
Outer shell	Carbon steel	284.7	0.50
Fire shield	Carbon steel	1352.4	0.50
Cavity bulk air (peak nodal temperature)	Air	270.8	0.77
Cavity air (peak bulk average temperature)	Air	181.3[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	38.7	0.5001
Maximum temperature difference: outer shell	0.0	19.6	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	275.6	0.5334

---

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

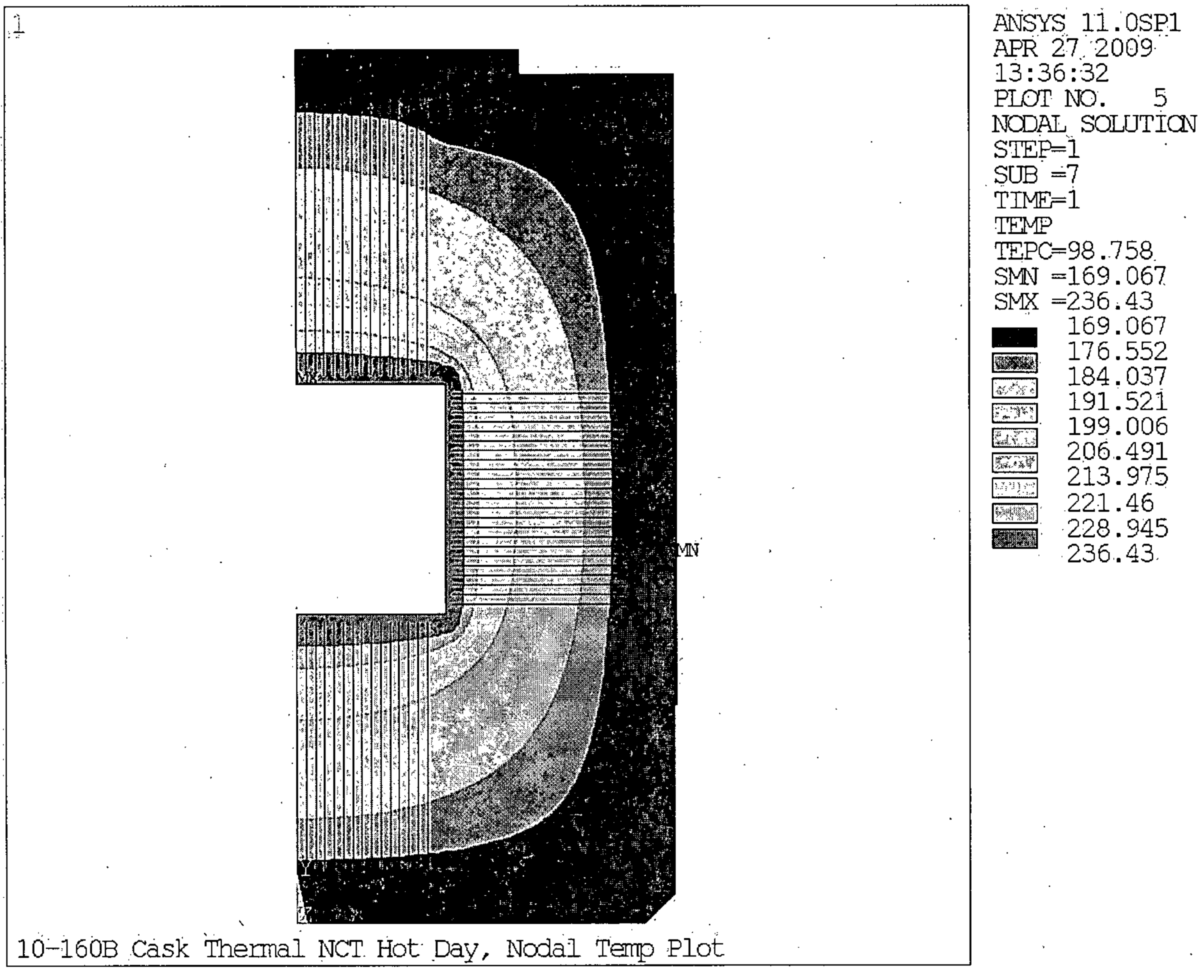


Figure 8 – 10-160B Cask NCT Hot Day (air, lead and steel): Nodal Temps

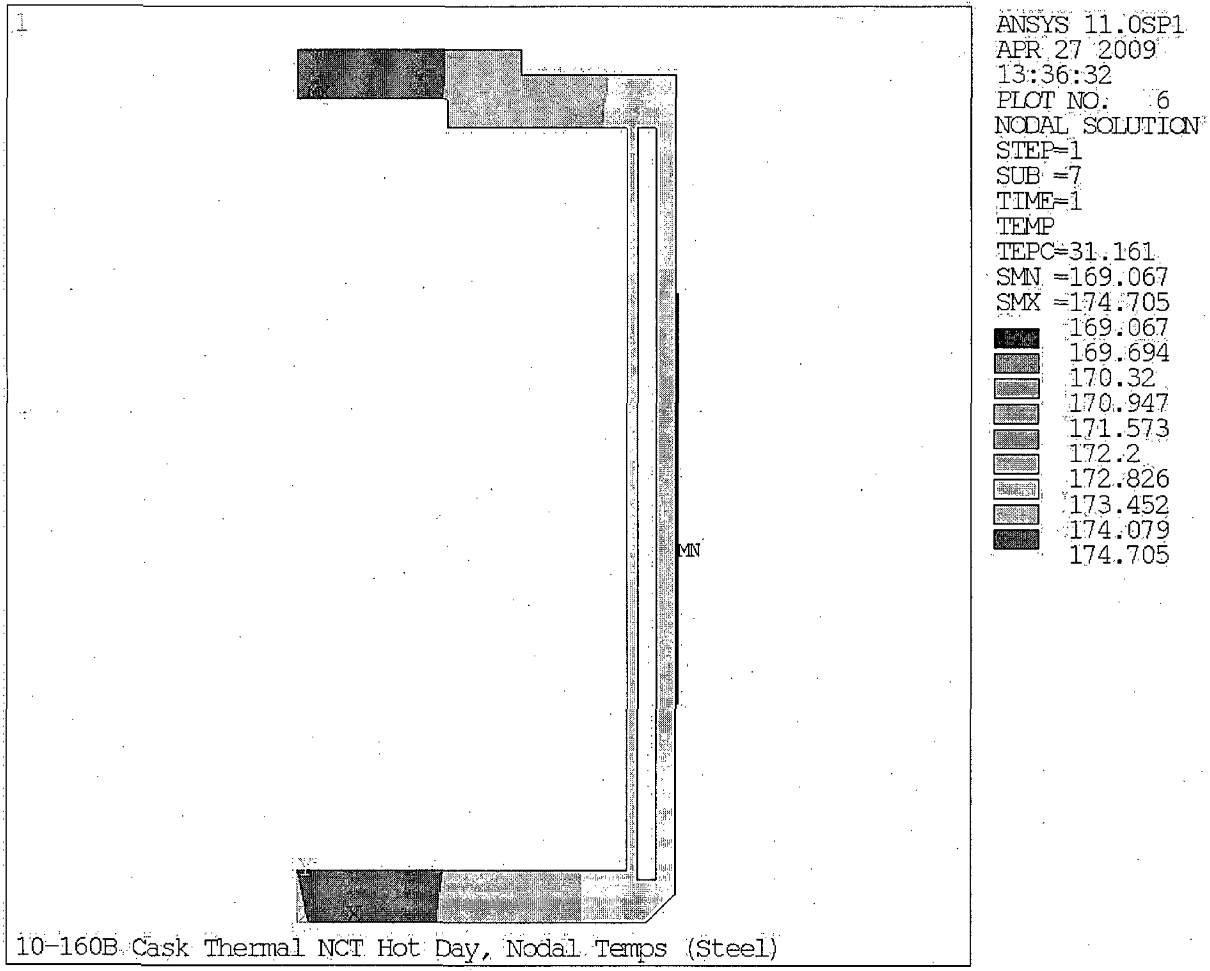


Figure 9 – 10-160B Cask NCT Hot Day (steel, only): Nodal Temps

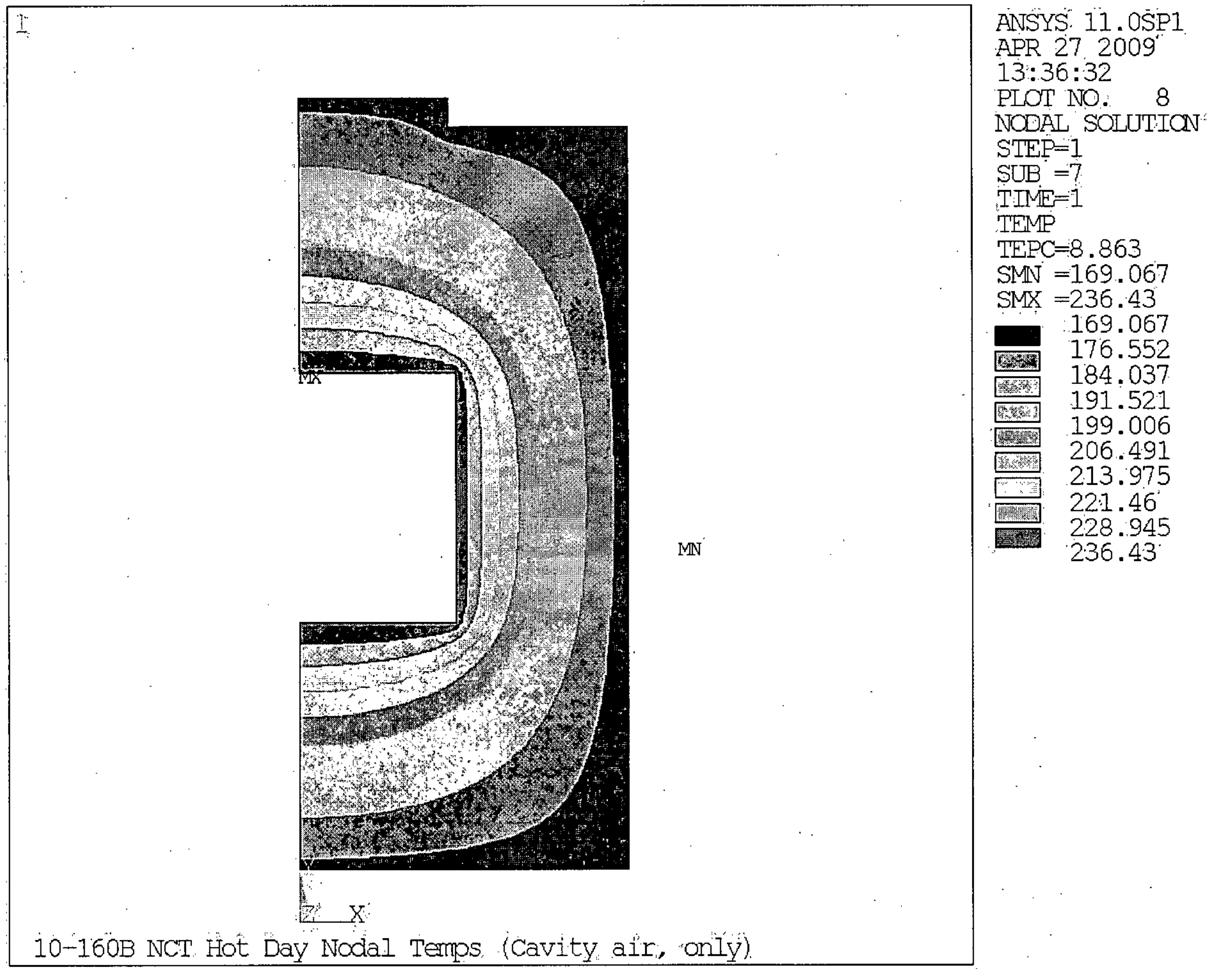


Figure 10 – 10-160B Cask NCT Hot Day (air, only): Nodal Temps

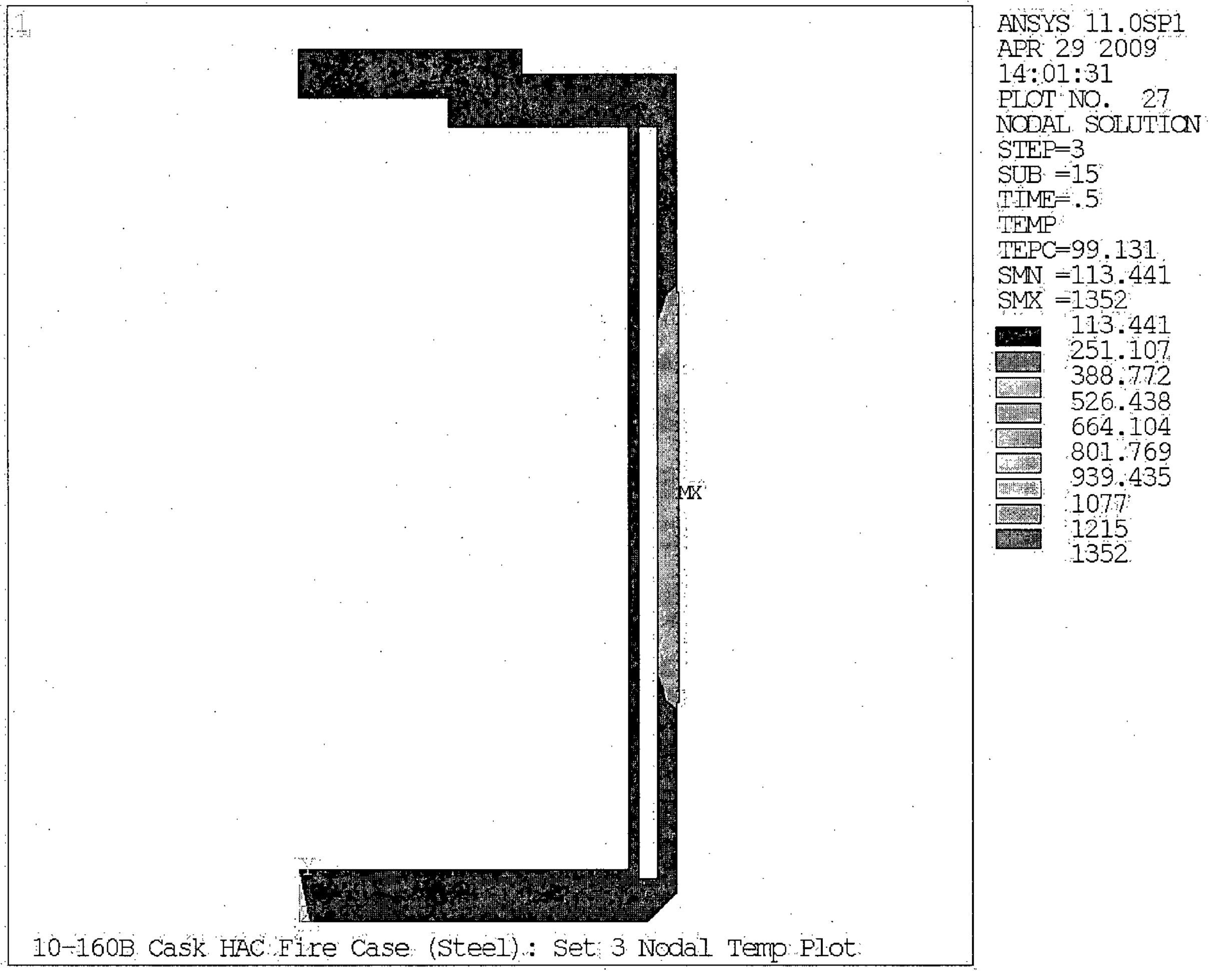


Figure 11 – 10-160B Cask HAC Fire (steel): Nodal temps @ End of 30 Min Fire

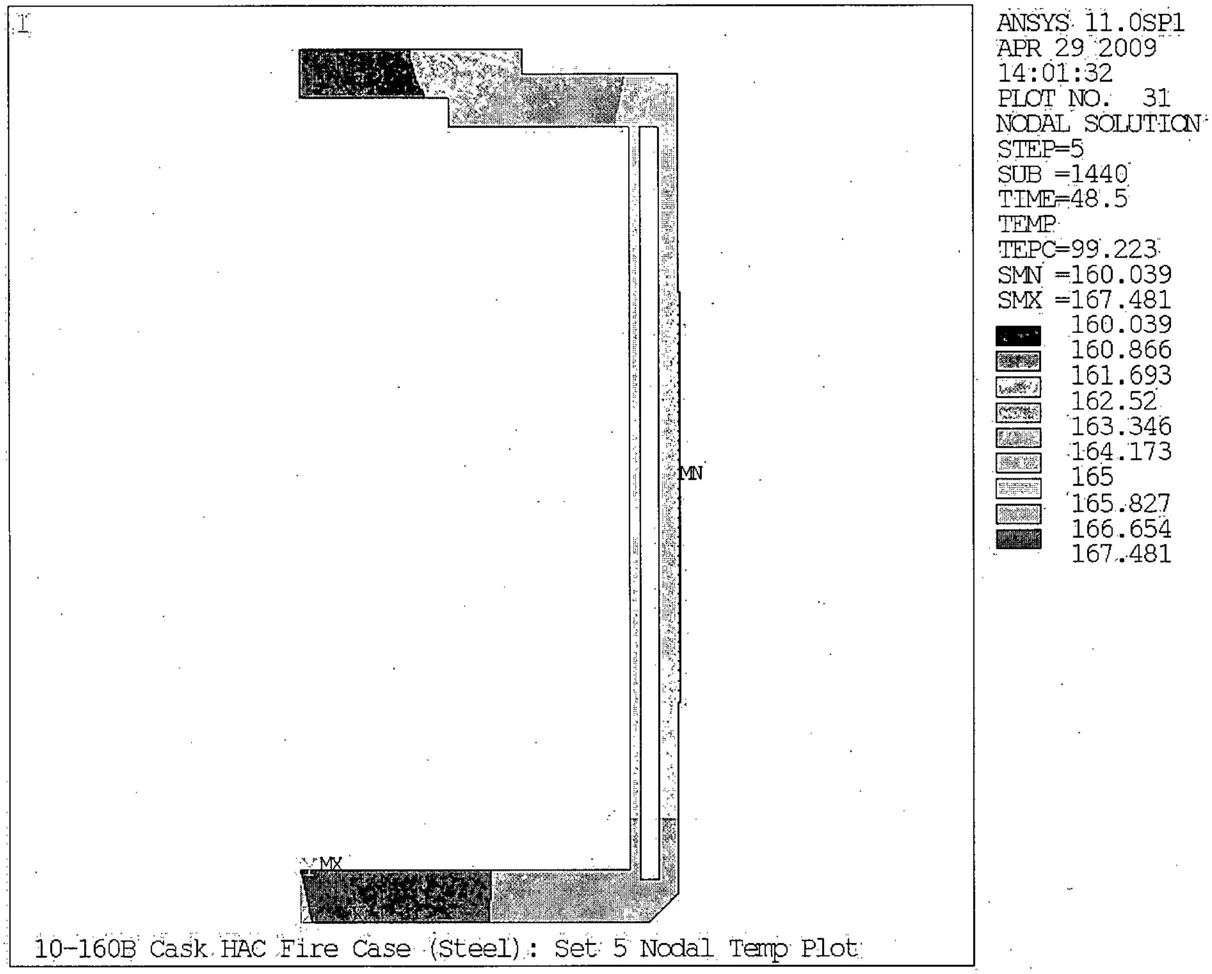


Figure 12 – 10-160B Cask HAC Fire (steel): Nodal Temps @ End of 48-hr Cool-down

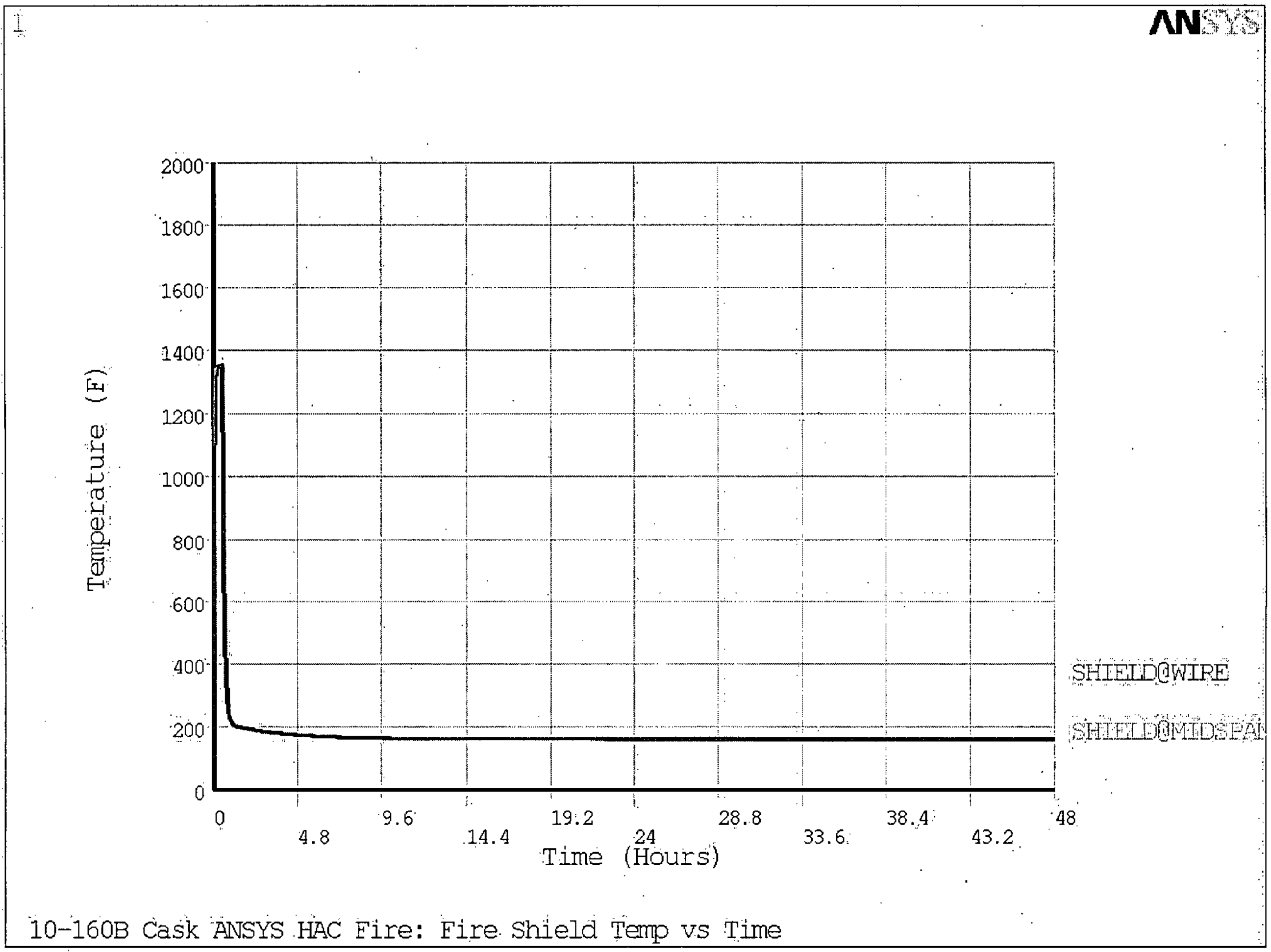


Figure 13 – HAC Fire: Fire Shield Temperature Transient Plot

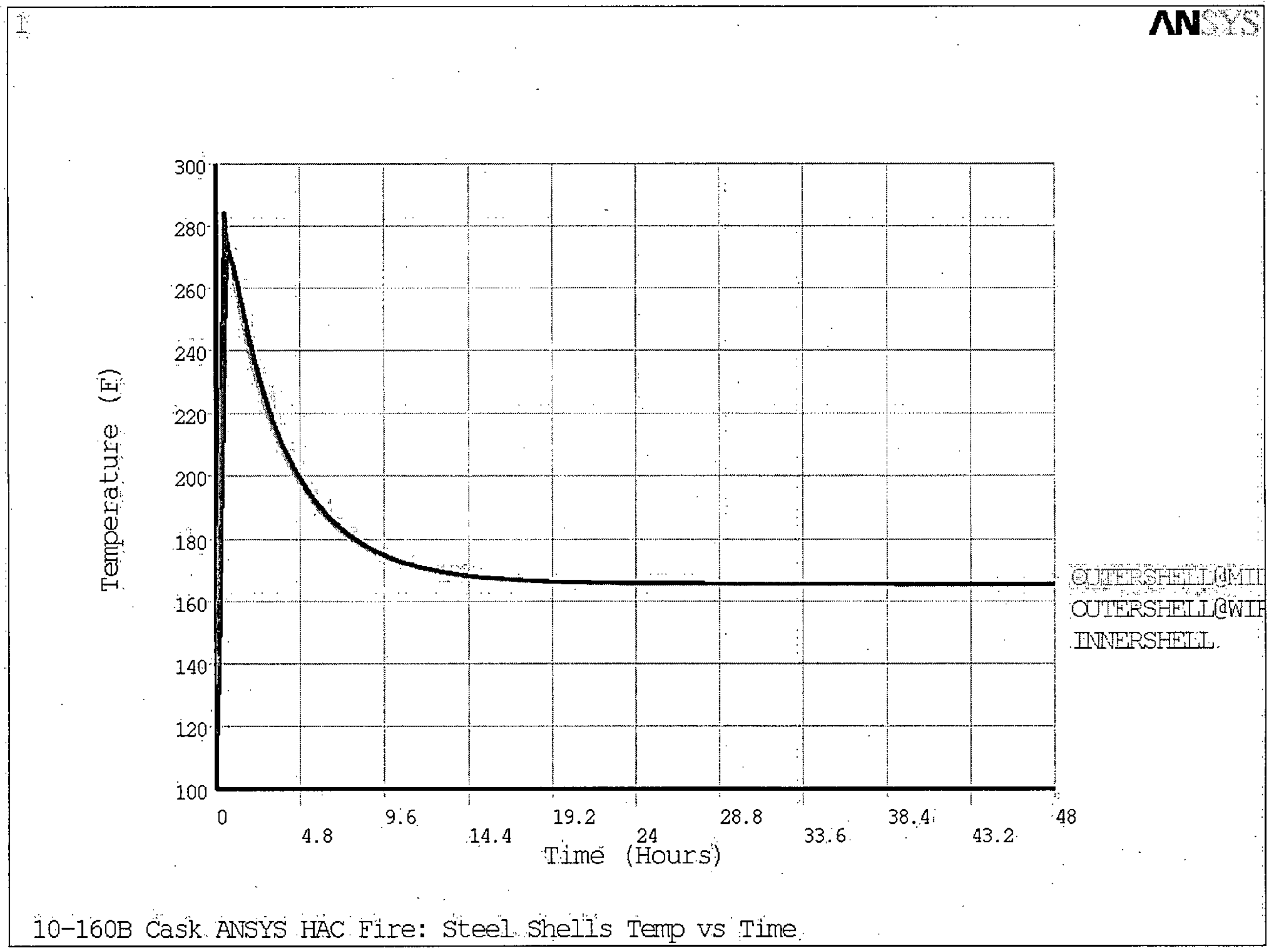


Figure 14 – HAC Fire: Inner and Outer Carbon Steel Shells Temperature Transient Plot

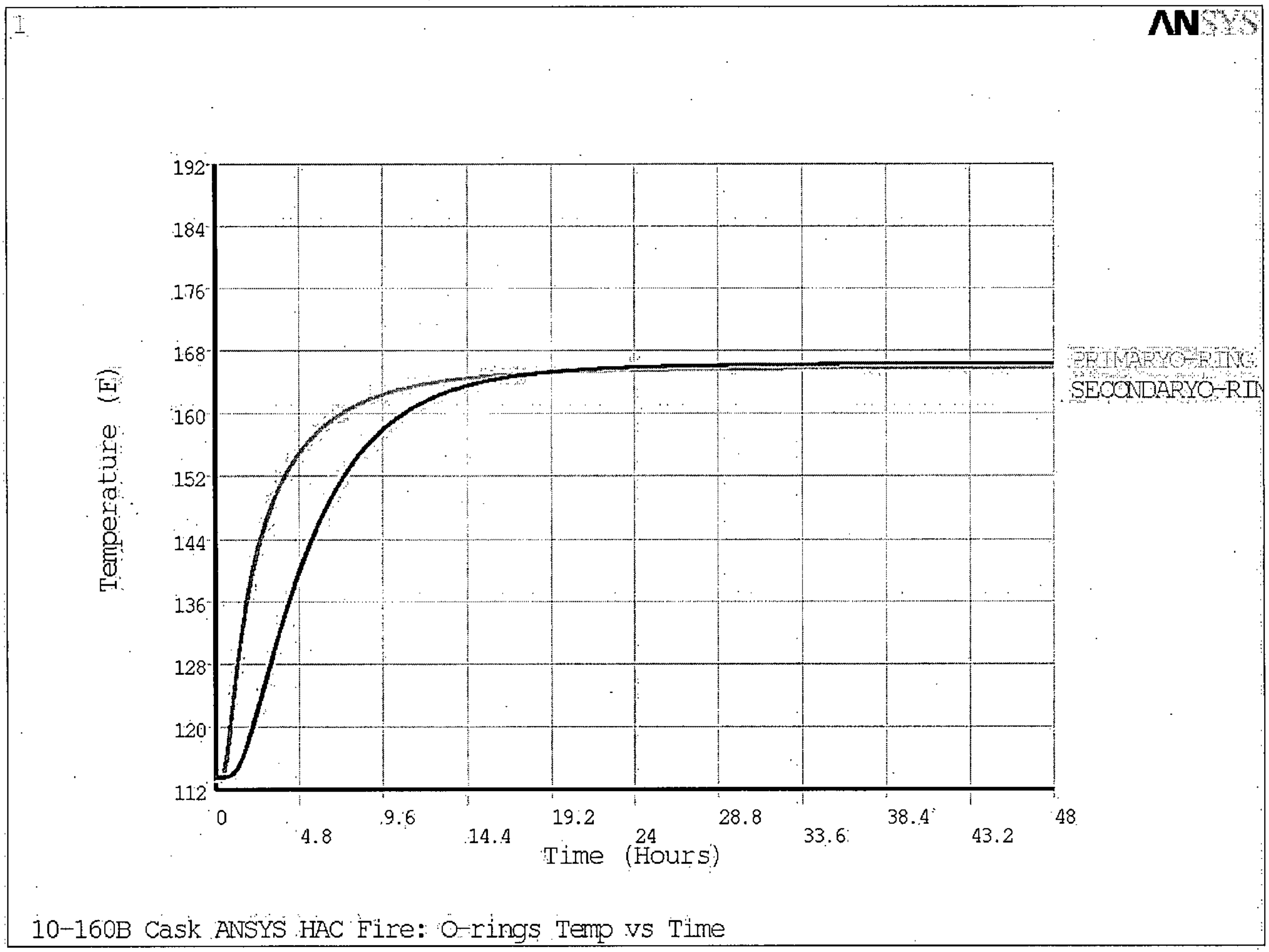


Figure 15 – HAC Fire: O-ring Temperature Transient Plot

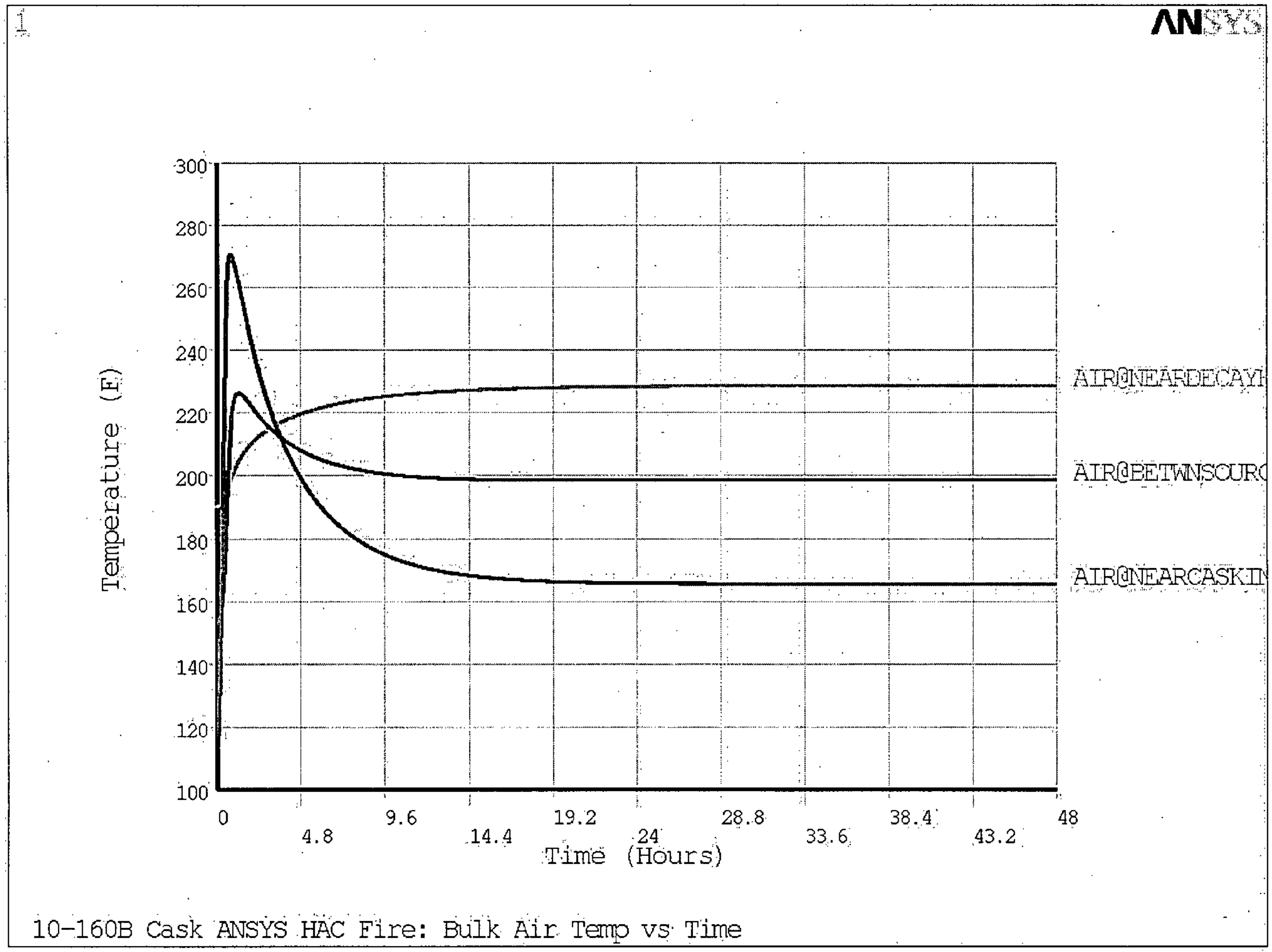


Figure 16 – HAC Fire: Cavity Bulk Air Temperature Transient Plot

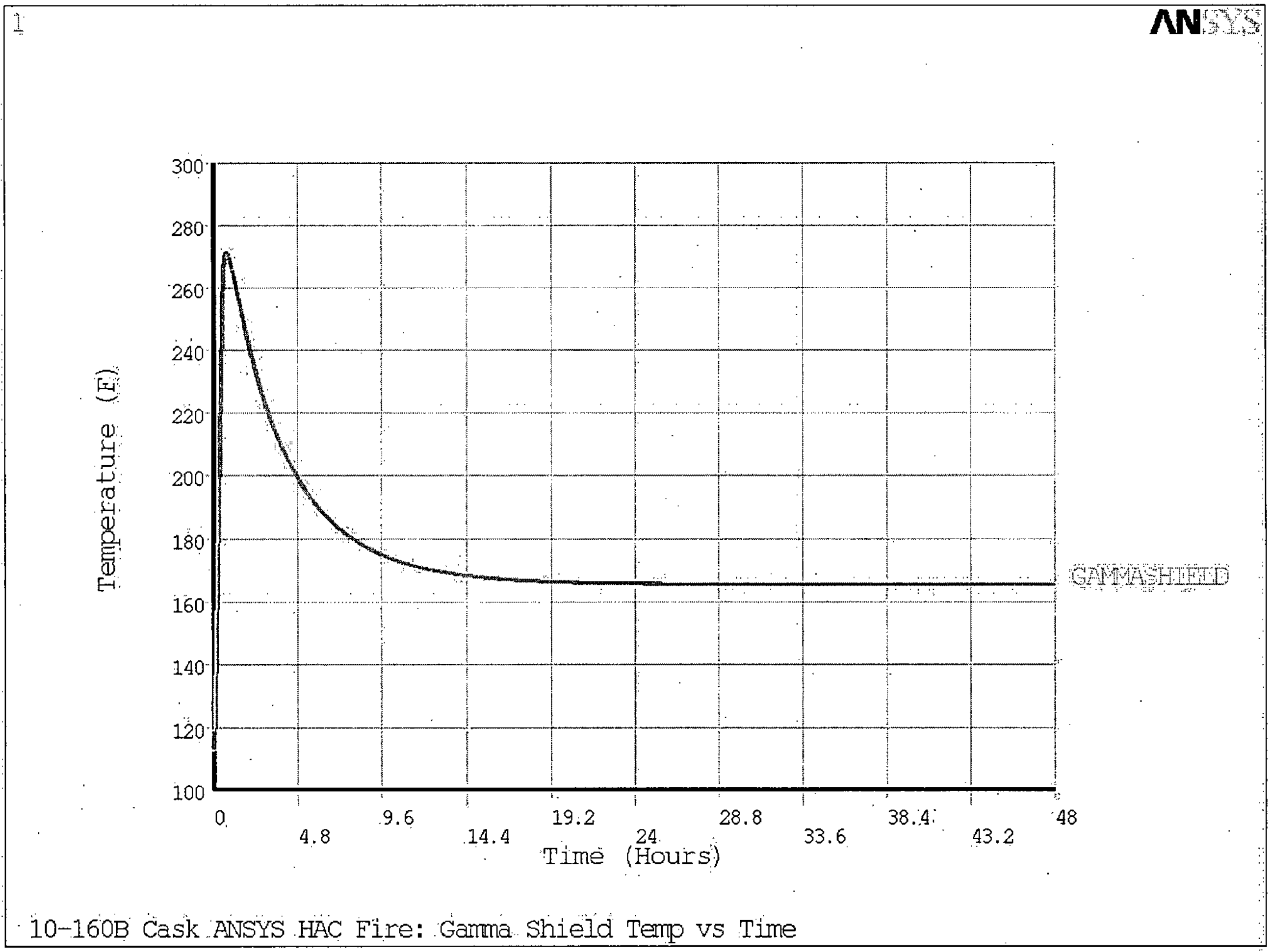


Figure 17 – HAC Fire: Gamma Shield Temperature Transient Plot

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 1352.4°F, the maximum temperatures of the other cask components do not exceed 284.7°F. In addition, for the HAC fire case, the maximum bulk average temperature of the air within the cask cavity is approximately 181°F and the maximum O-ring temperature is 166°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 38.7°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_04_29_09.inp	4/29/2009	ANSYS	2	11	Windows XP x. 64 Edition	26831-D
10_160B_NCT_Hot_04_29_09.inp	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 volue with element volumes
ssum
smult,vtemp,tempe,volue,1,1   ! mult 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=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, 1,0.7347,0.7347,0.7347,0.7347,0.7347,0.7347
MPDATA,EMIS,4, 7,0.7347,0.7347,0.7347,0.7347,0.7347,0.7347
MPDATA,EMIS,4,13,0.7347,0.7347,0.7347,0.7347

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, 1,0.7347,0.7347,0.7347,0.7347,0.7347,0.7347
MPDATA,EMIS,6, 7,0.7347,0.7347,0.7347,0.7347,0.7347,0.7347
MPDATA,EMIS,6,13,0.7347,0.7347,0.7347,0.7347

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 @ WIRE
NSOL,4,NODE(X8,Y8+6,0),TEMP,,OUTER SHELL @ MIDSPAN
NSOL,5,NODE(X8,Y8,0),TEMP,,OUTER SHELL @ WIRE
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,Shieldspan_temp,vari,2,extrem,vmax
*get,Shieldspan_time,vari,2,extrem,tmax
*get,Shieldwire_temp,vari,3,extrem,vmax
*get,Shieldwire_time,vari,3,extrem,tmax

/nopr

/output,extreme_temps,txt,,
/com  Fire shield @ midspan
*vwrite,Shieldspan_temp,Shieldspan_time
(12F12.2)

/output,extreme_temps,txt,,append
/com  Fire shield @ wire
*vwrite,Shieldwire_temp,Shieldwire_time
(12F12.2)
```

```
/output
/gopr

*get,Outerspan_temp,vari,4,extrem,vmax
*get,Outerspan_time,vari,4,extrem,tmax
*get,Outerwire_temp,vari,5,extrem,vmax
*get,Outerwire_time,vari,5,extrem,tmax
*get,Innerspan_temp,vari,6,extrem,vmax
*get,Innerspan_time,vari,6,extrem,tmax
*get,Innerwire_temp,vari,6,extrem,vmax
*get,Innerwire_time,vari,6,extrem,tmax

/nopr

/output,extreme_temps,txt,,append
/com  Outer shell @ midspan
*vwrite,Outerspan_temp,Outerspan_time
(12F12.2)

/output,extreme_temps,txt,,append
/com  Outer shell @ wire
*vwrite,Outerwire_temp,Outerwire_time
(12F12.2)

/output,extreme_temps,txt,,append
/com  Inner shell @ midspan
*vwrite,Innerspan_temp,Innerspan_time
(12F12.2)

/output,extreme_temps,txt,,append
/com  Inner shell @ wire
*vwrite,Innerwire_temp,Innerwire_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,Gamma_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 2

1.0 GENERAL INFORMATION

1.1 Introduction

This Safety Analysis Report describes a reusable shipping package designed to protect radioactive material from both normal conditions of transport and hypothetical accident conditions as required by 10CFR71. The package is designated the Model 10-160B package.

1.2 Package Description

1.2.1 Packaging

The package consists of a steel and lead cylindrical shipping cask with a pair of cylindrical foam-filled impact limiters installed on each end. The package configuration is shown in Figure 1-1. Cask assembly drawings are included in Section 1.3. The internal cavity dimensions are 68 inches in diameter and 77 inches high. The cylindrical cask body is comprised of a 2 inch thick external steel shell and a 1 1/8 inch internal steel shell. The annular space between the shells is filled with 1 7/8 inch thickness of lead. The base of the cask consists of a 5½ inch thickness of flat circular steel plates (2½ and 3 inches) which are welded together. The cask primary lid also consists of a 5½ inch thickness flat circular steel plates (2½ and 3 inches) which are welded together. The primary lid is fastened to the cask body with twenty-four, 1 3/4 - 8 UNC bolts. There is a secondary lid in the middle of the primary lid. This secondary lid is attached to the primary lid with twelve, 1 3/4 - 8I UNC bolts. A 12 gauge stainless steel liner (0.105 inches) welded to the cask cavity and lid surface protects all accessible areas from contamination. Also, a steel thermal shield is welded to the exterior barrel of the cask and serves as protection during the fire accident.

The impact limiters are 102 inches in the outside diameter and extend about 12 inches beyond the outside wall of the cask. There is a 47½ inch diameter void at each end. Each limited has an external shell, fabricated from stainless steel which cans the foam and allows it to withstand large plastic deformation without fracturing. The volume inside the shell is filled with a crushable, shock and thermal insulating polyurethane foam. The polyurethane is sprayed into the shell and allowed to expand until the void is completely filled. The foam bonds to the shell, which creates a unitized construction for the impact limiters. The upper and lower impact limiters are held together with eight circumferentially located ratchet binders which secure the limiters to the cask. A general arrangement drawing of the package is included in Appendix 1.3. It shows the package dimensions as well as all materials of construction.

1.2.1.1 Containment Vessel

The containment vessel is defined as the inner steel shell of the cask body together with closure features comprised of the lower surface of the cask lid and the primary and secondary lid bolts.

1.2.1.2 Neutron Absorbers

There are no materials used as neutron absorbers or moderators in the package.

1.2.1.3 Package Weight

Maximum gross weight for the package is 72,000 lbs. including a maximum payload weight of 14,500 lbs.

1.2.1.4 Receptacles

There are no receptacles on this package.

1.2.1.5 Vent, Drain, Test Ports and Pressure Relief Systems

Pressure test ports with manual venting features exist between the twin O-ring seals for both the primary and secondary lids. This facilitate leak testing the package in accordance with ANSI N14.5.

The drain and vent ports are provided with same venting features for venting pressures within the containment cavity, which may be generated during transport, prior to lid removal. Each port is sealed with an elastomer gasket. Specification information for all seals and gaskets is contained in Chapter 3.

1.2.1.6 Lifting Devices

Lifting devices are a structural part of the package. The General Arrangement Drawing in Appendix 1.3 shows two lifting lugs provided for removal and handling of the cask. Three lid lifting lugs are used for removal and handling of the secondary and primary lid. Refer to Section 2.4.3 for a detailed analysis of the structural integrity of the lifting devices.

1.2.1.7 Tie-downs

From the General Arrangement Drawing shown in Appendix 1.3, it can be seen that the tie-down arms are an integral part of the external cask shell. Consequently, tie-down arms are considered a structural part of the package. Refer to Section 2.4.4 for a detailed analysis of the structural integrity of the tie-down arms.

1.2.1.8 Heat Dissipation

There are no special devices used for the transfer or dissipation of heat.

1.2.1.9 Coolants

There are no coolants involved.

1.2.1.10 Protrusions

There are no outer or inner protrusions except for the tie-down arms described above.

1.2.1.11 Shielding

Cask walls provide a shield thickness of 1 7/8 inches of lead and 3 inches of steel. Cask ends provide a minimum of 5 inches of steel. The contents will be limited such that the radiological shielding provided (nominally 3¼ inches lead equivalent based on Co-60) will assure compliance with DOT and IAEA regulatory requirements.

An optional, removable steel insert may be installed inside the cask to provide additional shoring and shielding for the cask contents. The insert fits closely to the inside walls of the cask, but is not attached to the cask nor the contents. It may vary in thickness between ½ inch and 1½ inch on the sides, and is open on the top and bottom. It is approximately ½ inch shorter than the cask cavity.

1.2.2 Operational Features

Refer to the General Arrangement Drawing of the package in Appendix 1.3. There are no complex operational requirements associated with this package.

1.2.3 Contents of Packaging

1.2.3.1 Cask Contents

The contents of the cask will consist of:

1) Greater than Type A quantities (up to a maximum of 3000 A_2) of radioactive material in the form of solids or dewatered materials in secondary containers.

2) Greater than Type A quantities (up to a maximum of 3000 A_2) of radioactive material in the form of activated reactor components or segments of components of waste from a nuclear power plant.

3) That quantity of any radioactive material which does not exceed 3000 A_2 and which does not generate spontaneously more than 200 thermal watts of radioactive decay heat.

4) The weight of the contents in the cask cavity will be limited to 14,500 lbs. If an insert is installed in the cavity, the maximum payload is reduced by the weight of the insert.

5) Transuranic Waste (TRU) with not more than 325 fissile gram equivalents (FGE) of fissile radioactive material up to a maximum of 3000 A_2.

1.2.3.2 Waste Forms

The type and form of waste material will include:

1) By-product, source, or special nuclear material consisting of process solids or resins, either dewatered, solid, or solidified in secondary containers. (See Section 4.2.1 for specific limitations). Contents containing greater than 20 Ci of plutonium must be in solid form.

2) Neutron activated metals or metal oxides in solid form.

3) Miscellaneous radioactive solid waste materials, including special form materials.

4) TRU wastes are limited as described in Appendix 4.10.2, Transuranic (TRU) Waste Compliance Methodology for Hydrogen Gas Generation. TRU exceeding the fissile limits of 10 CFR 71.15 must not be machine compacted and must have no more than 1% by weight of special reflectors and no more than 25% by volume of hydrogenous material.

10-160B GENERAL ARRANGEMENT

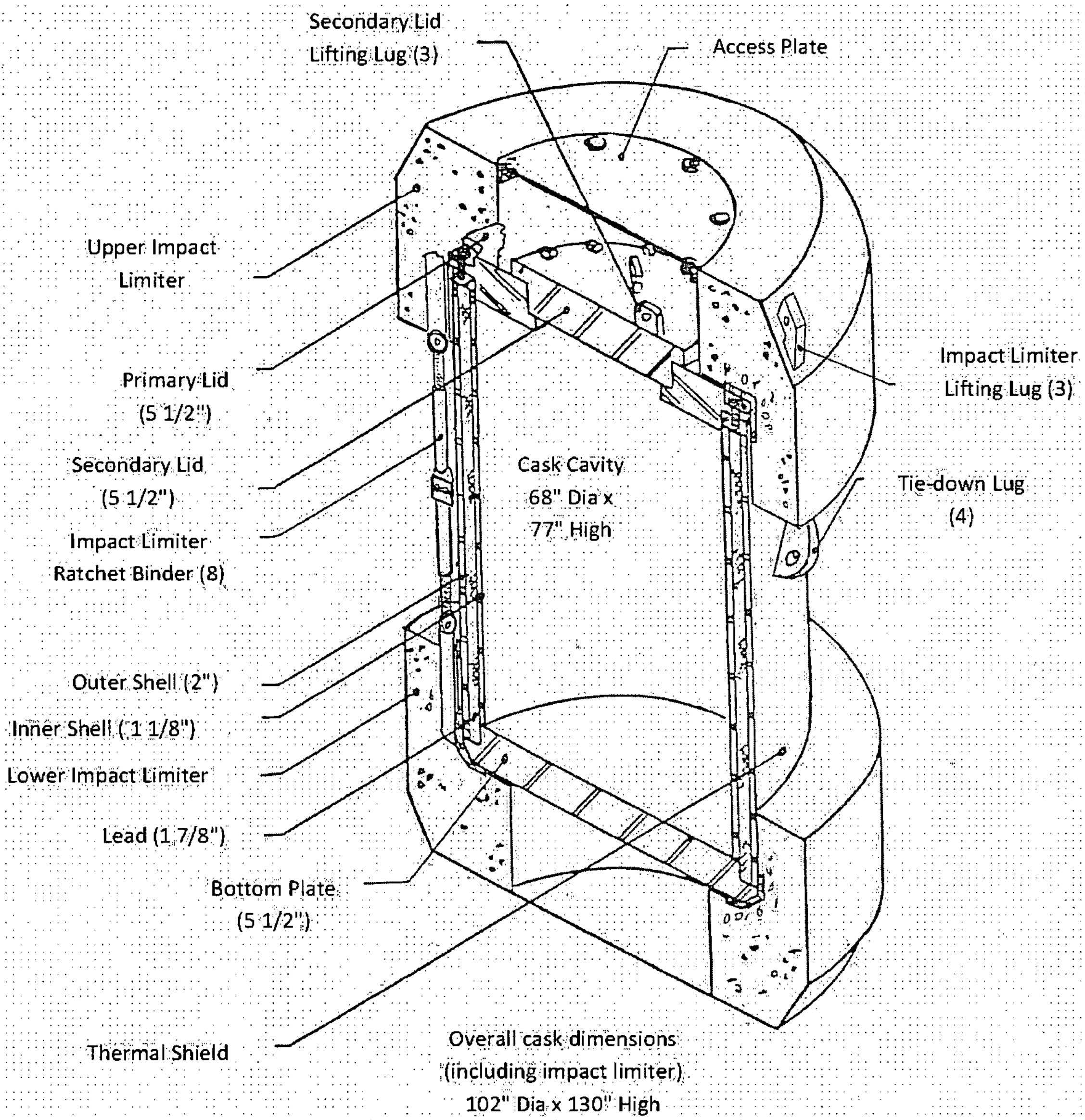


Figure 1-1

1.3 Appendix

10-160B Shipping Cask Drawing

(withheld as security-related sensitive information)

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	188
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	38.7	45	(4)
Maximum temperature difference across the outer shell (°F)	15.3	19.6	24	(4)
Maximum temperature difference across the inner shell (°F)	1.7	2.3	2	(4)
Maximum average wall temperature (°F)	243	285	334	(4)
Maximum lead temperature (°F)	243	272	335	622
Maximum cask body temperature (°F)	252	285	352	(4)
Maximum seal temperature (°F)	-	166	352	400(5)
Average bulk air temperature (°F)	-	181	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

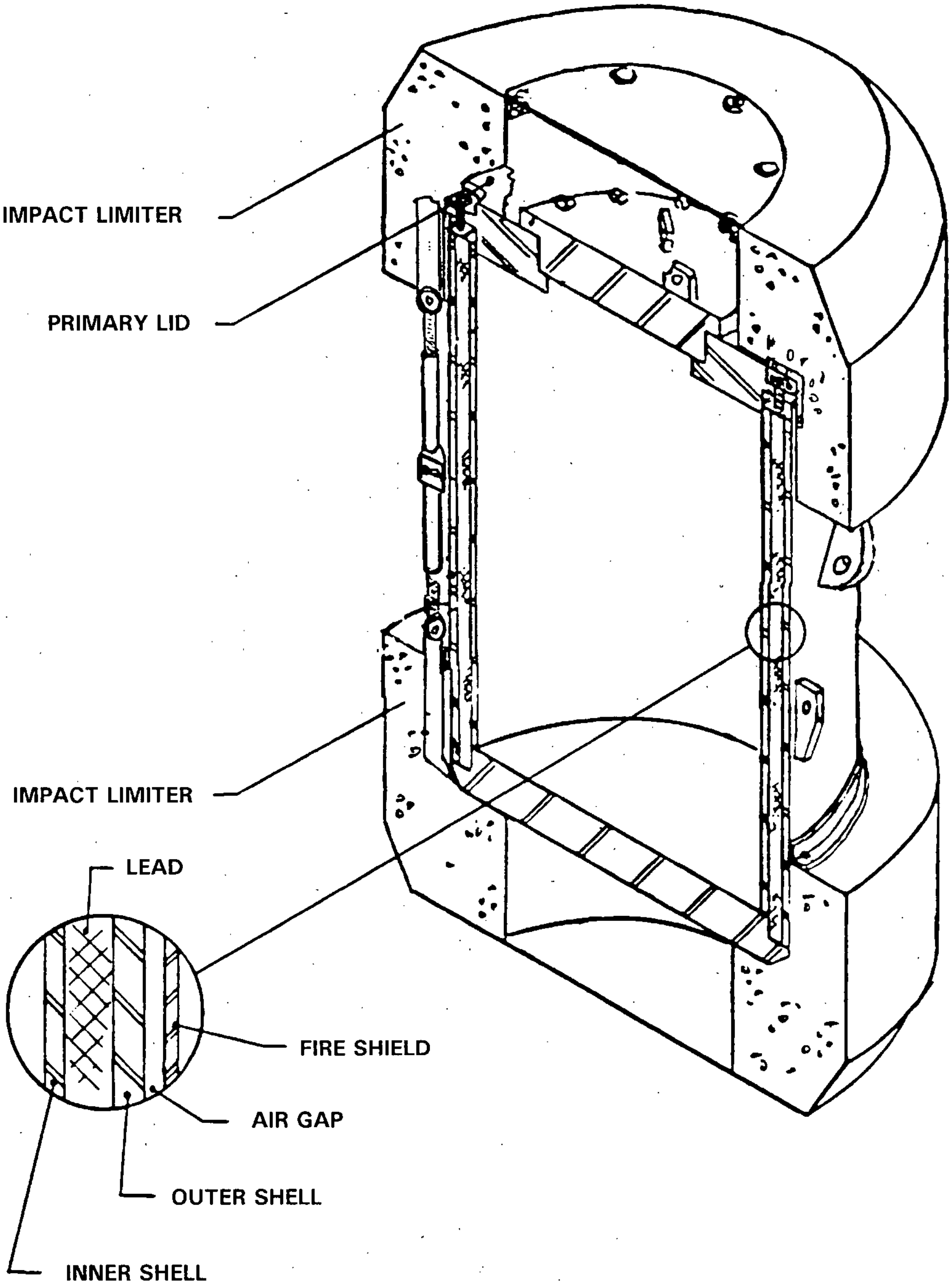


Figure 3.1
Location of Components Analyzed in Thermal Design

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. (°F)	Stainless Steel		Carbon Steel		Lead	Air		
	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
$= 1.7136 \times 10^{-9}$ (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

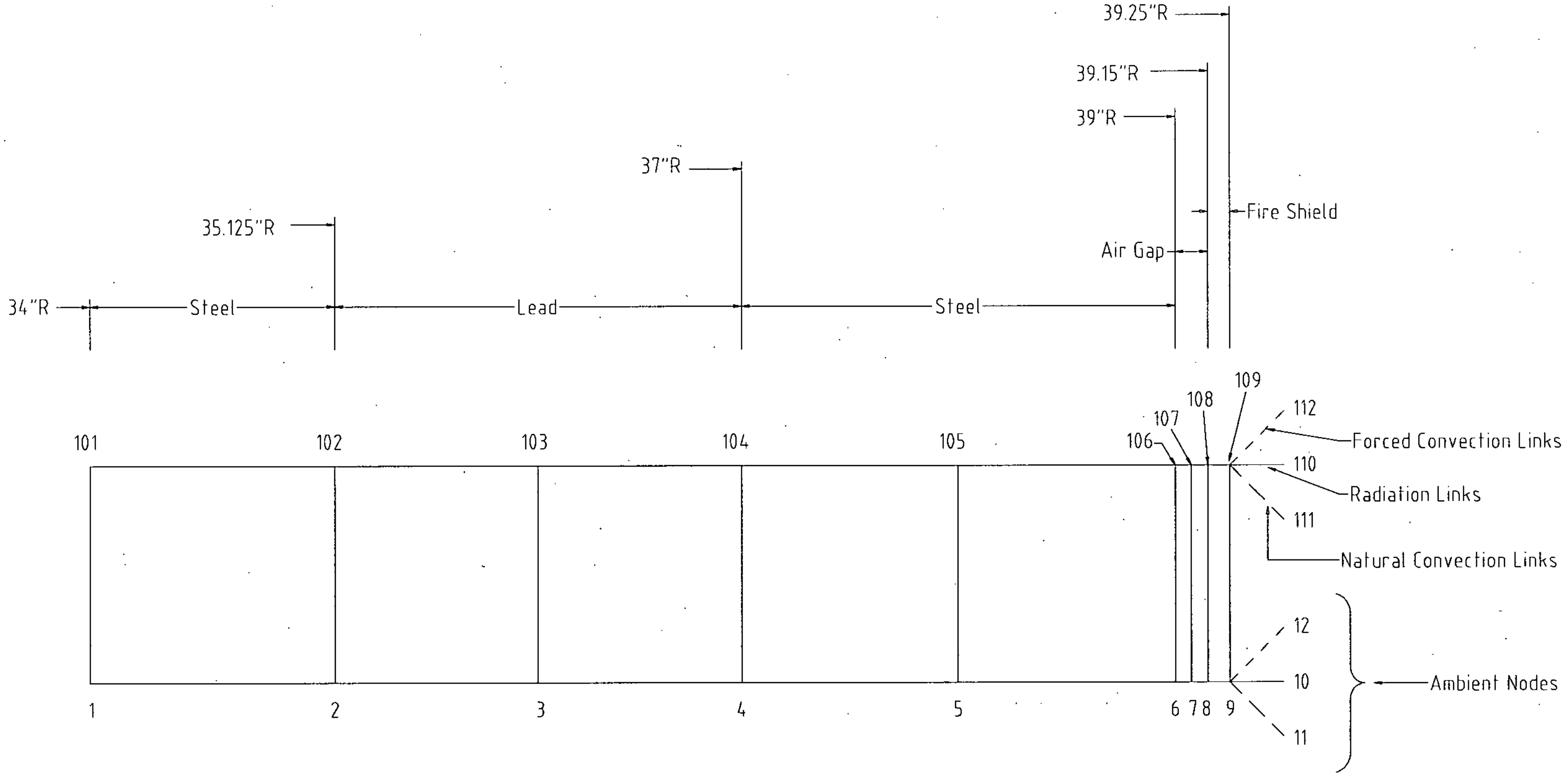


Figure 3.2

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)

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

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)

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

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 in the cask occurs at the inside surface of the secondary lid, and is calculated to be 175°F (see table 3.1-1). This is well within the service temperature of all materials and components used within the cask. The NCT temperature criterion for the seal material is conservatively set at 250°F for continuous use. The minimum temperature of the seals, calculated by the 2-d finite element model, is 174°F. 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:

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

$$1 \mathrm{~W} = 9.4804 \times 10^{-4} \mathrm{~Btu/sec}$$

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.
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 after 48.5 hours of 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.

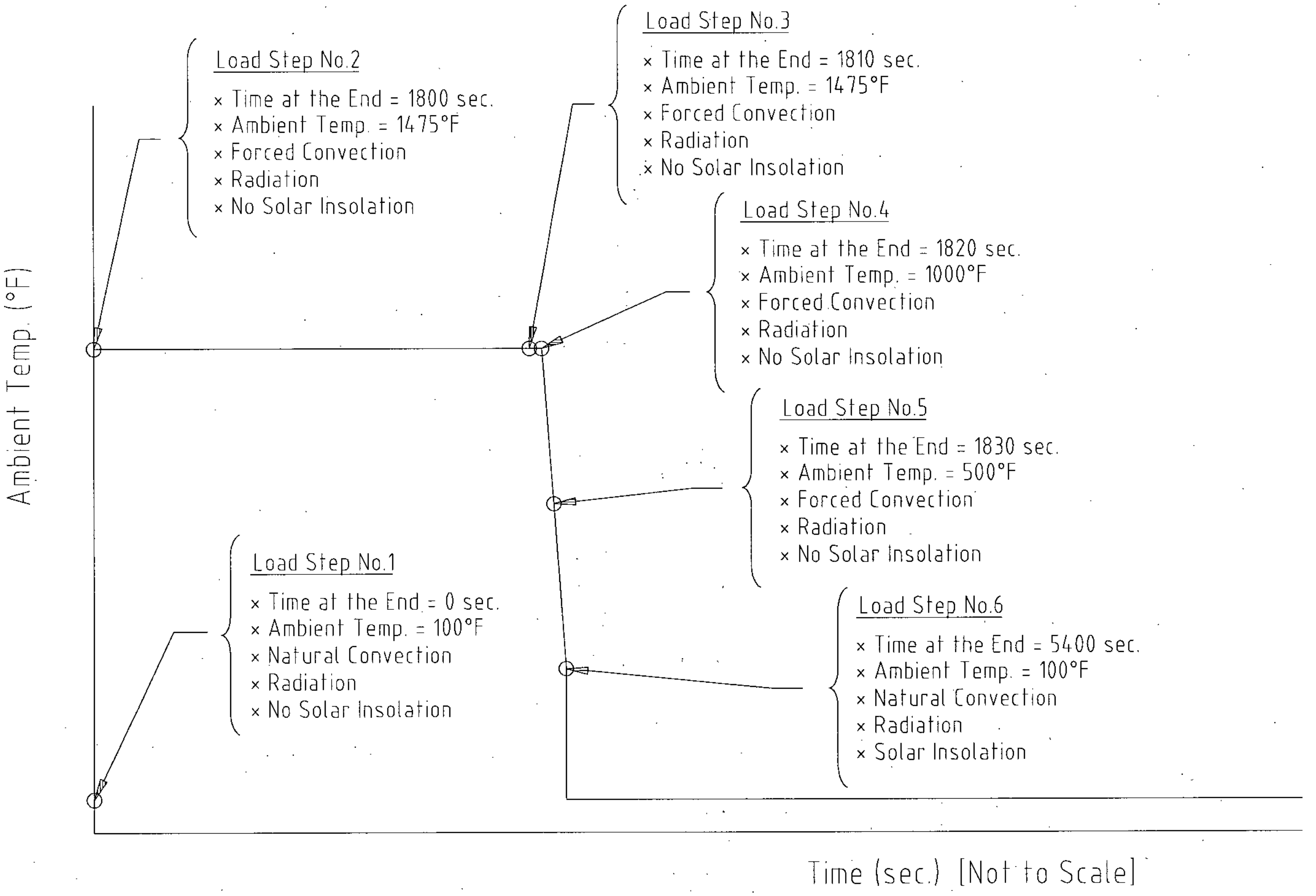


Figure 3.3
Transient Fire Analysis - Load Step and Boundary Conditions Schematic

Table 3.4

Summary of Maximum Hypothetical Accident Temperatures

Component	**Maximum Calculated Temp.**			**Maximum Allowable Temperature (°F)**
	Location	**Time (hrs)**	**Value (°F)**	
Fire Shield	Mid-Plane	0.5	1361(1)	N.A.
Structural Shell	Mid-Plane	0.5	285(2)	800
Lead	Mid-Plane	0.73	272(2)	622
Seals	N.A.	8.5	166.4(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.

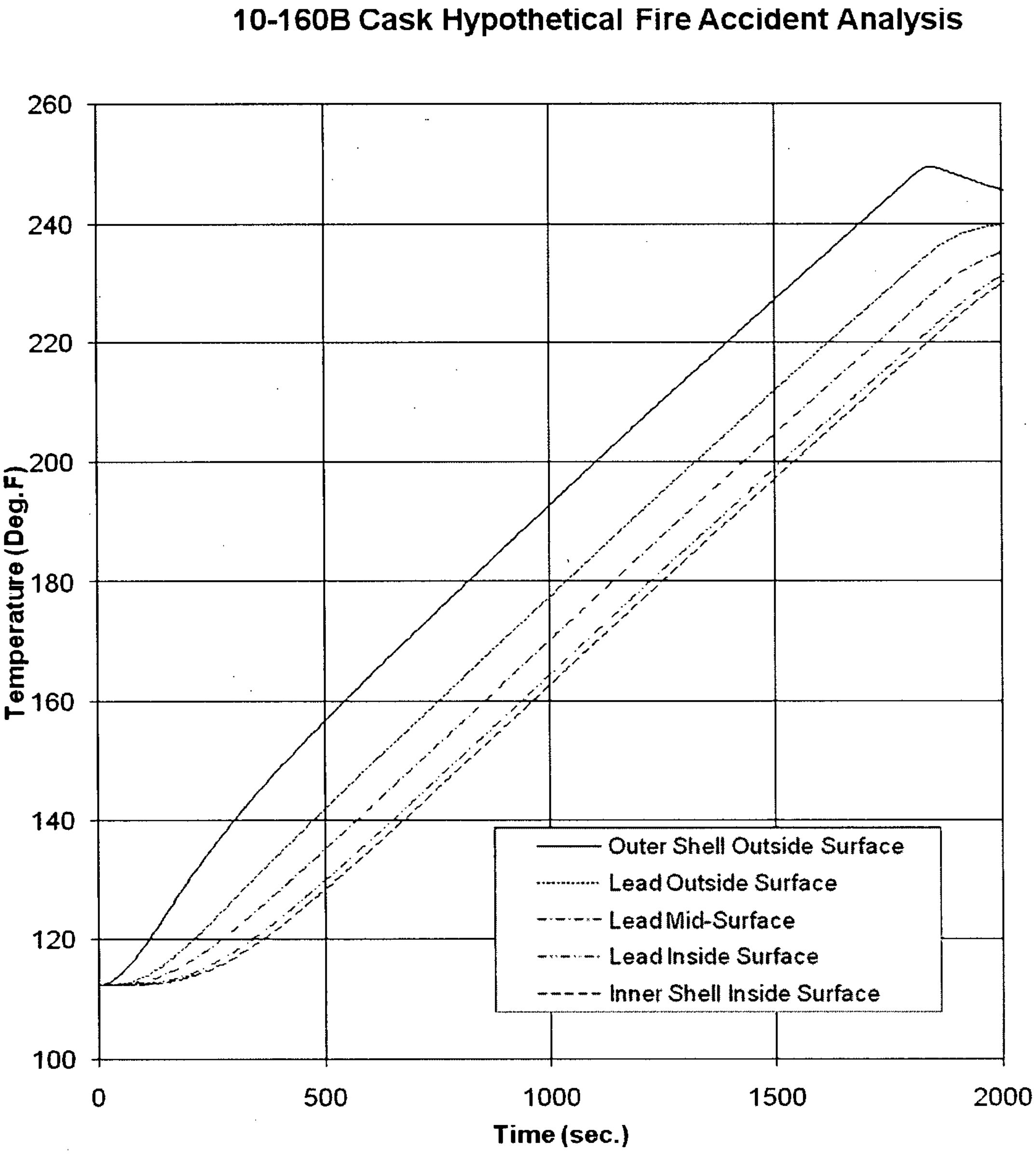


Figure 3.4

Hypothetical Accident - Fire Transient:
Temperature Versus Time

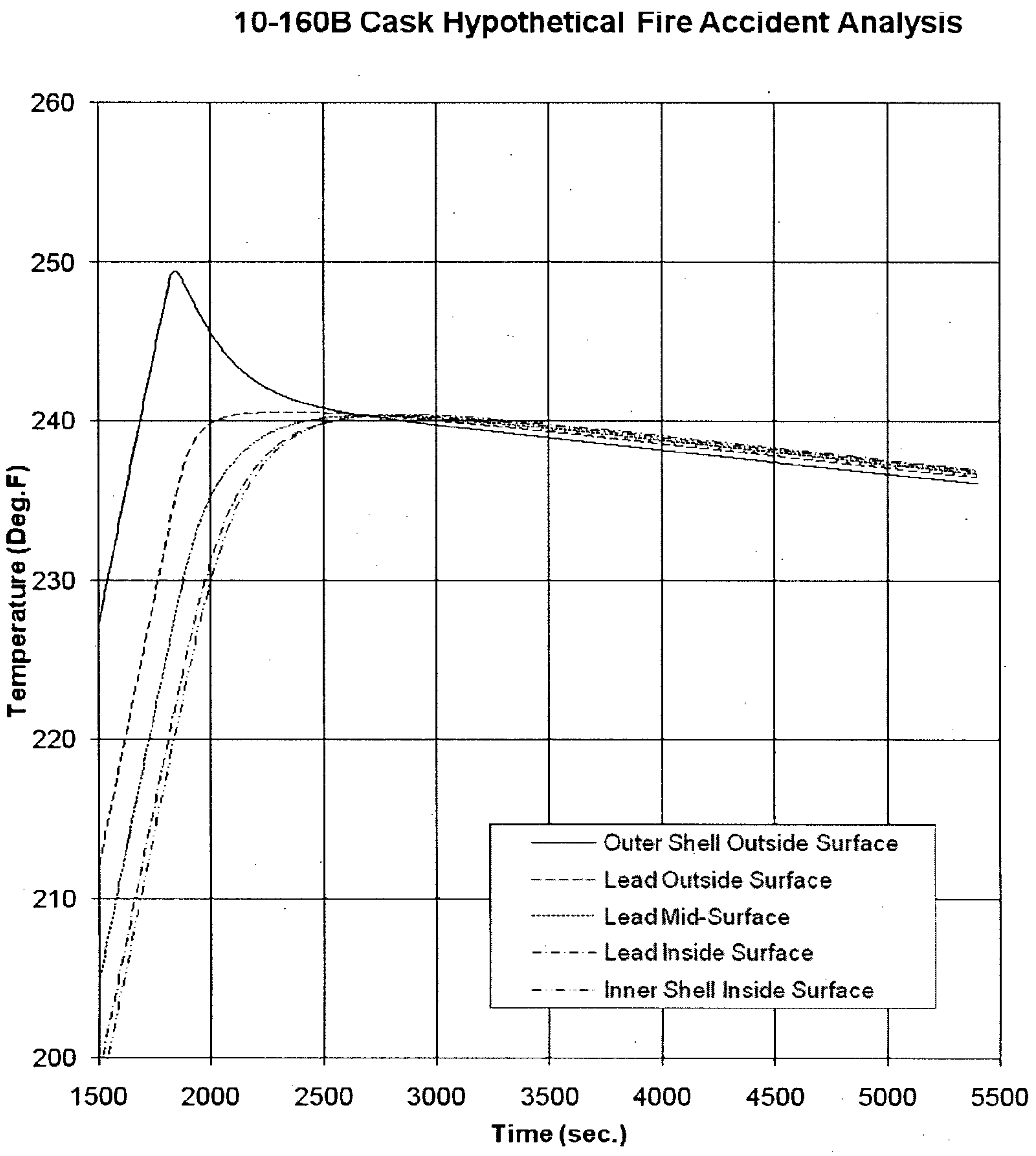


Figure 3.5

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 181°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)

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

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

$$P_1 = 18.31PSIA$$

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 8 minus the outside ambient pressure. Equation 9 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

The 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° F and occurs 30 minutes after the start of the fire. The maximum temperature difference across the outer shell is 19.6°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 285°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 seal temperature is calculated to be 174°F during the cool-down period of the fire transient (see Reference 11). The seal will also attain this temperature in the hot environment. The seals material is specified to meet the minimum temperature requirement of 400°F, which is well over their expected temperature during the NCT and HAC fire conditions. The maximum temperature in the lead shielding is calculated to be 271.5°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.1, 10-160B Transportation Cask Thermal Analyses.

4. CONTAINMENT

This chapter describes the containment configuration and test requirements for the 10-160B Cask. Both normal conditions of transport and hypothetical accident conditions are discussed.

4.1 Containment Boundary

4.1.1 Containment Vessel

The package containment vessel is defined as the inner shell of the shielded transport cask and the primary and secondary lids together with the associated o-ring seals and lid closure bolts. The inner shell of the cask, or containment vessel, consists of a right circular cylinder of 68 inches inner diameter and 77 inches inside height (nominal dimensions). The shell is fabricated of an outer shell of 2-inch thick steel plate, a 1 7/8 inch layer of lead, and an inner shell of 1 1/8 – inch thick steel. The cylindrical shell is attached at the base to a circular end plate construction with full penetration welds. The primary lid is attached to the cask body with 24, 1 ¾ inch 8 UN bolts. A secondary lid covers the 31 inch opening in the primary lid and is attached to the primary lid using 12, 1¾ inch 8 UN bolts. See Section 4.1.4 for closure details.

4.1.2 Containment Penetrations

There are two penetrations of the containment vessel. These are (1) an optional drain line, and (2) an optional cask vent port located in the secondary lid. The optional drain line is located at the cask base and consists of a ½ inch diameter hole drilled into the stainless steel cask bottom. The optional vent port penetrates the secondary lid into the main cask cavity. Both the vent and drain are sealed at the base of the exterior opening with an elastomer Parker Stat-o-Seal and a cap screw. The exterior openings are plugged by self-sealing Teflon-coated hex socket plugs.

4.1.3 Welds

The containment vessel is fabricated from steel using full penetration welds.

4.1.4 Closure and Seals

The primary lid closure consists of a two layer steel plate construction, stepped to fit over and within the top edge of the cylindrical body. The lid is supported at the perimeter of the cylindrical body by a 3.00-inch thick plate (bolt ring) welded to the top of the inner and outer cylindrical body walls. The lid confines two (2) solid, high temperature elastomer o-rings (Parker or equivalent) in machined grooves. Groove dimensions prevent over-compression of the o-rings by the lid closure bolt preload forces and hypothetical accident preload forces. The primary lid is attached to the cask body by 24 bolts. The primary lid is fitted with a secondary lid of similar construction attached with 12 bolts. The secondary lid is also sealed with two (2) solid, high temperature elastomer o-rings (Parker or equivalent) in machined grooves. Only the inner o-ring of each lid is part of the containment boundary.

The optional vent penetration, test ports, and drain penetrations are sealed as described in Section 4.1.2. The seal plugs in these penetrations are lockwired prior to each shipment. Table 4.1 gives the torque values for bolts and cap screws.

Table 4.1
Bolt and Cap Screw Torque Requirements

Location	Size	Torque Values +/- 10% (Lubricated)	
		In-lb	Ft-lb
Test Ports (2)	1/2 NPT	144	12
Primary Lid	1-3/4 inch, 8 UN	3600	300
Second Lid	1-3/4 inch, 8 UN	3600	300
Vent Port*	1/2 - 20 UNF	240	20
Drain Port*	1/2 - 20 UNF	240	20

*Optional - These ports may not be installed on cask.

4.2 Containment Requirements for Normal Conditions of Transport

4.2.1 Leak Test Requirements

The 10-160B cask is designed, fabricated, and leak tested to preclude a release of radioactive material in excess of the limits prescribed in NRC Regulatory Guide 7.4, paragraph C and 10CFR71.51(a)(1). The limits on leakage during normal conditions of transport are defined by 10CFR71.51(a)(1).

The leak test procedure must be able to detect leaks of 2.57×10^{-6} ref-cm^3/sec (based on dry air at 25°C with a pressure differential of one atmosphere) to assure compliance with 10CFR71.51(a)(1). A description of the calculational procedure used to determine this value follows.

10CFR71.51(a)(1) states the containment requirements for normal conditions of transport as:

> ...no loss or dispersal of radioactive contents, as demonstrated to a sensitivity of 10^{-6} A_2 per hour, no significant increase in external radiation levels, and no substantial reduction in the effectiveness of the packaging;

ANSI N14.5-1997 (Reference 4) states that the permissible leak rate shall be determined by equation 1 (below):

(Equation 1) $$L = \frac{R}{C}$$

where:

L = permissible volumetric leak rate for the medium
R = package containment requirement (Ci/sec)
C = activity per unit volume of the medium that could escape from the containment system

In Section 3.4.4, it is noted that the saturated water vapor in equilibrium at 188 degrees-F and 12.2 psig could exist within the internal shipping containers (liners or drains). It is assumed that these conditions exist within the cask cavity. The containment must limit the leakage of this water vapor to that prescribed in ANSI N14.5. It is very conservative to assume that the concentration of nuclides in the free liquid is equal to that of the solids which comprise the vast majority of material being transported in the cask. This value is determined below:

$$C = \frac{\text{Total Curie Content of Vapor}}{\text{Minimum Void Volume in Cask Cavity}}$$

- Cask curie content = 3000 x A_2 or less
- Free water is limited to restriction of one-percent of solid volume
- Hence the curie content = 0.01 x 3000 A_2
- The minimum void volume occurs when the largest liner is shipped

(Equation 2) $$V\text{ (cask cavity)} = \frac{\pi}{4} \times 67.25^2 \times 75.75 = 269{,}064\ \text{in}^3$$

The largest liner will have at least ¾ inch of radial clearance and a 1½ inch of height difference, giving a volume,

(Equation 3) $$V\,(\text{liner}) = \frac{\pi}{4} \times (67.25 - 2 \times 0.75)^2 \times (75.75 - 1.5)\ \text{in}^3$$
$$= 252{,}103\ \text{in}^3$$

Void Volume $= 269{,}064 - 252{,}103 = 16{,}961\ \text{in}^3$

$= 16{,}961\ \text{in}^3 \times 16.4\ \text{cm}^3/\text{in}^3$

$= 278{,}161\ \text{cm}^3$

Hence,

(Equation 4) $$C = \frac{30 A_2\ \text{Ci}}{278{,}161\ \text{cm}^3} = 1.08 \times 10^{-4}\ A_2\ \text{Ci/cm}^3$$

And,

(Equation 5) $$Ln = \frac{Rn}{C} = \frac{2.78 \times 10^{-10}\ A_2\ \text{Ci/sec}}{1.08 \times 10^{-4}\ A_2\ \text{Ci/cm}^3}$$ Eqn. 3, Ref. 4
$$= 2.57 \times 10^{-6}\ \text{cm}^3/\text{sec}$$

A leak rate at standard conditions will be calculated which is equivalent to a volumetric leak rate of 2.57×10^{-6} cm³/sec.

Equations B.3, B.4,and B.5 are used to determine the diameter of hole that would give a leak rate of 2.57×10^{-6} cm³/sec.

$$Lu = (Fc + Fm)(Pu - Pd)\left(\frac{Pa}{Pu}\right)$$ Eqn. B.5, Reference 4

$$Fm = \frac{3.81 \times 10^3 D^3 \sqrt{\frac{T}{M}}}{a\ Pa}$$ Eqn. B.4, Reference 4

$$Fc = \frac{2.49 \times 10^6 D^4}{a\ \mu}$$ Eqn. B.3, Reference 4

where:

L_u = upstream leakage rate, cm^3/sec

$\mu_{air} = 0.0185 cP$

$T = 188°F = 360°K$ Section 3.4.4

$P_u = 12.2$ psig = 1.83 atm

$P_d = 1.0$ atm

$P_a = (1.83 + 1.0)/2 = 1.42$ atm

$M_{water} = 18$ g/gmole

a = length of hole; assume 0.6 cm

The molecular weight of air is 29 g/gmole; using the molecular weight of water here is conservative.

Substituting into Eqns. B.3, B.4, and B.5:

$$F_c = 1.98 \times 10^8 D^4$$

$$F_m = 1.48 \times 10^4 D^3$$

$$2.57x10^{-6} = (1.98x10^8 D^4 + 1.48x10^4 D^3)(2.05 - 1.0)\left(\frac{1.53}{2.05}\right) \qquad \text{Solve for D}$$

$D = 3.54 \times 10^{-4}$ cm

Next, using Equation B.5 from Reference 4, determine the flow of air at standard conditions through a hole of this size. Where:

a = 0.6 cm

$M_{air} = 29$ g/gmole

$\mu_{air} = 0.0185$ cP

$P_u = 1.0$ atm

$P_d = 0.01$ atm

$P_a = (1.0 + 0.01)/2 = 0.505$ atm

$T = 298°K$

Substituting into B.5:

$$L_{std} = 2.45 \times 10^{-6} \frac{\text{ref - cm}^3}{\text{sec}}$$

4.2.2 <u>Pressurization of the Containment Vessel</u>

Section 2.4.4 summarizes normal condition temperatures and pressures within the containment vessel. These pressures and associated temperatures are used to evaluate the integrity of the 10-160B package. None of these conditions reduce the effectiveness of the package containment.

4.2.3 Coolant Containment

Not applicable; there are no coolants in the 10-160B package.

4.2.4 Coolant Loss

Not applicable; there are no coolants in the 10-160B package.

4.3 Containment Requirements for Hypothetical Accident Conditions

4.3.1 Leak Test Requirements

Section 2.7 demonstrates that the 10-160B cask will maintain its containment capability throughout the hypothetical accident conditions. Fission gas products will not be carried within the cask so there can be no release of fission gases. The 10-160B cask is designed, fabricated, and leak tested to preclude a release of radioactive material in excess of the limits prescribed in NRC Regulatory Guide 7.4, paragraph C and 10CFR71.51(a)(2). The limits on leakage during normal conditions of transport are defined by 10CFR71.51(a)(2).

The leak test procedure which assures compliance with leakage during normal conditions of transport will also be sufficient to assure compliance during hypothetical accident conditions. A description follows of the calculational procedure which demonstrates that the maximum leakage requirement during normal conditions of transport is more stringent than the maximum leakage requirement during the hypothetical accident.

10CFR71.51(a)(2) states the containment requirements for the hypothetical accident conditions as:

> … no escape of krypton-85 exceeding 10 A_2 in 1 week, no escape of other radioactive material exceeding a total amount A_2 in 1 week, and no external radiation dose rate exceeding 10 mSv/h (1 rem/h) at 1 m (40 in) from the external surface of the package.

Since the cask does not carry fission products or radioactive gases, only the A_2 per week requirement is limiting. A release of A_2 in one week is equivalent to the activity release rate, R_a, given by equation 9.

(Equation 9) $$\mathrm{Ra} = (\mathrm{A2}/\mathrm{week})(1\ \mathrm{week}/168\ \mathrm{hr}) = 5.952 \times 10^{-3}\ \mathrm{A2}/\mathrm{hr}$$

In Section 3.5.4, it is noted that the saturated water vapor in equilibrium at 250 degrees-F and 34.7 psig could exist within the internal shipping containers (liners or drains). It is assumed that these conditions exist within the cask cavity. The containment must limit the leakage of this water vapor to that prescribed in ANSI N14.5. It is very conservative to assume that the concentration of nuclides in the free liquid is equal to that of the solids which comprise the vast majority of material being transported in the cask. This value is determined below:

$$C = \frac{\text{Total Curie Content of Vapor}}{\text{Minimum Void Volume in Cask Cavity}}$$

- Cask curie content = 3000 x A_2 or less
- Free water is limited to restriction of one-percent of solid volume
- Hence the curie content = 0.01 x 3000 A_2
- The minimum void volume occurs when the largest liner is shipped

(Equation 10) $$V(\text{cask cavity}) = \frac{\pi}{4} \times 67.25 \times 75.75 = 269{,}064$$

The largest liner will have at least ¾ inch of radial clearance and a 1½ inch of height difference, giving a volume

(Equation 11) $$V\,(\text{liner}) = \frac{\pi}{4} \text{ x } (67.25 - 2 \text{ x } 0.75)^2 \text{ x } (75.75 - 1.5)\ \text{in}^3$$

$$= 252{,}103\ \text{in}^3$$

Void Volume $= 269{,}064 - 252{,}103 = 16{,}961$

$= 16{,}961\ \text{in}^3 \text{ x } 16.4\ \text{cm}^3/\text{in}^3$

$= 278{,}161\ \text{cm}^3$

Hence,

(Equation 12) $$C = \frac{30 A_2\ \text{Ci}}{278{,}161\,\text{cm}^3} = 1.08 \text{ x } 10^{-4}\ A_2\ \text{Ci/cm}^3$$

The corresponding volumetric leak rate, L, is calculated by substituting C given by equation 12 and R_a given by equation 9 into equation 1. Equation 13 results from these substitutions.

(Equation 13) $$La = \frac{5.952 \text{ x } 10^{-3} A_2\ \text{Ci/hr}}{1.08 \text{ x } 10^{-4}\ A_2\ \text{Ci/cm}^3}\ \frac{1\,\text{hr}}{3600\,\text{sec}}$$

$$= 1.53 \text{ x } 10^{-2}\ \text{cm}^3/\text{sec}$$

The allowable leak rate during the hypothetical accident is larger than during the normal conditions of transport, 2.45 x 10^{-6} ref-cm^3/sec. Thus, the leak rate for normal conditions of transport is limiting and will determine the maximum permissible leak rate during tests.

4.4 Determination of Test Conditions for Preshipment Leak Test

4.4.1 Test Method

The preshipment leak test is performed using the Gas Pressure Drop Method as shown in A.5.1, Table A-1 of ANSI N14,5-1997. The Gas Pressure Drop test is conducted on the 10-160B by pressurizing the annulus between the O-rings on the primary and secondary lids with dry air or nitrogen. If vent and drain ports are installed, these are tested by pressurizing the ports with dry air or nitrogen.

As required by ANSI N14.5, the test is conducted by holding the test pressure on the component being tested for a prescribed period of time (calculated below) and monitoring for any detectable drop in pressure. ANSI N14.5 – 1997 states (Reference 4, Table 1) that the acceptance criteria for the preshipment leak test is a leakage rate that is either less than the reference air leakage rate, L_R, or no detected leakage when tested to a sensitivity of $1x10^{-3}$ ref-cm^3/sec. This section will show that the requirement of ANSI N14.5 is met by testing to a sensitivity of $1x10^{-3}$ ref-cm^3/sec when performing the Gas Pressure Drop test for 15 minutes (10 minutes for vent or drain lines).

The calculations in 4.4.2 and 4.4.3 below are performed assuming dry air is the test gas, although as indicated in the above paragraph and in Chapter 8, nitrogen may be used as well. If nitrogen is the test gas used, the calculations for the required charge time in 4.4.2 and 4.4.3 below are conservative. Since air is primarily nitrogen, the physical properties of the two gases are very close. However, because the molecular weight and viscosity of nitrogen are slightly less than air's, the pressure drop experienced during the required charge time using nitrogen as the test gas will be slightly greater than for air.

	molecular wt	Viscosity (cP)	(Ref. 8)
air	29.0	.0185	
nitrogen	28.01	.0173	

4.4.2 Determining Required Charge Time for Gas Pressure Drop Test

The preshipment leak test is performed by charging the annulus of the O-rings (of the vent and drain port) with air and holding the pressure for the prescribed time. Any pressure drop larger than the minimum detectable increment on the pressure measuring instrument shall be corrected. In this section the minimum hold time is determined.

The annulus between the O-rings is pressurized with air. The annulus is centered between O-rings and is 1/8" deep and 1/8" wide with a minimum inner diameter of 68-15/16". The minimum volume of the annulus is 55 cm^3.

The required hold time for the Gas Pressure Drop test is determined using Equation 15 below, which is Equation B.14 of ANSI N14.5-1997. The same hold time determined below will be used for both the primary and secondary lids. Since the volume of the secondary lid annulus is approximately 28 cm^3, the test sensitivity will be greater than the primary lid's.

(Equation 15) $$LR = \frac{V\,Ts}{3600\,HPs}\left[\frac{P1}{T1} - \frac{P2}{T2}\right]$$ Eqn B.14, Reference 4

where:

L_R = atm-cm^3/sec of air at standard conditions
V = gas volume in the test annulus cm^3
T_s = reference absolute temperature, 298°K
H = test duration, hours
P_1 = gas pressure in test item at start of test, atm, abs
P_2 = gas pressure in test item at end of test, atm, abs
P_s = standard pressure = 1 atm
T_1 = gas temperature in test item at start of test, °K
T_2 = gas temperature in test item at end of test, °K

4.4.3 <u>Required Hold Time at the Test Pressure</u>

As discussed in Section 4.4.1 above, the maximum sensitivity for the preshipment leak test as prescribed in ANSI N14.5-1997 is 10^{-3} ref-cm^3/sec. Further, ANSI N14.5-1997 states that in cases where the test sensitivity has been established and the Gas Pressure Drop test is used, the maximum permitted leak rate is:

$L \leq S/2$ Equation B-17, Reference 4

Therefore the maximum permitted leak rate for the preshipment leak test is 5 x 10^{-4} ref-cm^3/sec. Substituting this in Eqn. B-17 above, determine the required hold time, where:

V = 55 cm^3
$T_s = T_1 = T_2 = 298°K$
$P_1 - P_2$ = pressure instrument sensitivity = 0.1 psig

$$5x10^{-4} = \frac{(55\,\text{cm}^3)(298^o K)}{3600(H\ hr)(1\,\text{atm})}\left(\frac{0.007\,\text{atm}}{298^\circ K}\right)$$

Solve for H:

H = 0.214 hr = 12.8 min.

For conservatism, the test will be conducted for 15 minutes.

4.5 Periodic Verification Leak Rate Determination Using R-12 Test Gas

This section contains calculations to determine the periodic verification test measurement that is equivalent to the maximum permissible leak rate as determined using ANSI N14.5-1997 (Reference 4).

The purpose of this calculation is to determine the allowable leak rate using the R-12 halogen gas that may be used to perform the annual verification leak tests on the 10-160B cask.

4.5.1 Introduction

The text of this document is prepared using Mathcad, Version 6.0, software. Most conventions used in the text are the same as normal practice. A benefit of the Mathcad code is that is automatically carries all units with the variables used in the calculations. The code also allows output of variables in any form of the fundamental units (length, mass, time, etc.), allowing for automatic conversions between unit systems without the need for conversion factors. All Mathcad calculations in this Section 4.5 have been verified by hand calculations.

This calculation uses formulas presented in ANSI N14.5 - 1997.

4.5.2 Detector Sensitivity Calculation – Test Conditions

This section determines the sensitivity necessary for a leak test performed with R-12 halogen gas. This test is performed using a halogen leak detector. A leak standard, traceable to NIST, is used to calibrate the leak detector to detect the maximum allowable test leak rates specified in Figure 4.3. The test is performed as follows: The annulus between the o-ring seals of the 10-160B primary and secondary lids will be evacuated to a minimum vacuum of 20"Hg, and then be pressurized to a minimum pressure of 25 psig with R-12 halogen gas. In section 4.2.1, it was determined that the maximum possible diameter hole in the cask O-ring (D_{max}) that would permit the standard leak rate ($L_{std} = 2.45 \times 10^{-6}$) is:

The maximum possible diameter of hole in the O-ring is:

$D_{max} = 3.54 \times 10^{-4}$ cm From Section 4.2.1

$$L_{std}(D) = (F_c(D) + F_m(D) \bullet (P_u - P_d) \bullet \frac{P_a}{P_d}$$ Eqn. B5 – ANSI N14.5 - 1997

Determine the equivalent air/R12 mixture (L_{mix}) that would leak from D_{max} during a leak test. Assume the O-ring void is first evacuated to 20"Hg vacuum (9.92"Hg abs) and then pressurized to 25 psig (2.7 atm) with an air/R12 mixture.

$P_{mix} := 2.7 \cdot atm$

$P_{air} := 9.92 \cdot in\_Hg$

$P_{air} = 0.33 atm$

$P_{R12} := P_{mix} - P_{air}$

$P_{R12} = 2.37 atm$ $P_d := 1.0 \cdot atm$

$P_a := \frac{P_{mix} + P_{air}}{2} \Rightarrow P_a = 1.85 atm$

$M_{R12} := 121 \cdot \frac{gm}{mole}$ ANSI N14.5 – 1997

$\mu_{R12} := 0.0124 \cdot cP$ ANSI N14.5 – 1997

$$M_{mix} := \frac{M_{R12} \cdot P_{R12} + M_{air} \cdot P_{air}}{P_{mix}}$$ Eqn. B7 - ANSI N14.5

$$\Rightarrow \quad M_{mix} = 109.7 \frac{gm}{mole}$$

$$\mu_{mix} := \frac{\mu_{air} \cdot P_{air} + \mu_{R12} \cdot P_{R12}}{P_{mix}}$$ Eqn. B8 – ANSI N14.5 - 1997

$$\Rightarrow \quad \mu_{mix} = 0.0131 cP$$

Determine L_{mix} as a function of temperature. Assume the viscosities of air and R12 do not change significantly over the range of temperatures evaluated:

$T := 273 \cdot K, 278 \cdot K .. 318 \cdot K$ Temperature range for test: $32^{O}F$ to $113^{O}F$

$$F_c := \frac{2.49 \cdot 10^6 \cdot D_{max}{}^4 \cdot cP \cdot std}{a \cdot \mu_{mix} \cdot sec \cdot atm}$$

then,

$$F_m(T) := \frac{3.81 \cdot 10^3 \cdot D_{max}{}^3 \cdot \sqrt{\frac{T}{M_{mix}}} \cdot cm \cdot gm^{0.5}}{a \cdot P_a \cdot K^{0.5} \cdot mole^{0.5} \cdot sec}$$

$$L_{mix}(T) := \left(F_c + F_m(T)\right) \cdot \left(P_{mix} - P_{air}\right) \cdot \frac{P_a}{P_{mix}}$$

The R-12 component of this leak rate can be determined by multiplying the leak rate of the mixture by the ratio of the R-12 partial pressure to the total pressure of the mix, as follows.

$$L_{R12}(T) := L_{mix}(T) \cdot \frac{P_{R12}}{P_{mix}}$$

Determine the equivalent mass flow rate for L_{R12} in oz/yr:

$$N(T) := \frac{P_{R12} \cdot V}{R_o \cdot T}$$ Ideal Gas Law

where,

$$R_o := \frac{82.05 \, cm^3 \cdot atm}{mole \cdot K}$$

This data can then be used to convert the volumetric leak rate for R-12 calculated above to a mass leak rate. By dividing N by V, the number of moles per unit volume can be multiplied by the molecular weight of the gas and the maximum allowable volumetric leak rate to determine the maximum allowable mass leak rate, as a function of test temperature as shown in the graph below. The conversion from grams per second to ounces per year is also shown below.

$$L(T) := L_{R12}(T) \cdot \frac{N(T)}{V} \cdot M_{R12} \cdot \frac{yr}{oz}$$

$$\frac{gm}{sec} = 1.113 \times 10^6 \frac{oz}{yr}$$ Conversion of gm/sec to oz/yr

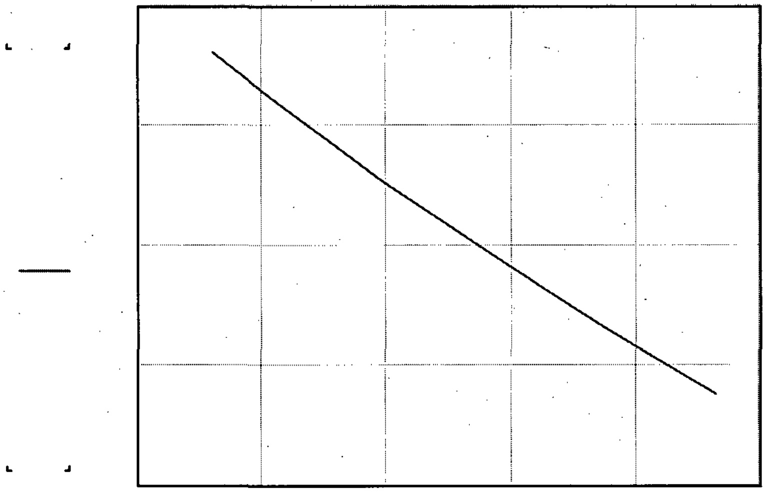


Fig.4.3 - Allowable R-12 test leakage, oz/yr, versus test temperature, deg.F

The graph above can be used to determine the allowable leak rate based on the temperature at the time of the test. According to ANSI N14.5 methodology, the maximum allowable leak rate must be divided by 2 to determine the minimum sensitivity for the test. A graph of the required sensitivity in oz/yr is presented below:

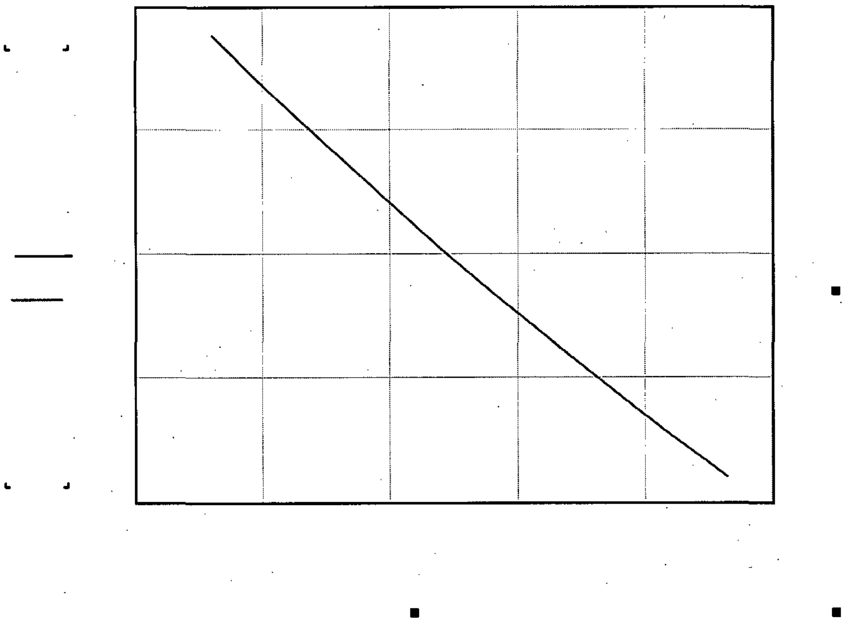


Fig.4.4 - Allowable R-12 test leakage sensitivity, oz/yr, versus test temperature, deg.F

The values presented in Figure 4.4 should be used to determine the sensitivity to calibrate the leak detector prior to the test.

4.6 Periodic Verification Leak Rate Determination Using Helium Test Gas

This section contains calculations to determine the periodic verification test measurement that is equivalent to the maximum permissible leak rate as determined using ANSI N14.5-1997 (Reference 4).

4.6.1 Introduction

The purpose of this calculation is to determine the allowable leak rate using the Helium gas that may be used to perform the annual verification leak tests on the 10-160B cask.

4.6.2 Detector Sensitivity – Test Conditions

In Section 4.2.1, it was determined that the maximum possible diameter hole in the cask O-ring (D_{max}) that would permit the standard leak rate ($L_{std} = 2.45 \times 10^{-6}$ ref- cm^3/sec) is:

$D_{max} = 3.54 \times 10^{-4}$ cm From Section 4.2.1

Next, determine the equivalent air/He mixture (L_{mix}) that would leak from D_{max} during a leak test. Assume the O-ring void is pressurized to 25 psig (2.7 atm) with an air/He mixture.

$P_{mix} := 2.7 \cdot atm$

$P_{air} := 1.0 \cdot atm$

$P_{He} := 1.7 \cdot atm$

$$P_a := \frac{P_{mix} + P_{air}}{2}$$

$P_a = 1.85 \cdot atm$

$M_{He} := 4.0 \cdot \frac{gm}{mole}$ ANSI N14.5 - 1997

$\mu_{He} := 0.0198 \cdot cP$ ANSI N14.5 - 1997

$$M_{mix} := \frac{M_{He} \cdot P_{He} + M_{air} \cdot P_{air}}{P_{mix}}$$ Eqn. B7 - ANSI N14.5

$$\Rightarrow \qquad M_{mix} = 13.26 \cdot \frac{gm}{mole}$$

$$\mu_{mix} := \frac{\mu_{air} \cdot P_{air} + \mu_{He} \cdot P_{He}}{P_{mix}}$$ Eqn. B8 - ANSI N14.5

$$\Rightarrow \qquad \mu_{mix} = 0.019 \cdot cP$$

Determine L_{mix} as a function of temperature. Assume the viscosities of air and Helium do not change significantly over the range of temperatures evaluated:

$T := 273 \cdot K, 278 \cdot K .. 318 \cdot K$ Temperature range for test: 32°F to approx. 113°F

$$F_c := \frac{2.49 \cdot 10^6 \cdot D_{max}^{\ 4} \cdot cP \cdot std}{a \cdot \mu_{mix} \cdot sec \cdot atm}$$

$$F_m(T) := \frac{3.81 \cdot 10^3 \cdot D_{max}^{\ 3} \cdot \sqrt{\frac{T}{M_{mix}}} \cdot cm \cdot gm^{0.5}}{a \cdot P_a \cdot K^{0.5} \cdot mole^{0.5} \cdot sec}$$

$$L_{mix}(T) := \left(F_c + F_m(T)\right) \cdot \left(P_{mix} - P_{air}\right) \cdot \frac{P_a}{P_{mix}}$$

$$T_F(T) := \left[(T \cdot F - 273 \cdot K) \cdot \frac{9}{5 \cdot K} + 32 \right]$$

The Helium component of this leak rate can be determined by multiplying the leak rate of the mixture by the ratio of the Helium partial pressure to the total pressure of the mix, as follows.

$$L_{He}(T) := L_{mi}(T) \cdot \frac{P_{He}}{P_{mi}}$$

Determine the equivalent mass flow rate for L_{He} in oz/yr:

$N(T) := \frac{P_{He} \cdot V}{R_o \cdot T}$ Ideal Gas Law

where,

$R_o := \frac{82.05\ cm^3 \cdot atm}{mole K}$

This data can then be used to convert the volumetric leak rate for Helium calculated above to a mass leak rate. By dividing N by V, the number of moles per unit volume can be multiplied by the molecular weight of the gas and the maximum allowable volumetric leak rate to determine the maximum allowable mass leak rate, as a function of test temperature as shown in the graph below. The conversion from grams per second to ounces per year is also shown below.

$L(T) := L_{He}(T) \cdot \frac{N(T)}{V} \cdot M_{He} \cdot \frac{yr}{oz}$

$\frac{gm}{sec} = 1.113 \cdot 10^{6} \cdot \frac{oz}{yr}$ Conversion of gm/sec to oz/yr

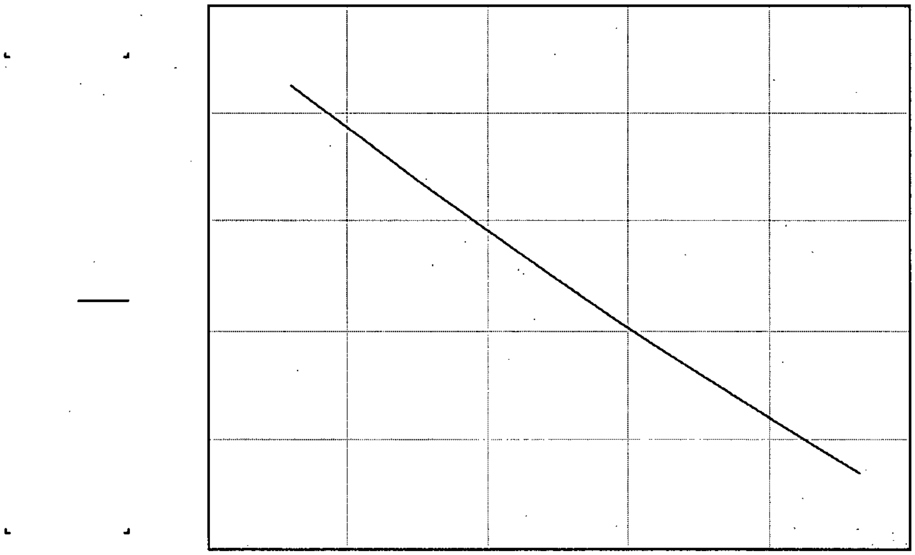


Fig.4.7 - Allowable helium test leakage, oz/yr, versus test temperature, deg.F

The graph above can be used to determine the allowable leak rate based on the temperature at the time of the test. According to ANSI N14.5 methodology, the maximum allowable leak rate must be divided by 2 to determine the minimum sensitivity for the test. A graph of the required sensitivity in oz/yr is presented below:

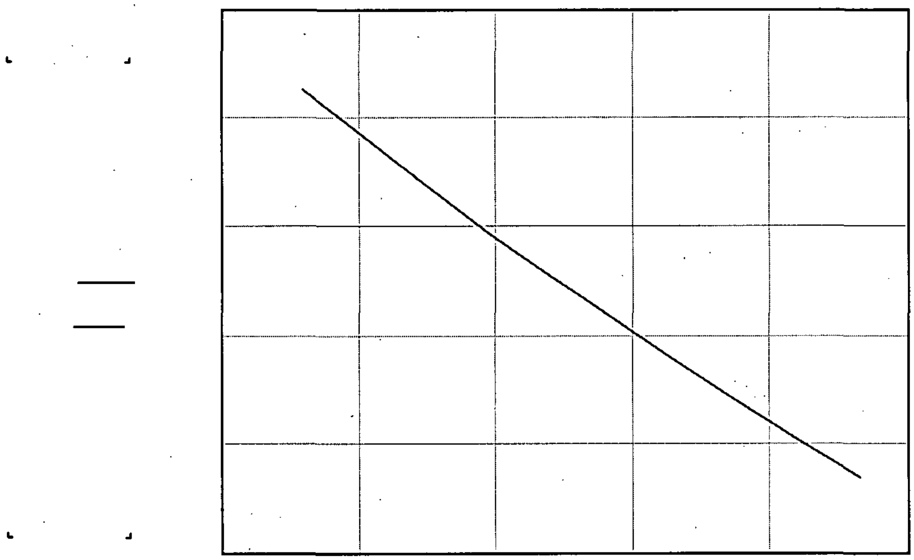


Fig.4.8 - Allowable helium test leakage sensitivity, oz/yr, versus test temperature, deg.F

The values presented in Figure 4.8 should be used to determine the sensitivity to calibrate the leak detector prior to the test.

4.7 Periodic Verification Leak Rate Determination Using R-134A Test Gas

This section contains calculations to determine the periodic verification test measurement that is equivalent to the maximum permissible leak rate as determined using ANSI N14.5-1997 (Reference 8).

4.7.1 Introduction

The purpose of this calculation is to determine the allowable leak rate using the R-134a halogen gas that will be used as an alternative to perform the annual verification leak tests on the 10-160B cask. This halogen gas is now in widespread use as a replacement gas for R-12 in many industrial applications. Properties for R134a are included in Appendix 4.1.

4.7.2 Detector Sensitivity Calculation - Test Conditions

This section determines the sensitivity necessary for a leak test performed with R-134a halogen gas. This test is performed using a halogen leak detector. A leak standard, traceable to NIST, is used to calibrate the leak detector to detect the maximum allowable test leak rates specified in Figure 4.11. The test is performed as follows: The annulus between the o-ring seals of the 10-160B primary and secondary lids will be evacuated to a minimum vacuum of 20"Hg, and then be pressurized to a minimum pressure of 25 psig with R-134a halogen gas. In section 4.2.1, it was determined that the maximum possible diameter hole in the cask O-ring (D_{max}) that would permit the standard leak rate ($L_{std} = 2.45 \times 10^{-6}$) is:

$D_{max} = 3.54 \times 10^{-4}$ cm

Next, determine the equivalent air/R134a mixture (L_{mix}) that would leak from D_{max} during a leak test. Assume the O-ring void is first evacuated to 20"Hg vacuum (9.92"Hg absolute) and then pressurized to 25 psig (2.7 atm) with an air/R134a mixture.

$P_{mix} := 2.7 \cdot atm$

$P_{air} := 9.92 \cdot in\_Hg$

$P_{air} = 0.33 atm$

$P_{R134a} := P_{mix} - P_{air}$

$P_{R134a} = 2.37 atm$ $P_d := 1.0 \cdot atm$

$$P_a := \frac{P_{mix} + P_{air}}{2}$$

$P_a = 1.85 atm$

The properties of R134a are given in the attached literature:

$$M_{R134a} := 102 \cdot \frac{gm}{mole}$$

$$\mu_{R134a} := 0.012 \cdot cP$$

$$M_{mix} := \frac{M_{R134a} \cdot P_{R134a} + M_{air} \cdot P_{air}}{P_{mix}}$$ Eqn. B7 - ANSI N14.5

$$\Rightarrow \qquad M_{mix} = 93.04 \frac{gm}{mole}$$

$$\mu_{mix} := \frac{\mu_{air} \cdot P_{air} + \mu_{R134a} \cdot P_{R134a}}{P_{mix}}$$ Eqn. B8 - ANSI N14.5

$$\Rightarrow \qquad \mu_{mix} = 0.013 cP$$

Determine L_{mix} as a function of temperature. Assume the viscosities of air and R134a do not change significantly over the range of temperatures evaluated:

$T := 273 \cdot K, 278 \cdot K .. 318 \cdot K$ Temperature range for test: 32°F to 113°F

$$F_c := \frac{2.49 \cdot 10^6 \cdot D_{max}{}^4 \cdot cP \cdot ref}{a \cdot \mu_{mix} \cdot sec \cdot atm}$$

$$F_m(T) := \frac{3.81 \cdot 10^3 \cdot D_{max}{}^3 \cdot \sqrt{\frac{T}{M_{mix}}} \cdot cm \cdot gm^{0.5}}{a \cdot P_a \cdot K^{0.5} \cdot mole^{0.5} \cdot sec}$$

$$L_{mix}(T) := \left(F_c + F_m(T)\right) \cdot \left(P_{mix} - P_{air}\right) \cdot \frac{P_a}{P_{mix}}$$

$$T_F(T) := \left[(T \cdot F - 273 \cdot K) \cdot \frac{9}{5 \cdot K} + 32 \right]$$

The R-134a component of this leak rate can be determined by multiplying the leak rate of the mixture by the ratio of the R-134a partial pressure to the total pressure of the mix, as follows.

$$L_{R134a}(T) := L_{mix}(T) \cdot \frac{P_{R134a}}{P_{mix}}$$

Determine the equivalent mass flow rate for L_{R134a} in oz/yr, the measurement used by the detector:

$$N(T) := \frac{P_{R134a} \cdot V}{R_o \cdot T}$$ Ideal Gas Law

where,

$$R_o := \frac{82.05\,\mathrm{cm}^3 \cdot \mathrm{atm}}{\mathrm{mole} \cdot \mathrm{K}}$$ Universal Gas Constant

This data can then be used to convert the volumetric leak rate for R-134a calculated above to a mass leak rate. By dividing N by V, the number of moles per unit volume can be multiplied by the molecular weight of the gas and the maximum allowable volumetric leak rate to determine the maximum allowable mass leak rate, as a function of test temperature as shown in the graph below. The conversion from grams per second to ounces per year is also shown below.

$$L(T) := L_{R134a}(T) \cdot \frac{N(T)}{V} \cdot M_{R134a} \cdot \frac{\mathrm{yr}}{\mathrm{oz}}$$

$$\frac{\mathrm{gm}}{\mathrm{sec}} = 1.113 \times 10^{6} \, \frac{\mathrm{oz}}{\mathrm{yr}}$$ Conversion of gm/sec to oz/yr

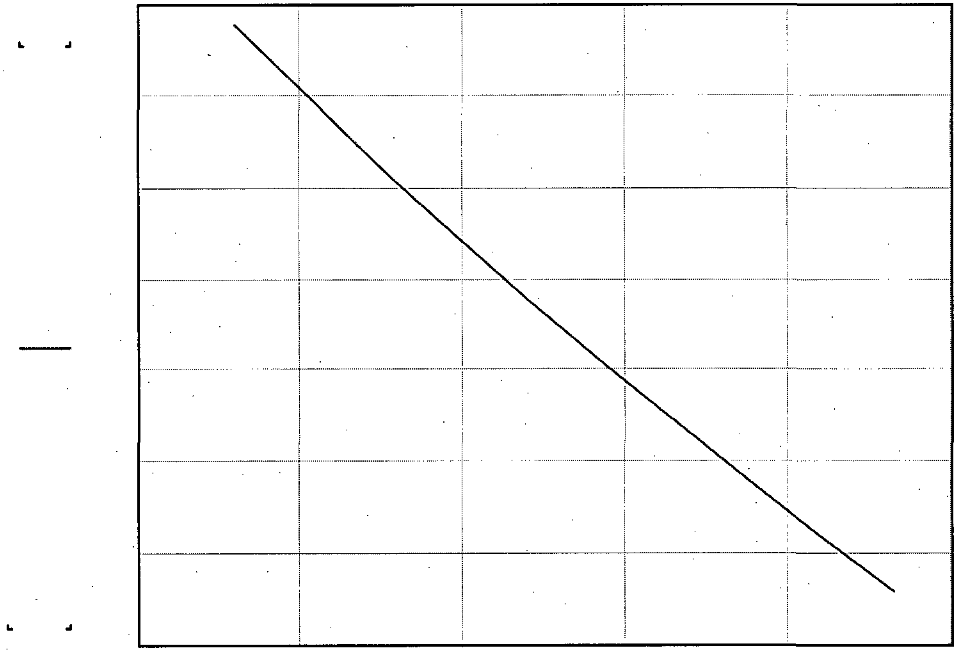


Fig.4.11 - Allowable R134a test leakage, oz/yr, versus test temperature, deg.F

The graph above can be used to determine the allowable leak rate based on the temperature at the time of the test. According to ANSI N14.5 methodology, the maximum allowable leak rate must be divided by 2 to determine the minimum sensitivity for the test. A graph of the required sensitivity in oz/yr is presented below:

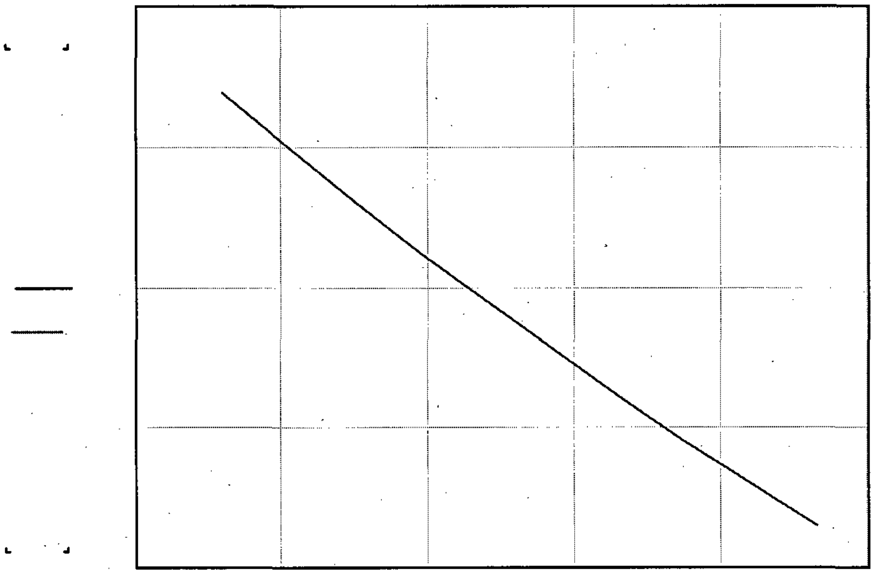


Fig.4.12 - Allowable R134a test leakage sensitivity, oz/yr, versus test temperature, deg.F

The values presented in Figure 4.12 should be used to determine the sensitivity to calibrate the leak detector prior to the test.

4.8 Combustible Gas Generation Safety Assurance

Assurance of safe shipment of vessels which may generate combustible gas is based on meeting the following criteria over the shipment period.

i) The quantity of hydrogen generated must be limited to a molar quantity that would be no more than 5% by volume at STP (or equivalent limits for other inflammable gases) of the secondary container gas void (i.e., no more than 0.063 gram moles/cubic foot, or

ii) The secondary container and the cask cavity (if required) must be inerted with a diluent to assure the oxygen, including that radiolytically generated, shall be limited to 5% by volume in those portions of the package which could have hydrogen greater than 5%. This criterion does not apply to TRU wastes, which shall be governed by the requirements of Appendix 4.10.2.

Criterion (i) essentially stipulates that the quantity of hydrogen shall be limited to 5% of the secondary container gas void at STP. This 5% hydrogen gas volume at standard conditions is equivalent to a hydrogen partial pressure of 0.735 psi or 0.063 gram moles/cubic foot. By actual experiment (Ref. 6), the produce an approximate 2.3 psi incremental pressure increase above a nominally atmospheric initial pressure. This is because 0.063 gram moles of hydrogen per cubic foot provides such a small source that the peak pressure rise resulting from ignition of this source is slight. (The pressure rise is independent of the total volume under test, i.e. the 0063 gram moles per cubic foot relationship to a 2.3 psi pressure rise is valid for one or many cubic feet of specimen volume). Methodology for demonstrating compliance with the 5% hydrogen concentration limit for TRU waste is described in Appendix 4.10.2, Transuranic (TRU) Waste Compliance Methodology for Hydrogen Gas Generation. This incremental pressure rise is an inconsequential load on the cask structure.

(Ref. 7), Criteria (ii) is invoked to ensure that when a secondary container's hydrogen concentration potentially exceeds 5% volume, release of that hydrogen to the then existing total volume (secondary container void plus cask void) will not result in a total mixture of greater than 5% volume hydrogen in a greater than 5% oxygen atmosphere. Maintaining the oxygen concentration lower than five (5) volume % assures a nonflammable mixture.

4.9 Periodic Verification Leak Rate Determination for Leaktight Status

4.9.1 Introduction

The purpose of this section is to describe the method for performing a periodic leak test to demonstrate meeting the leaktight criterion per ANSI N14.5-1997. This test method is only applicable to a 10-160B cask with butyl rubber o-rings and ethylene propylene seals.

4.9.2 Test Conditions

The test is performed with a mass spectrometer leak detector. The test is conducted on the 10-160B by evacuating the cask cavity to at least 90% vacuum then pressurizing the cask cavity with helium (+1 psig, -0 psig). The annulus between the o-rings is evacuated until the vacuum is sufficient to operate the helium mass spectrometer leak detector and the helium concentration in the annulus is monitored. The acceptance criterion is 1.0×10^{-7} atm-cm^3/sec of air (leaktight). The detector sensitivity must be less than or equal to 5.0×10^{-8} atm-cm^3/sec. Similar tests are performed on the vent and drain ports, if so equipped.

Appendix 4.10.2

TRU Waste Payload Control

1.0 INTRODUCTION

The purpose of this appendix is to identify the requirements for the control of remote handled transuranic (RH-TRU) and contact-handled transuranic (CH-TRU) waste, as defined by the U.S. Department of Energy (DOE) (Reference 12.1), as payload for transport in the 10-160B cask.

The payload parameters that are controlled in order to ensure safe transport of the TRU waste in the 10-160B cask are as follows:

- Restrictions on the physical and chemical form of CH-TRU and RH-TRU waste.
- Restrictions on payload materials to ensure chemical compatibility among all constituents in a particular 10-160B cask (including the parts of the cask that might be affected by the payload).
- Restrictions on the maximum pressure in the 10-160B cask during the transport period. (As a conservative analysis, the maximum pressure calculations are performed for a period of one year. Attachment C discusses the transport period.)
- Restrictions on the amount of potentially flammable gases that might be present or generated in the payload during the transport period.
- Restrictions on the layers of confinement for RH-TRU and CH-TRU waste materials in the waste containers packaged in the cask.
- Restrictions on the fissile material content for the cask.
- Restrictions on the hydrogen generation rates or the decay heat for the waste containers packaged in the cask.
- Restrictions on the weight for the loaded cask.

The methods for determining or measuring each restricted parameter, the factors influencing the parameter values, and the methods used by each shipping site for demonstrating compliance, are provided in the site-specific sub tier appendices. A payload container previously demonstrated to be in compliance with this appendix and subsequently shipped to another site remains acceptable for shipping provided the payload container has not been opened.

This appendix also includes the following as attachments:

- Description of the use of dose-dependent G values for TRU wastes (Attachment A)
- Chemical compatibility analysis for the TRU waste content codes (Attachment B).
- Shipping period for TRU waste in the 10-160B cask (Attachment C)

2.0 PURPOSE

2.1 Payload Parameters

The purpose of this appendix is to describe the payload requirements for RH-TRU and CH-TRU waste for transport in the 10-160B cask. Detailed descriptions of the site compliance methods associated with these requirements shall be provided in the site-specific sub tier appendices. Any and all assumptions used in the site compliance methods will be specified in the site-specific sub tier appendices

Sub tier appendices will be added, as necessary, to incorporate additional site-specific waste content codes that may be identified in the future. These appendices shall be submitted to the U.S. Nuclear Regulatory Commission (NRC) for review and approval, with shipments under additional codes authorized only after NRC approval.

Section 2.2 describes some typical methods of compliance available to show compliance with the individual payload parameter requirements. Section 3.0 describes the relationship between payload parameters and the classification of RH-TRU and CH-TRU materials into 10-160B cask payload content codes. Sections 4.0 through 11.0 discuss each payload parameter requirements for the 10-160B cask.

The payload parameters addressed in this document include:

- Physical form
- Chemical form and chemical properties
- Chemical compatibility
- Gas distribution and pressure buildup
- Payload container and contents configuration
- Isotopic characterization and fissile content
- Decay heat and hydrogen generation rates
- Weight.

2.2 Methods of Compliance

This section describes some typical methods that may be used to determine compliance with each payload parameter requirement and the controls imposed on the use of each method. Each shipping site shall select and implement a single compliance method, or a combination of methods, to ensure that the payload is compliant with each requirement and is qualified for shipment. These methods shall be documented in the site-specific sub tier appendices associated with this appendix.

A summary of typical methods of compliance that may be used for the 10-160B cask payload control is provided in the following sections.

2.2.1 Visual Examination

Visual examination at the time of waste generation may be used to qualify waste for transport. The operator(s) of a waste generating area shall visually examine the physical form of the waste according to site/equipment-specific procedures and remove all prohibited waste forms prior to its placement in the payload container. Observation of the waste generation process by an independent operator may be used as an independent verification of the compliance of the waste prior to closure of the payload container.

2.2.2 Visual Inspection

Visual inspection may be used to evaluate compliance with specific restrictions (e.g., visual inspection of payload container type, number of filters, etc.).

2.2.3 Radiography

Radiography may be used as an independent verification to qualify waste for transport. Radiography may be used to nondestructively examine the physical form of the waste, and to verify the absence of prohibited waste forms, after the payload container is closed.

2.2.4 Process Knowledge (Records and Database Information)

Process knowledge (PK) (also referred to as acceptable knowledge for the purposes of this document) refers to applying knowledge of the waste in light of the materials or processes used to generate the waste. PK is detailed information on the waste obtained from existing published or documented waste analysis data or studies conducted on wastes generated by processes similar to that which generated the waste. PK may include information on the physical, chemical, and radiological properties of the materials associated with the waste generation process(es), the fate of those materials during and subsequent to the process, and associated administrative controls. PK commonly includes detailed information on the waste obtained from existing waste analysis data, review of waste generating process(es), or detailed information relative to the properties of the waste that are known due to site-specific or process-specific factors (e.g., material accountability and tracking systems or waste management databases may supply information on waste isotopic composition or quantity of radionuclides, among other waste attributes). PK sources may include information collected by one or more of the compliance methods described in Sections 2.2.1 through 2.2.7.

Information obtained from existing site records and/or databases or knowledge of process may be used as a basis for reporting the absence of prohibited waste forms within waste containers. PK may also be used to show compliance with the physical and chemical form requirements and the payload container and contents requirements.

2.2.5 Administrative and Procurement Controls

Site-specific administrative and procurement controls may be used to show that the payload container contents are monitored and controlled, and to demonstrate the absence of prohibited items within waste containers.

2.2.6 Sampling Programs

Sampling programs may be used as an independent verification of compliance.

2.2.7 Measurement

Direct measurement or evaluation based on analysis using the direct measurement may be used to qualify waste (e.g., direct measurement of the weight or analysis of assay data to determine decay heat).

3.0 TRU WASTE PAYLOAD FOR 10-160B CASK

RH-TRU and CH-TRU waste is classified into content codes, which give a description of the RH-TRU and CH-TRU waste material in terms of processes generating the waste, the packaging methods used in the waste container(s), and the generating site. Content codes for the RH-TRU and CH-TRU waste to be shipped from each site are provided in the site-specific sub tier appendices to this appendix. Each content code provides a listing of all the payload parameters, their corresponding limits and restrictions, and the methods used by the site to meet these limits.

4.0 PHYSICAL FORM REQUIREMENTS

The physical form of waste comprising the 10-160B cask payload is restricted to solid or solidified materials in secondary containers. The total volume of residual liquid in a secondary container is restricted to less than 1% by volume. A secondary container is any container placed inside the primary container, the 10-160B cask. Secondary containers must be shored to prevent movement during accident conditions. Sharp or heavy objects in the waste shall be blocked, braced, or suitably packaged as necessary to provide puncture protection for the payload containers packaging these objects. Sealed containers greater than four liters in volume that do not have a known, measured, or calculated hydrogen release rate or resistance are prohibited.

5.0 CHEMICAL FORM AND CHEMICAL PROPERTIES

The chemical constituents allowed in a given content code determine the chemical properties of the waste. Specific requirements regarding the chemical form of the waste are as follows:

- Explosives, nonradioactive pyrophorics, compressed gases, and corrosives are prohibited.
- Pyrophoric radionuclides may be present only in residual amounts less than 1 weight percent.
- The total amount of potentially flammable volatile organic compounds (VOCs) present in the headspace of a secondary container is restricted to 500 parts per million (ppm).

6.0 CHEMICAL COMPATIBILITY

Each content code has an associated chemical list based on PK information. Chemical constituents in a payload container assigned to a given content code shall conform to these chemical lists (included in each site-specific sub tier appendix). Chemicals or materials that are not listed are allowed in trace amounts (quantities less than one weight percent) in a payload container provided that the total quantity of trace chemicals or materials is restricted to less than five weight percent.

Chemical compatibility of the waste within itself and with the packaging shall ensure that chemical processes would not occur that might pose a threat to safe transport of the payload in the 10-160B Cask. The basis for evaluating the chemical compatibility shall be the U.S. Environmental Protection Agency (EPA) document, "A Method for Determining the Compatibility of Hazardous Wastes" (Reference 12.2). This method provides a systematic means of analyzing the chemical compatibility of specific combinations of chemical compounds and materials. Any incompatibilities between the payload and the packaging shall be evaluated separately if not covered by the EPA method.

As described in Attachment B to this appendix, the EPA method classifies individual chemical compounds, identified in the list of allowable chemicals and materials, into chemical groups and identifies the potential adverse reactions resulting from incompatible combinations of the groups. Attachment B presents the methodology and results for the chemical compatibility analyses performed on the list of allowable chemicals and materials associated with the TRU waste content codes expected to be shipped in the 10-160B Cask.

Chemicals and materials included on the content code chemical lists (in concentrations greater than one weight percent) shall be a subset of the list of allowable materials identified in Table B-1 of Attachment B to this appendix to demonstrate compliance with the compatibility requirement. The results of the compatibility analyses show that these content codes can be transported without any incompatibilities.

7.0 GAS DISTRIBUTION AND PRESSURE BUILDUP

Gas distribution and pressure buildup during transport of TRU waste in the 10-160B cask payload are restricted to the following limits:

- The gases generated in the payload must be controlled to prevent the occurrence of potentially flammable concentrations of gases within the payload confinement layers and the void volume of the inner vessel (IV) cavity. Specifically, hydrogen concentrations within the payload confinement layers are limited to 5 percent by volume during the shipping period (see Attachment C).
- The gases generated in the payload and released into the IV cavity must be controlled to maintain the pressure within the IV cavity below the acceptable packaging design limit of 31.2 pounds per square inch gauge (psig).

The primary mechanism for gas generation during TRU waste transportation in the 10-160B cask is by radiolysis of the waste materials. Gas generation from other mechanisms such as chemical, thermal, or biological activity is expected to be insignificant for the TRU waste payload. As discussed in Section 6.0, the chemicals and materials in the TRU waste are compatible and inert, and the restrictions of the materials that can be present in each content code precludes the occurrence of chemical reactions that can produce excessive gas. Gas generation from biological activity is expected to be insignificant given the transportation time, the nature of the waste (solid or solidified), and the environment of the payload (lack of nutrients, lack of water content, etc.). The temperatures of the payload, given the decay heat limits applicable, are expected to be below the normal usage range for the payload materials, resulting in very little potential for gas generation due to thermal decomposition.

8.0 PAYLOAD CONTAINER AND CONTENTS CONFIGURATION

Thirty-gallon and 55-gallon secondary containers may be used as payload containers in the 10-160B. The available volume of the cask cavity limits the number of payload containers that may be shipped at one time. In the case of 55-gallon drums, a maximum number of ten drums can be loaded into the 10-160B cask. Payload containers must have at least one filter vent. Filter vents shall be legibly marked to ensure both (1) identification of the supplier and (2) date of manufacture, lot number, or unique serial number. Typically, for purposes of radiological safety, TRU waste in the payload container may be packaged in one or more layers of confinement (plastic bags). Bags are closed with a twist and tape, fold and tape or heat-sealed closure. Heat-sealed bags may have a filter vent or be unvented.

Any drum or rigid polymer liner present inside a payload container shall have a filter vent or an opening that is equivalent to or larger than a 0.3-inch diameter hole before the container is transported in the 10-160B.

9.0 ISOTOPIC CHARACTERIZATION AND FISSILE CONTENT

9.1 Requirements

The 10-160B cask payload allows 325 FGE of fissile materials. Plutonium content in excess of 0.74 TBq (20 curies) per cask must be in solid form.

Compliance with the isotopic characterization and fissile content requirements involves the following steps:

- Determination of isotopic composition

- Determination of the quantity of radionuclides
- Calculation of the fissile mass and comparison with 325 FGE limit
- Calculation of plutonium content and confirmation of solid form if exceeding the 20 curie limit.

9.1.1 Isotopic Composition

The isotopic composition of the waste may be determined from direct measurements taken on the product material during the processing or post-process certification at each site, analysis of the waste, or from existing records and PK. The isotopic composition of the waste need not be determined by direct analysis or measurement of the waste unless PK is not available.

9.1.2 Quantity of Radionuclides

The quantity of the radionuclides in each payload container shall be estimated by either PK or direct measurement of the individual payload container, a summation of assay results from individual packages in a payload container, or a direct measurement on a representative sample of a waste stream (such as solidified inorganics). An assay refers to one of several radiation measurement techniques that determine the quantity of nuclear material in TRU wastes. Assay instruments detect and quantify the primary radiation (alpha, gamma, neutron) emanating from specific radionuclides, or a secondary radiation emitted from neutron interrogation techniques. The measured quantity of radiation is then used to calculate the quantity of other radionuclides. That calculation requires knowledge of the isotopic composition of the waste. Combinations of gamma spectroscopy and neutron measurements are often needed to calculate the quantity of nonfissile radionuclides.

9.1.3 Calculation of Fissile Mass

The calculation of the fissile mass shall be performed to demonstrate compliance with the 325 FGE limit using the values in Table 9.1.3.

Table 9.1.3 – Pu-239 Fissile Gram Equivalent, U-235 Fissile Equivalent Mass, Decay Heat, and Specific Activity of Selected Radionuclides

NUCLIDE	SPECIFIC ATOMIC NUMBER	Pu-239 FGE[1,2]	U-235 FEM[1,2,3]	DECAY HEAT[4] (W/g)	SPECIFIC ACTIVITY[5] (Ci/g)
U-233	92	9.00E-01	1.80E+00	2.84E-04	9.76E-03
U-235	92	6.43E-01	1.00E+00	6.04E-08	2.19E-06
Np-237	93	1.50E-02	3.00E-02	2.09E-05	7.13E-04
Pu-238	94	1.13E-01	2.25E-01	5.73E-01	1.73E+01
Pu-239	94	1.00E+00	2.00E+00	1.95E-03	6.29E-02
Pu-240	94	2.25E-02	4.50E-02	7.16E-03	2.30E-01
Pu-241	94	2.25E+00	4.50E+00	3.31E-03	1.04E+02
Pu-242	94	7.50E-03	1.50E-02	1.17E-04	3.97E-03
Am-241	95	1.87E-02	3.75E-02	1.16E-01	3.47E+00
Am-242m	95	3.46E+01	6.92E+01	4.32E-03	9.83E+00
Am-243	95	1.29E-02	2.57E-02	6.49E-03	2.02E-01
Cm-243	96	5.00E+00	1.00E+01	1.90E+00	5.22E+01
Cm-244	96	9.00E-02	1.80E-01	2.86E+00	8.18E+01
Cm-245	96	1.50E+01	3.00E+01	5.77E-03	1.74E-01
Cm-247	96	5.00E-01	1.00E+00	2.98E-06	9.38E-05
Cf-249	98	4.50E+01	9.00E+01	1.54E-01	4.14E+00

Cf-251	98	9.00E+01	1.80E+02	5.89E-02	1.60E+00

1 American National Standards Institute/American Nuclear Society (ANSI/ANS), 1981, "Nuclear Criticality Control of Special Actinide Elements," ANSI/ANS-8.15-1981, American National Standards Institute/American Nuclear Society, Washington, D.C.
2 American National Standards Institute/American Nuclear Society (ANSI/ANS), 1998, "Nuclear Criticality Safety in Operations with Fissionable Materials Outside Reactors," ANSI/ANS-8.1-1998, American National Standards Institute/American Nuclear Society, Washington, D.C.
3 American National Standards Institute/American Nuclear Society (ANSI/ANS), 1987, "Nuclear Criticality Control and Safety of Plutonium-Uranium Fuel Mixtures Outside Reactors," ANSI/ANS-8.12-1987, American National Standards Institute/American Nuclear Society, Washington, D.C.
4 International Commission on Radiological Protection, 1983. International Commission on Radiological Protection, 1983, "Radionuclide Transformations: Energy and Intensity of Emissions," Annals of the International Commission on Radiological Protection-38, Volumes 11-13, Pergamon Press, Oxford.
5Walker, F.W., Kiravac, G.J., and Rourke, F.M., 1983, Chart of the Nuclides, 13th Edition, Knolls Atomic Power Laboratories, Schenectady, NY.
Ci/g = Curies per gram.
W/g = Watts per gram.

9.1.4 Calculation of Plutonium Curies

The total plutonium (all plutonium isotopes) activity (curies) for each payload container shall be determined as described above and summed for the entire payload. If contents exceed 20 Ci, the plutonium waste form shall be confirmed as solid.

10.0 DECAY HEAT AND HYDROGEN GAS GENERATION RATES

10.1 Requirements

The hydrogen gas concentration shall not exceed five percent by volume in all void volumes within the 10-160B cask payload during the shipping period (see Attachment C). Payload containers of different content codes with different bounding G values and resistances may be assembled together as a payload, provided the decay heat limit and hydrogen gas generation rate limit for all payload containers within the payload is conservatively assumed to be the same as that of the payload container with the lowest decay heat limit and hydrogen gas generation rate limit.

10.2 Methodology of Ensuring Compliance with Flammable Gas Concentration Limits

As stated in Section 7, chemical, biological, and thermal gas generation mechanisms are expected to be insignificant in the 10-160B cask. In addition, potentially flammable VOCs are restricted to 500 ppm in the headspace of the 10-160B cask secondary containers (Section 5). Therefore, the only flammable gas of concern for transportation purposes is hydrogen. The concentration of hydrogen within any void volume in a layer of confinement of the payload or in the cask IV has been evaluated during the shipping period (see Attachment C).

Each content code shall have a unique and completely defined packaging configuration. Modeling the movement of hydrogen from the waste material to the payload voids, using the release rates of hydrogen through the various confinement layers, defines the relationship between generation rate and void concentration. This modeling allows determination of the maximum allowable hydrogen generation rate for a given content code to meet the 5% concentration limit. Based on hydrogen gas generation potential, quantified by hydrogen gas generation G values, the gas concentration limit can be converted to a decay heat limit. The maximum allowable hydrogen generation rates and decay heat limits for each site-specific content code shall be determined and reported in the site-specific payload compliance appendix (sub tier to this appendix). The modeling methodology for determining the hydrogen gas generation rate limit and the decay heat limit shall be presented in each site-specific payload compliance appendix. Conservative assumptions may be used in site-specific subtier appendices to introduce an additional margin of safety.

Parameters that govern the maximum allowable hydrogen generation rates and maximum allowable decay heat limits are listed below:

- Waste packaging configuration (i.e., the number and type of confinement layers).
- Release rates of hydrogen from each of these confinement layers.
- Void volume in the cask IV available for gas accumulation.
- Operating temperature and pressure for the payload in the 10-160B cask IV during the shipping period.
- Duration of the shipping period (see Attachment C).
- Hydrogen generation rates quantified by the G value of a waste material (the number of molecules of hydrogen produced per 100 eV of energy absorbed) (see Attachment A for description of dose-dependent G values and the Matrix Depletion Program).

10.3 Determination of Maximum Allowable Hydrogen Generation Rate

The modeling for determination of the maximum allowable generation rates is described below.

10.3.1 Input Parameters

The model parameters that must be quantified include the following:

Waste Packaging Configuration and Release Rates:
Packaging configurations are content code specific and will be documented in the sub-tier appendices. The bags, any rigid container with an opening or filter vent, and the drum filter vent all provide some resistance to the release of hydrogen from the container.

Pressure: The pressure is assumed to be isobaric and equal to one atmosphere. The mole fraction of hydrogen in each void volume would be smaller if pressurization is considered and would result in a greater maximum allowable hydrogen gas generation rate. Furthermore, the amount of hydrogen gas generated during the shipping period would be negligible compared to the quantity of air initially present at the time of sealing the 10-160B cask.

Temperature: The system temperature increases and decreases as the result of diurnal and seasonal variations in the environment (i.e, weather, solar radiation). Heat released from the radioactive components in the waste can also contribute to thermal input in the system.

The input parameters that can be described as a function of temperature are the release rate across the different confinement layers in the payload containers and the hydrogen G values for the waste streams. The resistance to the release of hydrogen is a function of temperature as documented in Appendix 6.9 of the CH-TRU Payload Appendices (Reference 12.3). The resistance generally decreases with increasing temperature and increases with decreasing temperature. The release rates across each confinement layer shall be defined at a specified temperature. The specified temperature shall be defined in terms of the expected operating temperature range. Since the release rates decrease with decreasing temperature, the use of the minimum expected operating temperature to calculate the lowest release rate will provide the maximum margin of safety when calculating the hydrogen gas generation rate or decay heat limit.

Theoretically, the G value for a waste stream increases with increasing temperature (Reference 12.3). The G values at room temperature (i.e., 70°F) will be adjusted to the maximum expected operating temperature using the Arrhenius equation, unless it is demonstrated that the G values for the waste streams are not a function of temperature. The G values adjusted to reflect the maximum expected operating temperature would provide the maximum margin of safety in the calculated hydrogen gas generation rate or decay heat limits.

These are the important input parameters for determining the maximum allowable hydrogen generation rate limit. Other assumptions used in the mathematical analysis are included in Section 10.3.2.

10.3.2 Mathematical Analysis For Determining the Maximum Allowable Hydrogen Gas Generation Rates

At steady state, the flow rate of hydrogen across each of the confinement layers is equal to the same value and to the hydrogen generation rate. The maximum hydrogen concentration in a payload container with filter vents is reached at steady state. That is, a filter vented container with a hydrogen generation source has increasing concentrations of hydrogen with time until steady state conditions are reached. For the purpose of these calculations, it has been assumed that all payload containers are at steady state at the start of transport.

Once the drums are sealed inside the 10-160B cask IV, concentrations of hydrogen in the different layers increase due to the accumulation of hydrogen in the IV cavity. Some of the hydrogen generated during the transport period would accumulate in the payload containers, with the remainder being released into the cavity. For the purpose of these calculations, the mole fraction of hydrogen in a bag layer is set equal to the steady state value plus the mole fraction of hydrogen that has accumulated in the cavity. The IV cavity mole fraction of hydrogen is obtained by assuming that all of the hydrogen generated is released into the IV cavity. The maximum hydrogen concentration in the innermost layer is then limited to less than or equal to five (5) volume percent at the end of the shipping period by suitably choosing the gas generation rates. The maximum number of moles of hydrogen which can accumulate in the IV cavity is:

$$N_{gen} = (CG)(n_{gen})(t)$$

Where:

N_{gen} = total moles of hydrogen generated
CG = hydrogen gas generation rate per innermost layer of confinement (moles/sec)
n_{gen} = number of hydrogen generators (payload containers) in the 10-160B cask
t = shipping period duration, s

The maximum mole fraction of hydrogen in the 10-160B IV cavity is then equal to:

$$X_{fh} = (N_{gen}/N_{tg}) = \{N_{gen}/[P(V_{void})/RT]\}$$

Where:

X_{fh} = maximum mole fraction of hydrogen in the 10-160B IV cavity
N_{tg} = total moles of gas inside the 10-160B IV cavity
P = pressure inside the 10-160B, assumed to be constant at 1 atm (760 mm Hg), because the amount of gas generated is much less than the total amount of air originally in the cavity
V_{void} = void volume inside the 10-160B IV cavity (liters)
R = gas constant = 62.361 mm Hg-liter/mole-K

T = absolute temperature of air in the 10-160B IV cavity at the time of closure = 70°F = 294K

The gas generation rate per innermost confinement layer that will yield a maximum hydrogen concentration of five (5) volume percent is then computed as the following:

$X_{inner} = X_{fh} + (CG)(R_{eff})$

Where:

X_{inner} = mole fraction of hydrogen in innermost confinement layer (a value of 0.05 has been used for this parameter since this is the maximum permissible concentration)

R_{eff} = the effective resistance to the release of hydrogen (sec/mole)

The effective resistance is computed by summing the individual confinement layer resistances. The resistance of a layer is equal to the reciprocal of the release rate from that layer. After substituting the first two equations into the third for X_{inner} and solving for the gas generation rate the following results:

$CG = (X_{inner})/\{R_{eff} + [(t)(n_{gen})/N_{tg}]\}$

where all terms are as defined previously.

10.4 Determination of Maximum Allowable Decay Limits for Content Codes

The maximum allowable decay heat limit for the CH-TRU waste content codes will be calculated assuming 100% deposition of the emitted energy into the waste within the drum. Specifically, the decay heat limit is calculated from the hydrogen gas generation rate and effective G-Value through the following expression:

$Q = [(CG)(N_A)/(G_{eff}\text{ molecules/100eV})][1.602\times10^{-19}\text{ watt-sec/eV}]$

Where:

CG = Hydrogen gas generation rate per innermost confinement layer in one drum (mol/sec).

Q = decay heat per innermost confinement layer (watts)

N_A = Avogadro's number = 6.023×10^{23} molecules/mole

G_{eff} = G (hydrogen gas) = effective G value for flammable gas (molecules of hydrogen formed/100 electron volts [eV] emitted energy).

The maximum allowable decay heat limits for the RH-TRU waste content codes will be determined using the RadCalc Software (Reference 12.4). The current version of RadCalc is a Windows-compatible software program with applications in the packaging and transportation of radioactive materials. Its primary function is to calculate the generation of hydrogen gas by radiolytic production in the waste matrix of radioactive wastes. It contains a robust algorithm that determines the daughter products of selected radionuclides. The various functions in RadCalc can be used separately or together. The procedure is outlined below.

The first step in the evaluation of decay heat limits involves determining the activities of the radionuclides and daughters and the associated hydrogen gas generation rate at the time of sealing based on an initial isotopic ratio for the waste. The generation of hydrogen gas by radiolysis is a function of the energy absorbed by the waste. The second step in the evaluation of decay heat limits involves iterating on the total activity (decay heat limit) given the activity fractions from step one until the allowable hydrogen gas generation rate is obtained.

10.4.1 Databases and Input Parameters Used For Calculation of Maximum Allowable Decay Heat Limits

10.4.1.1 Radionuclide Databases

RadCalc uses radionuclide information, calculated gamma absorption fractions for selected container types, and G values to determine decay heat values. Radionuclide information is taken from FENDL/D-1.0 database (Reference 12.5). The following are a list of radionuclide parameters taken from FENDL/D-1.0 and the values they are used to calculate:

- Radionuclide half-lives are used in calculating specific activity
- Average heavy particle, beta-type radiation, and gamma radiation energies per disintegration are used in decay heat and hydrogen gas generation calculations
- Discrete gamma energies and abundances are used in hydrogen gas generation calculations.

RadCalc uses the ORIGEN2 (Reference 12.6) database for decay calculations. The decay algorithms calculate the activity of the user specified source and daughter products over a specified period of time and the total number of disintegrations accumulated over this same time interval for each radionuclide. Parameters relevant to these calculations include atomic mass, atomic number, and state. These parameters are used for radionuclide identification and conversions. The decay constant and the branching ratios for decay modes are also used in the decay algorithms.

10.4.1.2 Gamma Absorption Fraction Input Parameters

RadCalc uses the total energy emitted by heavy particle and beta-type decay in calculating the volume of hydrogen produced. However, only a percent of gamma energy will be absorbed in the package and the waste. The absorbed gamma energy is a function of energy, waste density, material type, and geometry. The gamma energy absorbed by the waste is a function of the gamma emission strength, the quantity of gamma ray energy that is absorbed by collision with a waste particle, and the number of particles which interact with the gamma ray. Therefore, gamma energy absorption increases with increasing waste density. For a given waste density, a larger container will contain more particles, and therefore a higher percentage of the gamma ray energy would be absorbed than in a smaller container. The total cumulative absorbed dose for all nuclides and decay modes at time, t is evaluated as:

$$D_{\underset{i=1}{total}}(t) = \overset{NR}{\Gamma} AC_i/\&_i \, (0.82E_i^{\forall} + E_i^{\exists} + E_i^{\ni} + E_i^{x})[1 - \exp(-\&_i t)]$$

where,

$D_{total}(t)$ = Total cumulative absorbed dose at time, t (rad)
A = A proportionality constant equal to 1.84×10^{10} rad gram MeV^{-1} yr^{-1} Ci^{-1}
C_i = The specific activity of the "i"th nuclide in Curies/gram of waste
$\&_i$ = The decay constant of the "i"th radionuclide (yr^{-1})
NR = Number of radionuclides

$E_i^{\forall}$ = ∀ energy in MeV of the "i"th radionuclide extracted from Flaherty et al. (Reference 12.11)

$E_i^{\exists}$ = Average beta energy in MeV of the "i"th nuclide. The average beta energy is approximately one-third of the sum of the possible beta emissions multiplied by the relative abundance of each emission and were obtained from Flaherty et al. (Reference 12.7).

Eix = The absorbed secondary energy in MeV of the "i"th radionuclide. The secondary radiations result from the transition of a radionuclide from an excited state to the ground state and were obtained from Flaherty et al. (Reference 12.7).

$Ei\ni$ = The absorbed gamma ray energy in MeV of the "i"th nuclide. The fraction of gamma energy that is absorbed by the waste is a function of the waste density and waste container geometry, and is evaluated for each radionuclide "i" as:

$$E_i^{\ni} = \Gamma_j n_{ij} f_{ij} E_{ij}^{\ni}$$

where,

Γj = the summation of the fractions of the gamma ray energies absorbed for all gamma emissions of the "i"th nuclide.

n_{ij} = the abundance of the "j"th gamma ray per decay of the "i"th nuclide

fij = the fraction of energy, of the "j"th gamma ray of the "i"th nuclide that is absorbed in the waste.

$E_{ij}^{\ni}$ = the energy in MeV, of the "j"th gamma ray of the "i"th nuclide.

RadCalc uses curve fits obtained from Flaherty et al. (Reference 12.7) and recalculated using the Monte Carlo N-Particle (MCNP) transport code (Reference 12.8) for ten containers, for obtaining the absorbed gamma dose.

The cask is not currently recognized by the RadCalc software. Therefore, another container with dimensions directly proportional to the cask was used in the calculations.

10.4.1.3 G Value Data

G values for TRU waste are content specific. G values are determined based on the bounding materials present in the payload. The G values at room temperature (i.e., 70°F) will be adjusted to the maximum expected operating temperature using the Arrhenius equation (unless data shows that the G values are temperature independent) in order to introduce a greater margin of safety in the calculated hydrogen gas generation rate or decay heat limits. The use of temperature-dependent and or dose-dependent G values for authorized content codes is discussed in the individual site-specific sub tier appendices. The methodology associated with the determination of dose-dependent G values pursuant to the Matrix Depletion Program is further discussed in Attachment A of this Appendix.

10.4.2 Input Parameters

The input parameters for the RadCalc software can be placed in three groups: (1) container data, (2) waste data, and (3) source data.

10.4.2.1 Container Data

RadCalc requires as input the following parameters associated with the container for which the maximum allowable decay heat limit is being calculated:

Container Type - The payload container for the waste material
Container Dates - Date of generation, date of sealing, and shipping period
Package Void Volume - void volume of the payload container.

A 6- by 6-foot liner with a volume equal to the cask is used to represent the payload container in the RadCalc input file as the RadCalc database does not include the cask. The package void volume for a 10-160B cask is 1938 liters as shown earlier.

10.4.2.2 Waste Data

RadCalc requires as input the following parameters associated with the waste for which the maximum allowable decay heat limit is being calculated:

Physical Form – liquid, solid, or gas
Waste Volume – volume of the waste, cm^3
Waste Mass – mass of the waste, g
G Value – G value of the waste, molecules per 100 eV

Liquids and gas wastes are prohibited in the 10-160B cask. The volume of the waste is determined based on the maximum number of 55-gallon drums that can be placed in the 10-160B cask. The waste volume in one drum is assumed to be 217 liters per drum (the external volume of a 55-gallon waste drum) and 2170 liters for 10 drums of waste in the cask. The waste volume is used by RadCalc, along with the waste mass, to determine the volume of hydrogen generated in the cask. The mass of the waste is calculated based on the assumed bulk density of the waste. The volume of hydrogen generated is a function of container waste density and geometry (Reference 12.7). The most conservative estimate of the volume of hydrogen (greatest volume) would occur at the highest possible bulk density of the waste. Appropriate density values for the RH-TRU content codes are discussed in the individual site-specific sub-tier appendices.

10.4.2.3 Source Data

RadCalc requires as input the following parameters associated with the source for which the maximum allowable decay heat limit is being calculated:

Isotopic Composition - List of radionuclides present in the waste
Activity - Reported activities of the listed radionuclides in curies or Becquerel.

10.4.3 Procedure For Determining Maximum Allowable Decay Heat Limits

The necessary inputs are provided to the code prior to initiating a run. A time period equivalent to the shipping period (Attachment C) is conservatively assumed between the date of beginning of decay and date of analysis. The model is run with the initial isotopic composition and activity and the corresponding hydrogen gas generation rate is obtained. It is compared with the maximum allowable hydrogen gas generation rate as obtained from Section 10.3, and the scaling factor is obtained by dividing the maximum allowable hydrogen gas generation rate by the RadCalc obtained rate. The isotopic composition is scaled by this differential factor. This is done on the basis of the assumption that the maximum decay heat occurs at the time of maximum activity that will result in the maximum hydrogen gas generation rate. The associated decay heat value will be the maximum decay heat limit as the decay heat limit shares a direct relationship with the hydrogen gas generation rate, independent of time.

10.5 Methodology for Compliance with Payload Assembly Requirements

Prior to shipping, the Transportation Certification Official at the shipping site (TCO) shall ensure that the 10-160B Cask payload consists of payload containers belonging to the same or equivalent content code. In the event that payload containers of different content codes with different bounding G values and resistances are assembled together in the 10-160B Cask, the TCO shall ensure that the decay heat and hydrogen gas generation rate for all payload containers within the payload are less than or equal to the limits associated with the payload container with the lowest decay heat limit and hydrogen gas generation rate limit.

11.0 WEIGHT

The weight limit for the contents of the loaded cask is 14,500 pounds.

12.0 REFERENCES

12.1 U.S. Department of Energy (DOE), 2002, "Contact-Handled Transuranic Waste Acceptance Criteria for the Waste Isolation Pilot Plant," Rev. 0, *DOE/WIPP-02-3122*, U.S. Department of Energy, Carlsbad Field Office, Carlsbad, New Mexico.

12.2 Hatayama, H.K., J.J. Chen, E.R. de Vera, R.D. Stephens, and D.L. Storm, "A Method for Determining the Compatibility of Hazardous Wastes," *EPA-600/2-80-076*, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1980.

12.3 U.S. Department of Energy (DOE), "Safety Analysis Report for the TRUPACT-II Shipping Package," and associated Contact Handled Transuranic Waste Authorized Methods for Payload Control (CH-TRAMPAC) and CH-TRU Payload Appendices, Current Revisions, U.S. Department of Energy Carlsbad Field Office, Carlsbad, New Mexico.

12.4 Duratek Federal Services, Richland, Washington, "RadCalc 3.0 Volume I: User's Manual," prepared for the National Transportation Program, U. S. Department of Energy, (November 2001).

12.5 FENDL/D Version 1, January 1992 is a decay data library for fusion and (other) applications. Summary documentation by A. B. Pashchenko. Index No. IAEA-NDS-167 in Index to the IAEA-NDS-Documentation Series.

12.6 Croff, A. G., 1980, A Revised and Updated Version of the Oak Ridge Isotope Generation and Depletion Code, ORNL-5621, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

12.7 Flaherty, J.E., A. Fujita, C.P. Deltete, and G.J. Quinn, 1986, "A Calculational Technique to Predict Combustible Gas Generation in Sealed Radioactive Waste Containers," GEND 041, EG&G Idaho, Inc., Idaho Falls, Idaho.

12.8 Breismeister, J.F., editor, "MCNP - A General Monte Carlo N-Particle Transport Code," Version 4a, Los Alamos National Laboratory Report LA 12625, Los Alamos, New Mexico.

Attachment A

Use of Dose-Dependent G Values for TRU Wastes

A.1.0 BACKGROUND

This attachment describes controlled studies and experiments that quantify the reduction in the rate of hydrogen gas generation (G value) over time based on the total dose received by the target matrix. Over time and with constant exposure to radiation, hydrogen is removed from the hydrogenous waste or packaging material (the matrix), thus decreasing the number of hydrogen bonds available for further radiolytic breakdown (the matrix is depleted). Therefore, when the alpha-generating source is dispersed in the target matrix, it will affect only that portion of the target material that is present in a small spherical volume surrounding the source particle. As the amount of available hydrogen is reduced over time, the effective G value decreases with increasing dose toward a value that is defined as the "dose-dependent G value." This phenomenon of matrix depletion has been studied and observed in previous studies (see Appendix 3.3 of the CH-TRU Payload Appendices [Reference A.7.1]). A formal study was recently undertaken to quantify dose-dependent G values under strictly controlled conditions and evaluate their applicability to transuranic (TRU) wastes (Reference A.7.2). This appendix summarizes the results of this study and derives dose-dependent G values for TRU waste materials, as applicable.

A.2.0 OVERVIEW OF THE MATRIX DEPLETION PROGRAM

The Matrix Depletion Program (MDP), established as a joint venture by the U.S. Department of Energy (DOE) National TRU Waste Program and the DOE Mixed Waste Focus Area, is comprised of the following elements:

1. Laboratory experiments for the assessment of effective G values as a function of dose for matrices expected in contact-handled (CH)-TRU wastes (polyethylene, polyvinyl chloride, cellulose, etc.), as well as an assessment of the impact of other variables (isotope, temperature, etc.) on the dose-dependent G values.

2. Measurements of effective G values and hydrogen concentrations in real waste and comparisons with dose-dependent G values.

3. Analysis to calculate effective G values from fundamental nuclear and molecular mechanisms.

A total of 60 one-liter test cylinders containing the simulated TRU waste materials were used, with two replicates for each test. Solid waste matrices (plastics and cellulose) were prepared by sprinkling the radioactive isotope powders over the matrix, folding the matrix over the contaminated surfaces, securing them, and placing them in test cylinders. Solidified waste matrices (cement) were mixed with a solution of dissolved plutonium oxide, water, and sodium hydroxide to adjust the pH. The test cylinders were connected to measurement devices that facilitated sampling of generated gases and quantifying the gas generation over time. The entire test apparatus was controlled by a personal computer through LABVIEW software.

All activities of the MDP were performed under a documented quality assurance (QA) program that specified the performance-based QA/quality control requirements for all aspects of the program (Reference A.7.3). The experiments under the MDP were designed using an U.S. Environmental Protection Agency established procedure to formulate data quality objectives. QA objectives for the MDP were defined in terms of precision, accuracy, representativeness, completeness, and comparability. All data were validated and verified pursuant to the performance objectives of the program. The MDP was run for a duration of approximately three years.

A.3.0 RESULTS AND CONCLUSIONS FROM THE MDP

Results from the MDP are described in detail in the MDP final report (Reference A.7.2) and are summarized in Table A-1 in terms of the dose-dependent G values for each matrix tested.

For all matrices, these dose-dependent G values were achieved within a maximum dose of 0.006 watt*year (product of watts times years). For example, for a waste container with a watt loading of 0.1 watt, the dose-dependent G value shown in Table A-1 would be reached after 0.06 years or 22 days. The lower the watt loading, the longer it would take for the watt*year criteria to be satisfied and the dose-dependent G value to be applicable.

Table A-1. Experimental Dose-Dependent G Values

Matrix	**Current Waste Material Type G Value**	**Number of Observations**	**Mean**	**Standard Deviation**	**95% Upper Tolerance Limit**
Cement	1.3	202	0.25	0.18	0.58
Dry Cellulose	3.4	302	0.27	0.18	0.59
Polyethylene	3.4	186	0.23	0.22	0.64
Polyvinyl Chloride	3.4	99	0.14	0.19	0.50
Wet Cellulose	3.4	276	0.44	0.36	1.09

Source: Reference A.7.1.

The following conclusions can be drawn from the results of the MDP:

- Increasing dose (product of the decay heat loading and elapsed time) decreases the effective G value for hydrogen due to depletion of the matrix in the vicinity of the alpha-emitting radioactive source particle. The lower G value, called the "dose-dependent G value," is applicable after a dose of 0.006 watt*years.

- As with initial G values, the dose-dependent G values are a function of the waste matrix.

- Dose-dependent G values for wet cellulosics were higher than those for dry cellulosics because of the presence of water.

- The dose-dependent G values were independent of temperature based on testing performed at room temperature and at 140°F.

- Experiments performed with different particle sizes show that while initial G values could be higher for smaller particle sizes, the dose-dependent G values for all particle sizes tested are bounded by the values shown in Table A-1.

- Previous experiments that included agitation of cylinders similar to those used in the MDP indicated that agitation did not affect dose-dependent G values (See Section A.4.0).

- Isotopic composition did not have a significant impact on the dose-dependent G values based on experiments performed with two different isotopes of Pu (^{238}Pu and ^{239}Pu).

Data from actual CH-TRU waste containers at the Rocky Flats Environmental Technology Site and the Idaho National Engineering and Environmental Laboratory show that even when compared to the mean dose-dependent G values from the matrix depletion experiments, G values from real waste containers are lower. Theoretical analysis, using nuclear and molecular level mechanisms, also shows that hydrogen generation from radiolysis and matrix depletion is consistent with the experimental results from the MDP.

A.4.0 EFFECTS OF AGITATION ON DOSE-DEPENDENT G VALUES

The effects of agitation on dose-dependent G values have been evaluated by previous studies at both the laboratory-scale and drum-scale levels, and agitation has been found to have no impact on dose-dependent gas generation rates. Agitation could occur under transportation conditions but, as shown below, does not cause redistribution of the radionuclides to a nondepleted portion of the waste matrix and therefore does not cause an increase in the dose-dependent G values as shown in this section.

The earliest study of the effects of agitation on gas generation rates was performed by Zerwekh at the Los Alamos National Laboratory (LANL) in the late 1970s (Reference A.7.4). Zerwekh prepared an experimental array of 300-cm^3 stainless steel pressure cylinders, each loaded with 52.5 grams of a single or a combination of TRU waste matrix materials. Materials tested included cellulosics, polyethylene (PE) (low-density) bags, PE (high-density) drum liner material, and other typical TRU waste material. Net gas G values as a function of elapsed time were derived for each of the test cylinders and showed the characteristic decrease in G value with dose. Thorough mechanical shaking of two of the cylinders on two different occasions did not affect the rate of gas generation (Reference A.7.4).

In a second study, researchers at LANL retrieved six drums of ^{238}Pu contaminated waste from storage to study gas generation (Reference A.7.5). The wastes were contained in 30-gallon drums and consisted of either mixed cellulosic wastes or mixed combustible wastes. The drums ranged in age from four to ten years. Two of the drums containing mixed combustible wastes were tumbled end over end in a drum tumbler for four hours (Reference A.7.5). The researchers also reported G values for three drums of newly generated waste that were previously characterized. All six retrieved drums had measured G values that were lower than those measured for newly generated drums. The researchers concluded that the retrieved drums' effective hydrogen G values corroborate the matrix depletion observed for the laboratory-scale experiments in Reference A.7.4. Also, because of the vigorous nature of the agitation experienced by two of the four-year-old drums, the researchers concluded that radionuclide redistribution does not occur under transportation conditions (Reference A.7.5).

More recently, experiments on alpha radiolysis were conducted at LANL by Smith et al. (Reference A.7.6) to determine radionuclide loading limits for safe on-site storage of containers at LANL. Simulated TRU waste matrices in the form of cellulose (cheesecloth and computer paper) and PE (bottle and bag material forms) were contaminated with pre-weighed amounts of $^{238}PuO_2$ powder. The first PE experiment (referred to as PE test cylinder 1) used a PE bottle to allow any potential later redistribution of the radionuclide particles to fresh matrix surfaces. The radionuclide powder was poured into the bottle, which was sealed and gently rolled to allow contamination of the sides of the bottle. The bottle was returned to an upright position and the lid was punctured with an approximately 0.5-inch diameter hole to allow free movement of generated gas from the bottle to the test canister. It was noted that the $^{238}PuO_2$ powder adhered to the walls of the bottle and very little, if any, collected at the bottom. The remaining five test sample matrices were prepared by uniformly sprinkling the powder across a letter-sized sheet of the waste matrix, folding the sheet in toward the center from each end, and finally rolling each sheet into a cylindrical shape of about 2 by 4 inches. The six test matrices were placed inside six cylindrical, 2.06 liter stainless steel sealed canisters. Gas samples were extracted periodically and analyzed by mass spectrometry.

The first test canister for each waste material was subjected to vigorous dropping, rolling several times, and shaking on day 188 to simulate drum handling and transportation that could result in redistribution of the $^{238}PuO_2$ to fresh nondepleted portions of the waste matrix. Any agitation effects were expected to be most pronounced for the test canister containing the PE bottle in PE test cylinder 1, because some aggregation of the powder at the bottom of the bottle was expected. However, no change in the effective hydrogen G value was observed for either the cellulose or PE test canisters.

In summary, three separate studies have investigated the ability of agitation to redistribute radionuclide particles to nondepleted surfaces of TRU waste matrices. All three studies conclusively showed that the dose-dependent G values are not impacted by agitation during transportation. Application of dose-dependent effective G values is discussed in Section A.5.0.

A.5.0 APPLICATION OF DOSE-DEPENDENT G VALUES TO CH- and RH-TRU WASTES

Application to CH-TRU dose-dependent G values, based on the results of the MDP, are applicable to solid organic and solid inorganic CH-TRU waste material types. Solidified organic and inorganic solid wastes will be governed by the initial G values under all conditions because the solidified, aqueous nature of these waste forms, in theory, precludes observation of matrix depletion (as the matrix near the Pu is depleted, water can move to replace the depleted matrix). The watt*year criteria used to apply dose-dependent G values is twice the highest value recorded in the experiments. The dose-dependent G values chosen for the TRU waste materials are the 95% upper tolerance limit values shown in Table A-1. The application of dose-dependent G values to the waste types is as follows:

- Solid Inorganic Waste: Dose-dependent G value (H_2) for containers meeting a watt*year criteria of 0.012 is governed by assuming polyethylene as the packaging material, with a G value (H_2) of 0.64.

- Solid Organic Waste: Dose-dependent G value for containers meeting a watt*year criteria of 0.012 is governed by wet cellulosic materials in the waste, with a G value (H_2) of 1.09.

As can be seen from Table A-1, the above dose-dependent G values represent conservative values that are more than two times the mean value from the experiments.

The phenomenon of matrix depletion primarily stems from the nature of the waste matrix and the type of penetrating radiation; thus, if the waste matrix and radiation type are properly accounted for, G value results obtained for CH-TRU waste can be applicable to RH-TRU waste as well.

With respect to waste matrix, both CH- and RH-TRU waste are characterized by a large percentage of the materials shown in Table A-1. Thus, the required level of conservatism will be attained by assuming that the waste is comprised of the matrix with the greatest associated G value.

With respect to radiation type, both CH- and RH-TRU waste are characterized by large amounts of alpha and beta emitters; the primary difference between the two waste forms is the noticeable presence of gamma emitters in RH-TRU waste. Thus, while the G value for CH-TRU waste is dependent primarily on the emitted decay heat (since most or all of the alpha and beta radiation is absorbed by the waste matrix and contributes to hydrogen gas generation), the G value for RH-TRU waste is dependent on the actual fraction of the decay heat that is absorbed by the waste matrix.

Since the results of the MDP are applicable only to alpha and beta radiation, while gamma radiation effects were not quantified, G values for RH-TRU waste can be separated into those for alpha, beta, and gamma radiation and treated accordingly. Thus, RH-TRU waste G values for alpha and beta radiation can be treated as being dose-dependent and the lower "dose-dependent G value" used after a dose of

0.012 watt*years (twice the highest value recorded in the experiments), while G values for gamma radiation can conservatively be treated as not being dose-dependent and the initial G value used.

A.6.0 COMPLIANCE WITH WATT*YEAR CRITERIA

For RH-TRU waste, content codes using dose-dependent G values to obtain maximum allowable decay heat limits are required to comply with the watt*year criteria of 0.012 watt*years. Demonstration of compliance with the 0.012 watt*year criteria is carried out as follows:

1. Determine maximum allowable decay heat (Q) using the a and ß dose-dependent G values and non-dose-dependent G values for γ radiation.
2. Determine decay heat limit that excludes the gamma radiation contribution (Q_{allow}) as a function of the maximum allowable hydrogen gas generation rate (Cg) and bounding G value for the content code as:

$$Q_{allow} = \frac{Cg \ * \ N_A \ * \ 1.602(10)^{-19} \ watt\text{-}\sec/eV}{G}$$

where,

Cg = Maximum allowable hydrogen gas generation rate limit obtained using the methodology described in site-specific sub tier appendices.

G = Bounding G value (molecules of hydrogen formed/100 electron volts [eV] emitted energy)

N_A = Avogadro's number ($6.023\text{x}10^{23}$ molecules/mole).

3. Determine the Q_{allow}/Q ratio, which represents the minimum fraction of the total container decay heat that excludes the gamma radiation contribution.
4. Calculate the decay heat value for a container ($Q_{watt*yr}$) for watt*year compliance as:

$$Q_{watt*yr} = \frac{Q_{allow}}{Q} * Q_{actual}$$

where, Q_{actual}, is the actual decay heat value for the container.

5. The watt*year for the payload is calculated as $Q_{watt*yr}$ times the elapsed time, and this value is compared to the 0.012 watt*year limit. The elapsed time is the time elapsed between the time of generation of the payload and the time of sealing of the payload.

A.7.0 REFERENCES

A.7.1. U.S. Department of Energy (DOE), "Safety Analysis Report for the TRUPACT-II Shipping Package," and associated Contact Handled Transuranic Waste Authorized Methods for Payload Control (CH-TRAMPAC) and CH-TRU Payload Appendices, Current Revisions, U.S. Department of Energy Carlsbad Field Office, Carlsbad, New Mexico.

A.7.2. Idaho National Engineering and Environmental Laboratory, "TRUPACT-II Matrix Depletion Program Final Report," *INEL/EXT-98-00987*, Rev. 1, prepared for the U.S. Department of Energy, Idaho Operations Office, Idaho Falls, Idaho (1999).

A.7.3. Connolly, M.J., G.R. Hayes, T.J. Krause, and J.S. Burt, "TRUPACT-II Matrix Depletion Quality Assurance Program Plan," INEL95/0361, Rev. 1, Idaho National Engineering and Environmental Laboratory, Idaho Falls, Idaho (1997).

A.7.4. Zerwekh, A. "Gas Generation from Radiolytic Attack of TRU-Contaminated Hydrogenous Waste." LA-7674-MS, Los Alamos National Laboratory, Los Alamos, New Mexico, 1979.

A.7.5. Zerwekh, A., J. Warren, and S. Kosiewicz. "The Effect of Vibration on Alpha Radiolysis of Transuranic (TRU) Waste." Proceedings of Symposium on Waste Management, Tucson, Arizona, 1993.

A.7.6. Smith, M.C., E.L. Callis, J.H. Cappis, E.M. Foltyn, R.S. Marshall, and J. Espinoza. "Alpha Radiolytic Gas Generation: Determination of Effective G-values." Benchmark Environmental Corporation, Albuquerque, New Mexico, 1997.

Attachment B

Chemical Compatibility of TRU Waste Content Codes

B.1.0 INTRODUCTION

This attachment describes the method used for demonstrating chemical compatibility in a given payload container, within a given waste stream/content code, and among content codes for the -10-160B Cask payload. The chemical compatibility analyses cover normal conditions of transport as well as hypothetical accident conditions.

B.2.0 METHODOLOGY FOR CHEMICAL COMPATIBILITY ANALYSES

The chemical compatibility analysis was performed using the methods described in the EPA document "A Method for Determining the Compatibility of Hazardous Wastes" (Reference B.3.1).

Waste streams/content codes are classified as potentially chemically "incompatible" if the potential exists for any of the following reactions:

- explosion
- heat generation
- gas generation (flammable gases)
- pressure build up (nonflammable gases)
- toxic by-product generation
- fire
- violent polymerization
- solubilization of toxic substances.

Note: Solubilization of toxic substances and toxic byproduct generation are not directly a concern for transportation of waste in the 10-160B Cask payload but have been included for completeness.

Each generator and storage site has produced a comprehensive list of chemicals present in an approved content code. These chemical components are determined by examining the process technology, and by comprehensive analyses of the process knowledge. Under this system, all chemical inputs into the system are accounted for, even though all of these components may not be a final part of the waste. For example, generator sites might include both acids and bases in their lists, even though the two groups have been neutralized prior to placement in a payload container.

A list of chemicals/materials that may be present in TRU waste in concentrations greater than or equal to 1 percent by weight was compiled based on process knowledge from the potential waste shipping sites, as shown in Table B-1. The chemical compatibility analyses for the 10-160B Cask payload are then based on this table.

Although Table B-1 only identifies chemicals/materials in TRU waste in concentrations greater than or equal to 1 percent by weight, interactions involving compounds present in trace quantities (<1 percent by weight) do not pose an incompatibility problem for the following reasons:

- Most trace chemicals reported by the sites are in concentrations well below the trace limit of 1 weight percent.

- The trace chemicals are usually dispersed in the waste, which further dilutes concentrations of these materials.

- Total trace chemicals within a payload container are limited to less than 5 weight percent.

Table B-1
Table of Allowable Materials for TRU Waste[a]

Absorbent polymers, organic
Absorbents/adsorbents (e.g., Celite®, diatomaceous earth, diatomite, Florco®, Oil-Dri®, perlite, vermiculite)
Acids (inorganic and organic)
Alcohols (e.g., butanol, ethanol, isopropanol, methanol)
Alumina cement
Aquaset® products (for aqueous solutions)
Aqueous sludges or solutions
Asbestos
Ash (e.g., ash bottoms, fly ash, soot)
Asphalt
Bakelite® b
Batteries, dry (e.g., flashlight)
Caustics
Cellulose (e.g., Benelex®, cotton Conwed®, paper, rags, rayon, wood)
Cellulose acetate butyrate
Cellulose propionate
Ceramics (e.g., molds and crucibles)
Chlorinated polyether
Clays (e.g., bentonite)
Concrete
Detergent, solid (e.g., emulsifiers, surfactants)
Envirostone® (no organic emulsifiers allowed)
Esters (e.g., ethyl acetate, polyethylene glycol ester)
Ethers (e.g., ethyl ether)
Fiberglass (inorganic and organic)
Filter media (inorganic and organic)
Firebrick
Glass (e.g., borosilicate glass, labware, leaded glass, Raschig rings)
Graphite (e.g., molds and crucibles)
Greases, commercial brands
Grit
Halogenated organics (e.g., bromoform; carbon tetrachloride; chlorobenzene; chloroform; 1,1-dichloroethane; 1,2-dichloroethane; 1,1-dichloroethylene; cis-1,2-dichloroethylene; methylene chloride; 1,1,2,2-tetrachloroethane; tetrachloroethylene; 1,1,1-trichloroethane; 1,1,2-trichloroethane; trichloroethylene; 1,1,2-trichloro-1,2,2-trifluoroethane)
Heel (e.g., ash heel; soot heel; firebrick heel; sand, slag, and crucible heel)
Hydrocarbons, aliphatic (e.g., cyclohexane, n-paraffin hydrocarbons)
Hydrocarbons, aromatic (e.g., benzene; ethyl benzene; toluene; 1,2,4-trimethylbenzene; 1,3,5-trimethylbenzene; xylene)
Insulation (inorganic and organic)
Ketones (e.g., acetone, methyl ethyl ketone, methyl isobutyl ketone)
Leaded rubber (e.g., gloves, aprons, sheet material)
Leather
Magnesia cement (e.g., Ramcote® cement)
Magnesium alloy
Metal hydroxides
Metal oxides (e.g., slag)

Table B-1
Table of Allowable Materials for TRU Waste[a]
(Continued)

Metals (e.g., aluminum, cadmium, copper, steel, tantalum, tungsten, zinc)
Nitrates (e.g., ammonium nitrate, sodium nitrate)
Oil (e.g., petroleum, mineral)
Organophosphates (e.g., tributyl phosphate, dibutyl phosphate, monobutyl phosphite)
Paint, dry (e.g., floor/wall paint, ALARA)
Petroset® products (for aqueous solutions)
Plastics [e.g., polycarbonate, polyethylene, polymethyl methacrylate (Plexiglas®, Lucite®), polysulfone, polytetrafluoroethylene (Teflon®), polyvinyl acetate, polyvinyl chloride (PVC), polyvinylidene chloride (saran)]
Polyamides (nylon)
Polychlorotrifluoroethylene (e.g., Kel-F®)
Polyesters (e.g., Dacron®, Mylar®)
Polyethylene glycol (e.g., Carbowax®)
Polyimides
Polyphenyl methacrylate
Polypropylene (e.g., Ful-Flo® filters)
Polyurethane
Polyvinyl alcohol
Portland cement
Resins (e.g., aniline-formaldehyde, melamine-formaldehyde, organic resins, phenol-formaldehyde, phenolic resins, urea-formaldehyde)
Rubber, natural or synthetic [e.g., chlorosulfonated polyethylene (Hypalon®), ethylene-propylene rubber, EPDM, polybutadiene, polychloroprene (neoprene), polyisobutylene, polyisoprene, polystyrene, rubber hydrochloride (pliofilm®)]
Salts (e.g., calcium chloride, calcium fluoride, sodium chloride)
Sand/soil (inorganic and organic)
Trioctyl phosphine oxide
Water
Waxes, commercial brands
Other inorganic materials

[a] Other chemicals or materials not identified in this table are allowed provided that they meet the requirements for trace constituents (less than one weight percent of the payload container individually; less than five weight percent of the payload container combined). All materials in the final waste form must be inert (nonreactive), be in a nonreactive form, or have been rendered nonreactive.

[b] Bakelite is a trademark for materials that can be composed of several different polymers, including polyethylene, polypropylene, epoxy, phenolic, polystyrene, phenoxy, perylene, polysulfone, ethylene copolymers, ABS, acrylics, and vinyl resins and compounds.

- Trace chemicals that might be incompatible with materials/chemicals in concentrations greater than or equal to 1 percent by weight would have reacted during the waste generating process prior to placement in payload containers.

- The waste is either solidified and immobilized (solidified materials) or present in bulk form as a solid (solid materials). In almost all cases, any possible reactions take place before the waste is generated in its final form.

Potential incompatibilities between the allowable materials/compounds listed in Table B-1 have been analyzed for the 10-160B payload. The analysis assigned EPA chemical reactivity group numbers and names to each allowable material. The reactivity group numbers were assigned based on information provided in Reference B.3.1. If the allowable material (or chemical) is a non-reactive inorganic material (not covered under the EPA reactivity group numbers), it was assigned a reactivity group number of "0" to reflect a complete analysis for all allowable materials (materials assigned a reactivity group number of "0" do not present a compatibility concern). The compiled list of allowable materials and assigned reactivity group numbers is provided in Attachment 1.0.

The list of allowable materials and assigned reactivity group numbers was sorted by reactivity group number and then condensed to form a list of the represented reactivity groups (Attachment 2.0).

Using the list of represented reactivity groups, a hazardous waste compatibility chart was generated. The chart, which is provided in Attachment 3.0, is a reduced version of the hazardous waste compatibility chart presented in Reference B.3.1. The chart summarizes the potential types of reactions possible between each of the reactivity groups represented in the list of allowable materials. The reaction codes and consequences of the reactions are specified for each combination of two reactivity groups.

Using the waste compatibility chart, a list of potential chemical incompatibilities in the TRU waste was generated. The list, which is presented in Attachment 4.0, also presents assessments of whether or not the reaction associated with each of the potential chemical incompatibilities will or will not occur. The results of the assessments indicated that no chemical incompatibilities will occur. Therefore, by precluding all potential incompatibilities, the chemicals/materials identified in Table B-1 are determined to be compatible for the 10-160B Cask payload.

Chemical lists provided for site-specific TRU waste content codes identified for shipment in the 10-160B Cask are a subset of Table B-1. Chemical incompatibilities therefore do not exist in and across these content codes. Only content codes with chemical lists that have been evaluated by this process and determined to be compatible shall be approved for shipment in the 10-160B Cask.

B.3.0 REFERENCES

B.3.1 Hatayama, H. K., Chen, J.J., de Vera, E.R., Stephens, R.D., Storm, D.L., "A Method for Determining the Compatibility of Hazardous Wastes," EPA-600/2-80-076, EPA, Cincinnati, Ohio, 1980.

Attachment 1.0

Lists of Allowable Materials and Associated Reactivity Groups

Lists of Allowable Materials and Associated Reactivity Groups		
Allowable Chemical/Material[a]	**Reactivity Group**[b]	
	Name	**Number**[c]
Absorbent polymers, organic	Combustible and flammable materials, miscellaneous	101
Absorbents/adsorbents (e.g., Celite®, diatomaceous earth, diatomite, Florco®, Oil-Dri®, perlite, vermiculite)	Other solidification materials and absorbents/adsorbents	0
Acids, inorganic	Acids, Mineral, Non-oxidizing	1
Acids, inorganic	Acids, Mineral, Oxidizing	2
Acids, organic	Acids, organic	3
Alcohols (e.g., butanol, ethanol, isopropanol, methanol)	Alcohols and Glycols	4
Alumina cement	Water reactive substance	107
Aquaset® products (for aqueous solutions)	Other solidification materials and absorbents/adsorbents	0
Aqueous sludges or solutions	Other solidification materials and absorbents/adsorbents	0
Asbestos	Other Inorganics (non-reactive)	0
Ash (e.g., ash bottoms, fly ash, soot)	Other Inorganics (non-reactive)	0
Asphalt	Combustible and flammable materials, miscellaneous	101
Bakelite®	Combustible and flammable materials, miscellaneous	101
Batteries, dry (e.g., flashlight)	Metals, alkali and alkaline earth, elemental and alloys	21
Caustics	Caustics	10
Cellulose (e.g., Benelex®, cotton Conwed®, paper, rags, rayon, wood)	Combustible and flammable materials, miscellaneous	101
Cellulose acetate butyrate	Polymerizable compounds	103
Cellulose propionate	Polymerizable compounds	103
Ceramics (e.g., molds and crucibles)	Other Inorganics (non-reactive)	0
Chlorinated polyether	Ethers	14
Clays (e.g., bentonite)	Other Inorganics (non-reactive)	0
Concrete	Other solidification materials and absorbents/adsorbents	0
Detergent, solid (e.g., emulsifiers, surfactants)	Esters	13
Detergent, solid (e.g., emulsifiers, surfactants)	Hydrocarbons, aromatic	16
Detergent, solid (e.g., emulsifiers, surfactants)	Hydrocarbons, aliphatic, unsaturated	28
Detergent, solid (e.g., emulsifiers, surfactants)	Organophosphates, phosphothioates, and phosphodithioates	32
Envirostone® (no organic emulsifiers allowed)	Other solidification materials and absorbents/adsorbents	0
Esters (e.g., ethyl acetate, polyethylene glycol ester)	Esters	13
Ethers (e.g., ethyl ether)	Ethers	14
Fiberglass, inorganic	Other Inorganics (non-reactive)	0

Lists of Allowable Materials and Associated Reactivity Groups		
	Reactivity Group[b]	
Allowable Chemical/Material[a]	Name	Number[c]
Fiberglass, organic	Combustible and flammable materials, miscellaneous	101
Filter media, inorganic	Other Inorganics (non-reactive)	0
Filter media, organic	Combustible and flammable materials, miscellaneous	101
Firebrick	Other Inorganics (non-reactive)	0
Glass (e.g., borosilicate glass, labware, leaded glass, Raschig rings)	Other Inorganics (non-reactive)	0
Graphite (e.g., molds and crucibles)	Other Inorganics (non-reactive)	0
Greases, commercial brands	Combustible and flammable materials, miscellaneous	101
Grit	Other Inorganics (non-reactive)	0
Halogenated organics (e.g., bromoform; carbon tetrachloride; chlorobenzene; chloroform; 1,1-dichloroethane; 1,2-dichloroethane; 1,1-dichloroethylene; cis-1,2-dichloroethylene; methylene chloride; 1,1,2,2-tetrachloroethane; tetrachloroethylene; 1,1,1-trichloroethane; 1,1,2-trichloroethane; trichloroethylene; 1,1,2-trichloro-1,2,2-trifluoroethane)	Halogenated Organics	17
Heel (e.g., ash heel; soot heel; firebrick heel; sand, slag, and crucible heel)	Other Inorganics (non-reactive)	0
Hydrocarbons, aliphatic (e.g., cyclohexane, n-paraffin hydrocarbons)	Hydrocarbon, aliphatic, unsaturated	28
Hydrocarbons, aliphatic (e.g., cyclohexane, n-paraffin hydrocarbons)	Hydrocarbon, aliphatic, saturated	29
Hydrocarbons, aromatic (e.g., benzene; ethyl benzene; toluene; 1,2,4-trimethylbenzene; 1,3,5-trimethylbenzene; xylene)	Hydrocarbons, aromatic	16
Insulation, inorganic	Other Inorganics (non-reactive)	0
Insulation, organic	Combustible and flammable materials, miscellaneous	101
Ketones (e.g., acetone, methyl ethyl ketone, methyl isobutyl ketone)	Ketones	19
Leaded rubber (e.g., gloves, aprons, sheet material)	Metals, Other elemental, and alloy, as sheets, rods, moldings, vapors, or sponges	23
Leaded rubber (e.g., gloves, aprons, sheet material)	Metals and metal compounds, toxic	24
Leaded rubber (e.g., gloves, aprons, sheet material)	Combustible and flammable materials, miscellaneous	101
Leather	Combustible and flammable materials, miscellaneous	101
Magnesia cement (e.g., Ramcote® cement)	Water reactive substance	107

Lists of Allowable Materials and Associated Reactivity Groups		
Allowable Chemical/Material[a]	**Reactivity Group**[b]	
	Name	**Number**[c]
Magnesium alloy	Metals, Other elemental, and alloy, as sheets, rods, moldings, vapors, or sponges	23
Metal hydroxides	Other Inorganics (non-reactive)	0
Metal oxides (e.g., slag)	Other Inorganics (non-reactive)	0
Metals (e.g., aluminum, cadmium, copper, steel, tantalum, tungsten, zinc)	Metals, alkali and alkaline earth, elemental	21
Metals (e.g., aluminum, cadmium, copper, steel, tantalum, tungsten, zinc)	Metals, Other elemental and alloy in the form of powders, vapors, or sponges	22
Metals (e.g., aluminum, cadmium, copper, steel, tantalum, tungsten, zinc)	Metals, Other elemental, and alloy, as sheets, rods, moldings, vapors, or sponges	23
Metals (e.g., aluminum, cadmium, copper, steel, tantalum, tungsten, zinc)	Metals and metal compounds, toxic	24
Metals (e.g., aluminum, cadmium, copper, steel, tantalum, tungsten, zinc)	Reducing agents, strong	105
Nitrates (e.g., ammonium nitrate, sodium nitrate)	Oxidizing Agents, Strong	104
Oil (e.g., petroleum, mineral)	Combustible and flammable materials, miscellaneous	101
Organophosphates (e.g., tributyl phosphate, dibutyl phosphate, monobutyl phosphite)	Organophosphates, phosphothioates, and phosphodithioates	32
Paint, dry (e.g., floor/wall paint, ALARA)	Combustible and flammable materials, miscellaneous	101
Petroset® products (for aqueous solutions)	Other solidification materials and absorbents/adsorbents	0
Plastics [e.g., polycarbonate, polyethylene, polymethyl methacrylate (Plexiglas®, Lucite®), polysulfone, polytetrafluoroethylene (Teflon®), polyvinyl acetate, polyvinyl chloride (PVC), polyvinylidene chloride (saran)]	Combustible and flammable materials, miscellaneous	101
Polyamides (nylon)	Amides	6
Polyamides (nylon)	Combustible and flammable materials, miscellaneous	101
Polychlorotrifluoroethylene (e.g., Kel-F®)	Combustible and flammable materials, miscellaneous	101
Polyesters (e.g., Dacron®, Mylar®)	Esters	13
Polyesters (e.g., Dacron®, Mylar®)	Combustible and flammable materials, miscellaneous	101
Polyethylene glycol (e.g., Carbowax®)	Alcohols and Glycols	4
Polyethylene glycol (e.g., Carbowax®)	Combustible and flammable materials, miscellaneous	101
Polyimides	Hydrocarbons, aromatic	16
Polyphenyl methacrylate	Combustible and flammable materials, miscellaneous	101

Lists of Allowable Materials and Associated Reactivity Groups		
	Reactivity Group[b]	
Allowable Chemical/Material[a]	**Name**	**Number[c]**
Polypropylene (e.g., Ful-Flo® filters)	Combustible and flammable materials, miscellaneous	101
Polyurethane	Combustible and flammable materials, miscellaneous	101
Polyvinyl alcohol	Alcohols and Glycols	4
Portland cement	Caustics	10
Portland cement	Water reactive substance	107
Resins (e.g., aniline-formaldehyde, melamine-formaldehyde, organic resins, phenol-formaldehyde, phenolic resins, urea-formaldehyde)	Aldehydes	5
Resins (e.g., aniline-formaldehyde, melamine-formaldehyde, organic resins, phenol-formaldehyde, phenolic resins, urea-formaldehyde)	Phenols and Creosols	31
Rubber, natural or synthetic [e.g., chlorosulfonated polyethylene (Hypalon®), ethylene-propylene rubber, EPDM, polybutadiene, polychloroprene (neoprene), polyisobutylene, polyisoprene, polystyrene, rubber hydrochloride (pliofilm®)]	Combustible and flammable materials, miscellaneous	101
Salts (e.g., calcium chloride, calcium fluoride, sodium chloride)	Other Inorganics (non-reactive)	0
Salts (e.g., calcium chloride, calcium fluoride, sodium chloride)	Fluorides, inorganic	15
Sand/soil, inorganic	Other Inorganics (non-reactive)	0
Sand/soil, organic	Combustible and flammable materials, miscellaneous	101
Trioctyl phosphine oxide	Organophosphates, phosphothioates, and phosphodithioates	32
Water	Water and Mixtures containing water	106
Waxes, commercial brands	Combustible and flammable materials, miscellaneous	101
Other inorganic materials	Other Inorganics (non-reactive)	0

[a] Chemicals in ***bold italic*** have been assigned to more than one reactivity group.
[b] Reactivity group from Hatayama, H.K., J. J. Chen, E.R. deVera, R.D. Stephens, and D.L. Storm, "A Method for Determining the Compatibility of Hazardous Wastes," EPA-600/2-80-076, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1980.
[c] Non-reactive inorganic materials or chemicals are assigned a reactivity group number of "0."

Attachment 2.0

Lists of Unique Reactivity Group Numbers in Lists of Allowable Materials

List of Unique Reactivity Group Numbers in Lists of Allowable Materials

Allowable Chemical/Material[a]	Reactivity Group[b]	
	Name	Number
Absorbents/adsorbents (e.g., Celite®, diatomaceous earth, diatomite, Florco®, Oil-Dri®, perlite, vermiculite)	Other solidification materials and absorbents/adsorbents	0
Acids, inorganic	Acids, Mineral, Non-oxidizing	1
Acids, inorganic	Acids, Mineral, Oxidizing	2
Acids, solid, organic	Acids, Organic	3
Polyethylene glycol (e.g., Carbowax®)	Alcohols and Glycols	4
Resins (e.g., aniline-formaldehyde, melamine-formaldehyde, organic resins, phenol-formaldehyde, phenolic resins, urea-formaldehyde)	Aldehydes	5
Polyamides (nylon)	Amides	6
Portland cement	Caustics	10
Esters (e.g., ethyl acetate, polyethylene glycol ester)	Esters	13
Ethers (e.g., ethyl ether)	Ethers	14
Salts (e.g., calcium chloride, calcium fluoride, sodium chloride)	Fluorides, inorganic	15
Hydrocarbons, aromatic (e.g., benzene; ethyl benzene; toluene; 1,2,4-trimethylbenzene; 1,3,5-trimethylbenzene; xylene)	Hydrocarbons, aromatic	16
Halogenated organics (e.g., bromoform; carbon tetrachloride; chlorobenzene; chloroform; 1,1-dichloroethane; 1,2-dichloroethane; 1,1-dichloroethylene; cis-1,2-dichloroethylene; methylene chloride; 1,1,2,2-tetrachloroethane; tetrachloroethylene; 1,1,1-trichloroethane; 1,1,2-trichloroethane; trichloroethylene; 1,1,2-trichloro-1,2,2-trifluoroethane)	Halogenated Organics	17
Ketones (e.g., acetone, methyl ethyl ketone, methyl isobutyl ketone)	Ketones	19
Batteries, dry (e.g., flashlight)	Metals, alkali and alkaline earth, elemental and alloys	21
Metals (e.g., aluminum, cadmium, copper, steel, tantalum, tungsten, zinc)	Metals, Other elemental and alloy in the form of powders, vapors, or sponges	22
Metals (e.g., aluminum, cadmium, copper, steel, tantalum, tungsten, zinc)	Metals, Other elemental, and alloy, as sheets, rods, moldings, vapors, or sponges	23
Leaded rubber (e.g., gloves, aprons, sheet material)	Metals and metal compounds, toxic	24
Hydrocarbons, aliphatic (e.g., cyclohexane, n-paraffin hydrocarbons)	Hydrocarbon, aliphatic, unsaturated	28
Hydrocarbons, aliphatic (e.g., cyclohexane, n-paraffin hydrocarbons)	Hydrocarbon, aliphatic, saturated	29

List of Unique Reactivity Group Numbers in Lists of Allowable Materials

Allowable Chemical/Material[a]	Reactivity Group[b]	
	Name	Number
Resins (e.g., aniline-formaldehyde, melamine-formaldehyde, organic resins, phenol-formaldehyde, phenolic resins, urea-formaldehyde)	Phenols and Creosols	31
Organophosphates (e.g., tributyl phosphate, dibutyl phosphate, monobutyl phosphite)	Organophosphates, phosphothioates, and phosphodithioates	32
Asphalt	Combustible and flammable materials, miscellaneous	101
Cellulose acetate butyrate	Polymerizable compounds	103
Nitrates (e.g., ammonium nitrate, sodium nitrate)	Oxidizing Agents, Strong	104
Metals (e.g., aluminum, cadmium, copper, steel, tantalum, tungsten, zinc)	Reducing agents, strong	105
Aqueous solutions/water	Water and Mixtures containing water	106
Portland cement	Water reactive substances	107

[a] Chemicals in ***bold italic*** have been assigned to more than one reactivity group.

[b] Reactivity group from Hatayama, H.K., J.J. Chen, E.R. deVera, R.D. Stephens, and D.L. Storm, "A Method for Determining the Compatibility of Hazardous Wastes," EPA-600/2-80-076, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1980.

Attachment 3.0

Waste Chemical Compatibility Chart

Hazardous Waste Chemical Compatibility Chart

Group No.	Reactivity Group Name																											
1	Acids, Mineral, Non-Oxidizing	1																										
2	Acids, Mineral, Oxidizing		2																									
3	Acids, Organic		G, H	3																								
4	Alcohols and Glycols	H	H, F	H, P	4																							
5	Aldehydes	H, P	H, F	H, P		5																						
6	Amides	H	H, GT				6																					
10	Caustics	H	H	H		H		10																				
13	Esters	H	H, F					H	13																			
14	Ethers	H	H, F							14																		
15	Fluorides, Inorganic	GT	GT	GT							15																	
16	Hydrocarbons, Aromatic		H, F									16																
17	Halogenated Organics	H, GT	H, GT, P					H, GF					17															
19	Ketones	H	H, F					H						19														
21	Metals, Alkali and Alkaline Earth, Elemental	GF, H, F	GF, H, F	GF, H, F	GF, H, F	GF, H, F	GF, H	GF, H	GF, H						21													
22	Metals, Other Elemental Alloys as Powders, Vapors, or Sponges	GF, H, F	GF, H, F	GF				GF, H					H, E			22												
23	Metals, Other Elemental Alloys as Sheets, Rods; Moldings, Etc.	GF, H, F	GF, H, F										H, F				23											
24	Metals and Metal Compounds, Toxic	S	S	S			S	S										24										
28	Hydrocarbons, Aliphatic, Unsaturated	H	H, F			H										H, E			28									
29	Hydrocarbons, Aliphatic, Saturated		H, F																	29								
31	Phenols and Cresols	H	H, F												GF, H						31							
32	Organophosphates,Phosphothioates, Phosphodithioates	GT, H	GT, H					H, E							H							32						
101	Combustible and Flammable Materials, Miscellaneous	H, G	GT, H, F												H, G, F								101					
103	Polymerizable Compounds	P, H	P, H	P, H				P, H							P, H	P, H	P, H	P, H			P, H			103				
104	Oxidizing Agents, Strong	GT, H		GT, H	H, F	H, F	GT, H, F		H, F	H, F		H, F	GT, H	H, F	H, F, E	H, F, E	H, F		H, F	H, F	H, F	GT, H, F	H, G, F	GT, H, F	104			
105	Reducing Agents, Strong	GF, H	GT, H, F	GF, H	GF, H, F	GF, H, F	GF, H		H, F				H, E	GF, H							Gf, H	GF, GT	GF, H	GF, H, P	H, F, E	105		
106	Water and Mixtures Containing Water	H	H												GF, H	GF, H		S								GF, GT	106	
107	Water Reactive Substances	E	X	T	R	E	M		A	C	T	I	V	!	D	O		N	M	I	!	!						107
Reactivity Group No.		1	2	3	4	5	6	10	13	14	15	16	17	19	21	22	23	24	28	29	31	32	101	103	104	105	106	107

Reactivity Code	Consequence
E	Explosion
F	Fire
G	Innocuous and Non-Flammable Gas Generation
GF	Flammable Gas Generation
GT	Toxic Gas Generation
H	Heat Generation
P	Violent Polymerazation
S	Solubilization of Toxic Substance

Source: Hatayama, H.K.,J.J. Chen, E.R. deVera, R.D. Stephens, and D.L.Strom, "A Method for Determining the Compatibility of Hazardous Wastes'" EPA-600/2-80-076, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1980

Attachment 4.0

Potential Chemical Incompatibilities

Potential Chemical Incompatibilities			
Combination of Reactivity Groups		Reaction Result (A x B)	Explanation of Potential Incompatibility
Group A	Group B		
1	4	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	5	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	5	Violent Polymerization	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	6	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	10	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; Bases/caustic materials are neutralized and solidified/immobilized prior to shipping
1	13	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	14	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	15	Toxic Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	17	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	17	Toxic Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	19	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	21	Flammable Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	21	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	21	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	22	Flammable Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	22	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	22	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	23	Flammable Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	23	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	23	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	24	Solubilization of Toxic Substances	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping Additionally, any solubilization of toxic substances

Potential Chemical Incompatibilities			
Combination of Reactivity Groups		**Reaction Result (A x B)**	**Explanation of Potential Incompatibility**
Group A	**Group B**		
			will not affect transportation of wastes.
1	28	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	31	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	32	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	32	Toxic Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	101	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	101	Innocuous and Non-Flammable Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	103	Violent Polymerization	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	103	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
1	104	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
1	104	Toxic Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
1	105	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
1	105	Flammable Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
1	106	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; free liquid content is limited to less than 1% of waste volume
1	107	Highly Reactive	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.

Potential Chemical Incompatibilities			
Combination of Reactivity Groups		**Reaction Result (A x B)**	**Explanation of Potential Incompatibility**
Group A	**Group B**		
2	3	Innocuous and Non-Flammable Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	3	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	4	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	4	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	5	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	5	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	6	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	6	Toxic Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	10	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; Bases/caustic materials are neutralized and solidified/immobilized prior to shipping
2	13	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	13	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	14	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	14	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	15	Toxic Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	16	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	16	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	17	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	17	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	17	Toxic Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	19	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	19	Fire	Reaction will not occur – Acids are neutralized and

Potential Chemical Incompatibilities			
Combination of Reactivity Groups		Reaction Result (A x B)	Explanation of Potential Incompatibility
Group A	Group B		
			solidified/immobilized prior to shipping
2	21	Flammable Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	21	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	21	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	22	Flammable Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	22	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	22	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	23	Flammable Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	23	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	23	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	24	Solubilization of Toxic Substances	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping Additionally, any solubilization of toxic substances will not affect transportation of wastes.
2	28	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	28	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	29	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	29	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	31	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	31	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	32	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	32	Toxic Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	101	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	101	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	101	Toxic Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping

Potential Chemical Incompatibilities			
Combination of Reactivity Groups		Reaction Result (A x B)	Explanation of Potential Incompatibility
Group A	Group B		
2	103	Violent Polymerization	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	103	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
2	105	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
2	105	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
2	105	Toxic Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
2	106	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; free liquid content is limited to less than 1% of waste volume
2	107	Highly Reactive	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
3	4	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
3	4	Violent Polymerization	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
3	5	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
3	5	Violent Polymerization	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
3	10	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; Bases/caustic materials are neutralized and solidified/immobilized prior to shipping
3	15	Toxic Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
3	21	Flammable Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
3	21	Heat Generation	Reaction will not occur – Acids are neutralized and

Potential Chemical Incompatibilities			
Combination of Reactivity Groups		**Reaction Result (A x B)**	**Explanation of Potential Incompatibility**
Group A	**Group B**		
			solidified/immobilized prior to shipping
3	21	Fire	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
3	22	Flammable Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
3	24	Solubilization of Toxic Substances	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping Additionally, any solubilization of toxic substances will not affect transportation of wastes.
3	103	Violent Polymerization	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
3	103	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping
3	104	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
3	104	Toxic Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
3	105	Heat Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
3	105	Flammable Gas Generation	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
3	107	Highly Reactive	Reaction will not occur – Acids are neutralized and solidified/immobilized prior to shipping; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
4	21	Flammable Gas Generation	Reaction will not occur – Alcohols and Glycols are solidified/immobilized prior to shipping
4	21	Heat Generation	Reaction will not occur – Alcohols and Glycols are solidified/immobilized prior to shipping
4	21	Fire	Reaction will not occur – Alcohols and Glycols are solidified/immobilized prior to shipping
4	104	Heat Generation	Reaction will not occur – Alcohols and Glycols are

Potential Chemical Incompatibilities

Combination of Reactivity Groups		Reaction Result (A x B)	Explanation of Potential Incompatibility
Group A	Group B		
			solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
4	104	Fire	Reaction will not occur – Alcohols and Glycols are solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
4	105	Heat Generation	Reaction will not occur – Alcohols and Glycols are solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
4	105	Flammable Gas Generation	Reaction will not occur – Alcohols and Glycols are solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
4	105	Fire	Reaction will not occur – Alcohols and Glycols are solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
4	107	Highly Reactive	Reaction will not occur – Alcohols and Glycols are solidified/immobilized prior to shipping; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
5	10	Heat Generation	Reaction will not occur – Aldehydes are solidified/immobilized prior to shipping; bases/caustic materials are neutralized and solidified/immobilized prior to shipping
5	21	Flammable Gas Generation	Reaction will not occur – Aldehydes are solidified/immobilized prior to shipping
5	21	Heat Generation	Reaction will not occur – Aldehydes are solidified/immobilized prior to shipping
5	21	Fire	Reaction will not occur – Aldehydes are solidified/immobilized prior to shipping
5	28	Heat Generation	Reaction will not occur – Aldehydes are solidified/immobilized prior to shipping
5	104	Heat Generation	Reaction will not occur – Aldehydes are solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
5	104	Fire	Reaction will not occur – Aldehydes are

Potential Chemical Incompatibilities			
Combination of Reactivity Groups		Reaction Result (A x B)	Explanation of Potential Incompatibility
Group A	Group B		
			solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
5	105	Heat Generation	Reaction will not occur – Aldehydes are solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
5	105	Flammable Gas Generation	Reaction will not occur – Aldehydes are solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
5	105	Fire	Reaction will not occur – Aldehydes are solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
5	107	Highly Reactive	Reaction will not occur – Aldehydes are solidified/immobilized prior to shipping; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
6	17	Heat Generation	Reaction will not occur – Amides are solidified/immobilized prior to shipping
6	17	Toxic Gas Generation	Reaction will not occur – Amides are solidified/immobilized prior to shipping
6	21	Flammable Gas Generation	Reaction will not occur – Amides are solidified/immobilized prior to shipping
6	21	Heat Generation	Reaction will not occur – Amides are solidified/immobilized prior to shipping
6	24	Solubilization of Toxic Substances	Reaction will not occur – Amides are solidified/immobilized prior to shipping Additionally, any solubilization of toxic substances will not affect transportation of wastes.
6	104	Heat Generation	Reaction will not occur – Amides are solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
6	104	Fire	Reaction will not occur – Amides are solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.

Potential Chemical Incompatibilities			
Combination of Reactivity Groups		Reaction Result (A x B)	Explanation of Potential Incompatibility
Group A	Group B		
6	104	Toxic Gas Generation	Reaction will not occur – Amides are solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
6	105	Heat Generation	Reaction will not occur – Amides are solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
6	105	Flammable Gas Generation	Reaction will not occur – Amides are solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
6	107	Highly Reactive	Reaction will not occur – Amides are solidified/immobilized prior to shipping; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
10	13	Heat Generation	Reaction will not occur – Caustics/bases are neutralized and solidified/immobilized prior to shipping
10	17	Heat Generation	Reaction will not occur – Caustics/bases are neutralized and solidified/immobilized prior to shipping
10	19	Heat Generation	Reaction will not occur – Caustics/bases are neutralized and solidified/immobilized prior to shipping
10	21	Flammable Gas Generation	Reaction will not occur – Caustics/bases are neutralized and solidified/immobilized prior to shipping
10	21	Heat Generation	Reaction will not occur – Caustics/bases are neutralized and solidified/immobilized prior to shipping
10	22	Flammable Gas Generation	Reaction will not occur – Caustics/bases are neutralized and solidified/immobilized prior to shipping
10	22	Heat Generation	Reaction will not occur – Caustics/bases are neutralized and solidified/immobilized prior to shipping
10	23	Flammable Gas Generation	Reaction will not occur – Caustics/bases are neutralized and solidified/immobilized prior to shipping

Potential Chemical Incompatibilities			
Combination of Reactivity Groups		Reaction Result (A x B)	Explanation of Potential Incompatibility
Group A	Group B		
10	23	Heat Generation	Reaction will not occur – Caustics/bases are neutralized and solidified/immobilized prior to shipping
10	24	Solubilization of Toxic Substances	Reaction will not occur – Caustics/bases are neutralized and solidified/immobilized prior to shipping; Additionally, any solubilization of toxic substances will not affect transportation of wastes.
10	32	Heat Generation	Reaction will not occur – Caustics/bases are neutralized and solidified/immobilized prior to shipping
10	32	Explosion	Reaction will not occur – Caustics/bases are neutralized and solidified/immobilized prior to shipping
10	103	Violent Polymerization	Reaction will not occur – Caustics/bases are neutralized and solidified/immobilized prior to shipping
10	103	Heat Generation	Reaction will not occur – Caustics/bases are neutralized and solidified/immobilized prior to shipping
10	107	Highly Reactive	Reaction will not occur – Caustics/bases are neutralized and solidified/immobilized prior to shipping; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
13	21	Flammable Gas Generation	Reaction will not occur – Esters are solidified/immobilized prior to shipping
13	21	Heat Generation	Reaction will not occur – Esters are solidified/immobilized prior to shipping
13	104	Heat Generation	Reaction will not occur – Esters are solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
13	104	Fire	Reaction will not occur – Esters are solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
13	105	Heat Generation	Reaction will not occur – Esters are solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.

Potential Chemical Incompatibilities

Combination of Reactivity Groups		Reaction Result (A x B)	Explanation of Potential Incompatibility
Group A	Group B		
13	105	Fire	Reaction will not occur – Esters are solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
13	107	Highly Reactive	Reaction will not occur – Esters are solidified/immobilized prior to shipping; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
14	104	Heat Generation	Reaction will not occur – Ethers are solidified / immobilized prior to shipping. Oxidizing agents are reacted prior to being placed in the waste/shipped.
14	104	Fire	Reaction will not occur – Ethers are solidified / immobilized prior to shipping. Oxidizing agents are reacted prior to being placed in the waste/shipped.
14	107	Highly Reactive	Reaction will not occur – Ethers are solidified / immobilized prior to shipping. Free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
15	107	Highly Reactive	Reaction will not occur – Salts are reacted during use and processing; Free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
16	104	Heat Generation	Reaction will not occur – Aromatic hydrocarbons are solidified/immobilized prior to shipping. Oxidizing agents are reacted prior to being placed in the waste/shipped.
16	104	Fire	Reaction will not occur – Aromatic hydrocarbons are solidified/immobilized prior to shipping. Oxidizing agents are reacted prior to being placed in the waste/shipped.

Potential Chemical Incompatibilities			
Combination of Reactivity Groups		**Reaction Result (A x B)**	**Explanation of Potential Incompatibility**
Group A	**Group B**		
16	107	Highly Reactive	Reaction will not occur – Aromatic hydrocarbons are solidified/immobilized prior to shipping. Free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
17	21	Heat Generation	Reaction will not occur – Halogenated organics are solidified/immobilized prior to shipping
17	21	Explosion	Reaction will not occur – Halogenated organics are solidified/immobilized prior to shipping
17	22	Heat Generation	Reaction will not occur – Halogenated organics are solidified/immobilized prior to shipping
17	22	Explosion	Reaction will not occur – Halogenated organics are solidified/immobilized prior to shipping
17	23	Heat Generation	Reaction will not occur – Halogenated organics are solidified/immobilized prior to shipping
17	23	Fire	Reaction will not occur – Halogenated organics are solidified/immobilized prior to shipping
17	104	Heat Generation	Reaction will not occur – Halogenated organics are solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
17	104	Toxic Gas Generation	Reaction will not occur – Halogenated organics are solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
17	105	Heat Generation	Reaction will not occur – Halogenated organics are solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
17	105	Explosion	Reaction will not occur – Halogenated organics are solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.

Potential Chemical Incompatibilities			
Combination of Reactivity Groups		Reaction Result (A x B)	Explanation of Potential Incompatibility
Group A	Group B		
17	107	Highly Reactive	Reaction will not occur – Halogenated organics are solidified/immobilized prior to shipping; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
19	21	Flammable Gas Generation	Reaction will not occur – Ketones are solidified/immobilized prior to shipping
19	21	Heat Generation	Reaction will not occur – Ketones are solidified/immobilized prior to shipping
19	104	Heat Generation	Reaction will not occur –Ketones are solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
19	104	Fire	Reaction will not occur –Ketones are solidified/immobilized prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped.
19	105	Flammable Gas Generation	Reaction will not occur –Ketones are solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
19	105	Heat Generation	Reaction will not occur –Ketones are solidified/immobilized prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped.
19	107	Highly Reactive	Reaction will not occur – Ketones are solidified/immobilized prior to shipping; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
21	31	Flammable Gas Generation	Reaction will not occur – Phenols and Creosols are solidified/immobilized prior to shipping; metals are typically in oxide form
21	31	Heat Generation	Reaction will not occur – Phenols and Creosols are solidified/immobilized prior to shipping; metals are typically in oxide form
21	32	Heat Generation	Reaction will not occur – Organophosphates are

Potential Chemical Incompatibilities			
Combination of Reactivity Groups		**Reaction Result (A x B)**	**Explanation of Potential Incompatibility**
Group A	**Group B**		
			solidified/immobilized prior to shipping; metals are typically in oxide form
21	101	Heat Generation	Reaction will not occur – Combustible materials are dry; free liquid content is limited to less than 1% of waste volume; metals are typically in oxide form
21	101	Innocuous and Non-Flammable Gas Generation	Reaction will not occur – Combustible materials are dry; free liquid content is limited to less than 1% of waste volume; metals are typically in oxide form
21	101	Fire	Reaction will not occur – Combustible materials are dry; free liquid content is limited to less than 1% of waste volume; metals are typically in oxide form
21	103	Violent Polymerization	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping; metals are typically in oxide form
21	103	Heat Generation	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping; metals are typically in oxide form
21	104	Heat Generation	Reaction will not occur –Oxidizing agents are reacted prior to being placed in the waste/shipped; metals are typically in oxide form
21	104	Fire	Reaction will not occur –Oxidizing agents are reacted prior to being placed in the waste/shipped; metals are typically in oxide form
21	104	Explosion	Reaction will not occur –Oxidizing agents are reacted prior to being placed in the waste/shipped; metals are typically in oxide form
21	106	Flammable Gas Generation	Reaction will not occur – Free liquids are limited to less than 1% of waste volume; metals are typically in oxide form.
21	106	Heat Generation	Reaction will not occur – Free liquids are limited to less than 1% of waste volume; metals are typically in oxide form.
21	107	Highly Reactive	Reaction will not occur – Metals are typically in oxide form; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
22	28	Heat Generation	Reaction will not occur – Unsaturated aliphatic hydrocarbons are solidified/immobilized prior to shipping
22	28	Explosion	Reaction will not occur – Unsaturated aliphatic hydrocarbons are solidified/immobilized prior to shipping

Potential Chemical Incompatibilities

Combination of Reactivity Groups		Reaction Result (A x B)	Explanation of Potential Incompatibility
Group A	Group B		
22	103	Violent Polymerization	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping
22	103	Heat Generation	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping
22	104	Heat Generation	Reaction will not occur – Oxidizing agents are reacted prior to being placed in the waste/shipped
22	104	Fire	Reaction will not occur – Oxidizing agents are reacted prior to being placed in the waste/shipped
22	104	Explosion	Reaction will not occur – Oxidizing agents are reacted prior to being placed in the waste/shipped
22	106	Flammable Gas Generation	Reaction will not occur – Free liquids are limited to less than 1% of waste volume; water reactive metals are reacted prior to shipping
22	106	Heat Generation	Reaction will not occur – Free liquids are limited to less than 1% of waste volume; water reactive metals are reacted prior to shipping
22	107	Highly Reactive	Reaction will not occur –Water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
23	103	Violent Polymerization	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping
23	103	Heat Generation	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping
23	104	Heat Generation	Reaction will not occur – Oxidizing agents are reacted prior to being placed in the waste/shipped
23	104	Fire	Reaction will not occur – Oxidizing agents are reacted prior to being placed in the waste/shipped
23	107	Highly Reactive	Reaction will not occur –Water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
24	103	Violent Polymerization	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping
24	103	Heat Generation	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping
24	106	Solubilization of Toxic Substances	Reaction will not occur – Free liquid content is limited to less than 1% of waste volume; Additionally, any solubilization of toxic substances will not affect

Potential Chemical Incompatibilities			
Combination of Reactivity Groups		Reaction Result (A x B)	Explanation of Potential Incompatibility
Group A	Group B		
			transportation of wastes.
24	107	Highly Reactive	Reaction will not occur – Water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
28	104	Heat Generation	Reaction will not occur – Unsaturated aliphatic hydrocarbons are immobilized/solidified prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped
28	104	Fire	Reaction will not occur – Unsaturated aliphatic hydrocarbons are immobilized/solidified prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped
28	107	Highly Reactive	Reaction will not occur – Unsaturated aliphatic hydrocarbons are immobilized/solidified prior to shipping; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
29	104	Heat Generation	Reaction will not occur – Saturated aliphatic hydrocarbons are immobilized/solidified prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped
29	104	Fire	Reaction will not occur – Saturated aliphatic hydrocarbons are immobilized/solidified prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped
29	107	Highly Reactive	Reaction will not occur – Saturated aliphatic hydrocarbons are immobilized/solidified prior to shipping; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
31	103	Violent	Reaction will not occur – Polymerizable compounds

Potential Chemical Incompatibilities			
Combination of Reactivity Groups		Reaction Result (A x B)	Explanation of Potential Incompatibility
Group A	Group B		
		Polymerization	are reacted or immobilized/solidified prior to shipping; phenols and creosols are immobilized/solidified prior to shipping
31	103	Heat Generation	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping; phenols and creosols are immobilized/solidified prior to shipping
31	104	Heat Generation	Reaction will not occur – Phenols and creosols are immobilized/solidified prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped
31	104	Fire	Reaction will not occur – Phenols and creosols are immobilized/solidified prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped
31	105	Flammable Gas Generation	Reaction will not occur – Phenols and creosols are immobilized/solidified prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped
31	105	Heat Generation	Reaction will not occur – Phenols and creosols are immobilized/solidified prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped
31	107	Highly Reactive	Reaction will not occur – Phenols and creosols are immobilized/solidified prior to shipping; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
32	104	Heat Generation	Reaction will not occur – Organophosphates are immobilized/solidified prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped
32	104	Fire	Reaction will not occur – Organophosphates are immobilized/solidified prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped
32	104	Toxic Gas Generation	Reaction will not occur – Organophosphates are immobilized/solidified prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped
32	105	Toxic Gas	Reaction will not occur – Organophosphates are

Potential Chemical Incompatibilities			
Combination of Reactivity Groups		Reaction Result (A x B)	Explanation of Potential Incompatibility
Group A	Group B		
		Generation	immobilized/solidified prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped
32	105	Flammable Gas Generation	Reaction will not occur – Organophosphates are immobilized/solidified prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped
32	105	Heat Generation	Reaction will not occur – Organophosphates are immobilized/solidified prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped
32	107	Highly Reactive	Reaction will not occur – Organophosphates are immobilized/solidified prior to shipping; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
101	104	Heat Generation	Reaction will not occur – Combustible materials are dry; oxidizing agents are reacted prior to being placed in the waste/shipped
101	104	Fire	Reaction will not occur – Combustible materials are dry; oxidizing agents are reacted prior to being placed in the waste/shipped
101	104	Innocuous and Non-Flammable Gas Generation	Reaction will not occur – Combustible materials are dry; oxidizing agents are reacted prior to being placed in the waste/shipped
101	105	Flammable Gas Generation	Reaction will not occur – Combustible materials are dry; reducing agents are reacted prior to being placed in the waste/shipped
101	105	Heat Generation	Reaction will not occur – Combustible materials are dry; reducing agents are reacted prior to being placed in the waste/shipped
101	107	Highly Reactive	Reaction will not occur – Combustible materials are dry; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
103	104	Heat Generation	Reaction will not occur – Polymerizable compounds

Potential Chemical Incompatibilities

Combination of Reactivity Groups		Reaction Result (A x B)	Explanation of Potential Incompatibility
Group A	Group B		
			are reacted or immobilized/solidified prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped
103	104	Fire	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped
103	104	Toxic Gas Generation	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping; oxidizing agents are reacted prior to being placed in the waste/shipped
103	105	Heat Generation	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped
103	105	Violent Polymerization	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped
103	105	Flammable Gas Generation	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping; reducing agents are reacted prior to being placed in the waste/shipped
103	107	Highly Reactive	Reaction will not occur – Polymerizable compounds are reacted or immobilized/solidified prior to shipping; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
104	105	Heat Generation	Reaction will not occur – Oxidizing agents are reacted prior to being placed in the waste/shipped; reducing agents are reacted prior to being placed in the waste/shipped
104	105	Fire	Reaction will not occur – Oxidizing agents are reacted prior to being placed in the waste/shipped; reducing agents are reacted prior to being placed in the waste/shipped
104	105	Explosion	Reaction will not occur – Oxidizing agents are reacted prior to being placed in the waste/shipped; reducing agents are reacted prior to being placed in the waste/shipped
104	107	Highly Reactive	Reaction will not occur – Oxidizing agents are reacted

Potential Chemical Incompatibilities			
Combination of Reactivity Groups		**Reaction Result (A x B)**	**Explanation of Potential Incompatibility**
Group A	**Group B**		
			prior to being placed in the waste/shipped; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
105	106	Flammable Gas Generation	Reaction will not occur – Reducing agents are reacted prior to being placed in the waste/shipped; free liquid content is limited to less than 1% of waste volume
105	106	Toxic Gas Generation	Reaction will not occur – Reducing agents are reacted prior to being placed in the waste/shipped; free liquid content is limited to less than 1% of waste volume
105	107	Highly Reactive	Reaction will not occur – Reducing agents are reacted prior to being placed in the waste/shipped; free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.
106	107	Highly Reactive	Reaction will not occur – Free liquid content is limited to less than 1% of waste volume; water reactive substances are reacted prior to being placed in the waste/shipped. Lime in Portland cement is most common water reactive substance expected in the waste. Portland cement is used as an absorbent and solidification agent for the wastes.

Attachment C

Shipping Period for TRU Waste in the 10-160B Cask

C.1.0 INTRODUCTION

This Attachment presents the basis for the shipping period for TRU wastes from the time of cask closure until cask opening. This shipping period is used in the analysis of the gas generation in the 10-160B cask.

The 10-160B cask may be used to ship TRU waste from generator sites to the Waste Isolation Pilot Plant (WIPP) for disposal or between sites (e.g., from the Battelle West Jefferson, OH site to the U.S. Department of Energy [DOE] Hanford, WA site) for interim storage. While the shipments are in transit, a satellite tracking system will be operational to monitor progress and provide direct communication between the driver and the transport dispatcher.

C.2.0 EXPECTED SHIPPING PERIOD

The expected shipping period is the amount of time from the sealing of the cask at the loading facility until the opening of the cask at the unloading facility. It consists of: the time from cask sealing to the release of the transport unit from the loading facility, the expected transit time, and the time from arrival at the unloading facility until the cask is opened. For assessing the expected shipping period, it will be assumed that there are no delays.

C.2.1 Loading

The loading process from cask sealing to unit release includes health physics surveys, installing the upper impact limiter, and vehicle inspections. The time from cask sealing until the unit is released for travel has been accomplished in less than four (4) hours. To be conservative, a one-day (24 hour) duration will be assumed.

C.2.2 Transit

The longest route of prospective intersite shipments is from Savannah River, SC to Hanford, approximately 2800 miles. Shipments to WIPP are encompassed by this distance. All TRU shipments will be made with two drivers. Using two drivers, on an appropriate rotational schedule, the truck can travel for twenty-four (24) hours per day for up to seven days. Assuming an average speed of 45 mph, which includes time for vehicle inspections, fueling, meals, and driver relief, the duration of a 2800 mile trip is expected to be 62 hours. Again, to be conservative, the transit duration will be assumed to be three days (72 hours).

C.2.3 Unloading

The unloading process includes receipt survey and security checks, positioning of the trailer in the TRU waste unloading area, removal of the cask from the trailer to a transfer cart, positioning of the cask in the cask unloading room, and removal of the lid. This process has been accomplished in less than eight (8) hours. Again, to be conservative, the unloading duration will be assumed to be one day (24 hours).

C.2.4 Total

The total expected shipping period, with no delays, is less than 75 hours. For the purpose of this analysis, a conservative period of 5 days (120 hours) will be assumed.

C.3.0 SHIPPING DELAYS

The maximum shipping time will be assumed to be the sum of the expected shipping time and the time for delays which could extend the shipping time. These delays are: loading delays; transit delays due to weather or road closures, shipping vehicle accidents, mechanical delays, or driver illness; and unloading delays. Each of these delays are assessed below.

C.3.1 Loading Delays

There are a number of situations that could extend the time between cask sealing and truck release. These include: loading preceding a holiday weekend, problems with a leak test, and handling equipment failure. Both the leak test problem and the handling equipment failure should be resolvable by replacing or obtaining temporary equipment. Each of these situations is unlikely to cause more than a two day delay. The holiday weekend could cause a delay of three days, i.e., from Friday afternoon until Tuesday. It is very unlikely that more than two of the three loading delays could occur on the same shipment, so a total of five days seems a reasonably conservative assessment for a loading delay.

C.3.2 Transit Delays

Transit delays due to weather, e.g., a road closed due to snow, are unlikely to cause a delay of more than five days. A road closure due to a vehicle accident or a roadway or bridge failure would result in re-routing which could add up to two days to the transit time. A transit time delay due to weather or road closure will be assumed to be five days.

Transit delays due to an accident with the truck could cause a lengthy delay. Response time for notification and to take immediate corrective action is assumed to be one day. (The use of the on-board satellite communication system will facilitate an early response.) Accident mitigation may require transferring the cask to a different trailer using cranes and other heavy equipment. Mitigation is assumed to take five days for a total accident delay of six days.

Mechanical problems with the truck or trailer could also cause multi-day delays. Significant failures may require a replacement tractor or trailer. An appropriate response to a mechanical failure is assumed to take four days.

Driver illness could also cause transit delays. If a driver it too ill to continue, a replacement driver will be brought in. A two day delay is assessed for bringing in a replacement driver.

C.3.3 Unloading Delay

An unloading delay will occur if the truck arrives just before a holiday weekend. This could result in a four day delay. Additionally, a delay due to unloading equipment failure could occur. Repair of such equipment should not require more than four days. The unloading delay will be conservatively assumed to be five days. If an unanticipated situation occurs that would result in a much longer delay, the cask can be vented.

C.3.4 Total Delay

The total delay, i.e., the sum of the delay times for each of the delay types, is 27 days. This assumes that each type of delay occurs on the same shipment.

C.4.0 MAXIMUM SHIPPING PERIOD

The maximum shipping period, as the sum of the expected shipping period and the total delay, is 32 days. This period assumes that each of the possible shipping delays occurs on the same shipment, a very unlikely occurrence. Further, for additional conservatism, the assumed maximum will be nearly doubled to 60 days. Thus, a 60 day shipping period will be the maximum used in analysis of gas generation in the sealed cask. A shorter, site-specific shipping period may be developed and included in the site-specific sub tier appendix, which contains the waste content codes for the site, that is submitted to the NRC for approval. This site-specific shipping period may be used in the gas generation analysis for the site's waste.

5. SHIELDING EVALUATION

5.1 Discussion and Results

5.1.1 Operating Design

The Model 10-160B packaging consists of a lead and steel containment vessel which provides the necessary shielding for the various radioactive materials to be shipped within the package. (Refer to Section 1.2.3 for packaging contents.) Tests and analysis performed under chapters 2.0 and 3.0 have demonstrated the ability of the containment vessel to maintain its shielding integrity under normal conditions of transport. Prior to each shipment, radiation readings will be taken based on individual loadings to assure compliance with applicable regulations as determined in 10CFR71.47 (see Section 7.1, step 13c).

The 10-160B will be operated under "exclusive use" such that the contents in the cask will not create a dose rate exceeding 200 mrem/hr on the cask surface, or 10 mrem/hr at two meters from the outer lateral surfaces of the vehicle. The package shielding must be sufficient to satisfy the dose rate limit of 10CFR71.51(a) (2) which states that any shielding loss resulting from the hypothetical accident will not increase the external dose rate to more than 1000 mrem/hr at one meter from the external surface of the cask.

5.1.2 Shielding Design Features

The cask side wall consists of an outer 2-inch thick steel shell surrounding 1 7/8 inches of lead and an inner containment shell wall of 1 1/8-inch thick steel.

The primary cask lid consists of two steel layers with a total thickness of 5½ inches. The lid closure is made in a stepped configuration to eliminate radiation streaming at the lid/cask body interface.

A secondary lid is located at the center of the main lid, covering a 31-inch opening. The secondary lid is constructed of steel plates with a total thickness of 5½ inches with multiple steps machined in its periphery. These steps match those in the primary lid, eliminating radiation streaming pathways.

The cask bottom has an identical shielding effectiveness to the cask lids. It also consists of two layers of steel with a total thickness of 5 ½ inches.

Foam filled impact limiters cover the top and bottom of the vertically oriented cask. The impact limiters are conservatively ignored for the purpose of the shielding evaluation.

5.1.3 Maximum Dose Rate Calculations

Table 5.1 gives both Normal Conditions of Transport (NCT) and Hypothetical Accident Conditions (HAC) dose rates resulting from the maximum point sources (neutron and gamma) which may be in contact with either the side wall or the top (or bottom) of the cask. Maximum allowable dose rates given in 10CFR71 are shown in Table 5.1 for comparison. The following assumptions were used to develop the values shown in the table.

5.1.3.1 Normal Conditions

- The source is conservatively modeled as a point source centered in the cask cavity.

5.1.3.2 Accident Conditions

- The source is modeled as a point source on the inner liner adjacent to the location of the lead slump and in contact with the lid.
- Lead slump (see Section 2.7.1.1) considers the effect of loss of lead shielding from the slumped region in the side wall.

Table 5.1
Summary of Maximum Dose Rates (mrem/hr)

	Package Surface		1 m from Surface		2m from 8' trailer
Condition	Side	Top/Bottom	Side	Top/Bottom	Side
NCT					
Neutron Source	114	86.3	N.A	N.A.	9.44
Gamma Source	126	179	N.A	N.A.	9.96
Allowable	200	200	N.A.	N.A.	10.0
HAC					
Neutron Source	N.A.	N.A.	82.7	39.5	N.A.
Gamma Source	N.A.	N.A.	144	99.9	N.A
Allowable	N.A.	N.A.	1000.0	1000.0	N.A

5.2 Source Specification

5.2.1 Methodology

A unit point source is placed at the cask center. A neutron source and a gamma source are evaluated independently. The dose rate from the unit source is determined at the cask outer surface and at 2m from the 8' wide trailer. The ratio between the dose limit and the calculated value is determined. An equivalent source is set equal to the activity of the unit source times the smallest ratio of the surface limit to the calculated dose rate from the unit source. This equivalent source, which is the largest activity source that meets the cask NCT dose limits, is then used to evaluate the effects of the hypothetical accident. If the HAC limits are met for the maximum activity source, the cask complies with the requirements of 10 CFR 71. A mixed gamma and neutron source will also comply as the sum of the gamma and neutron dose rates must be less than the NCT dose limit and thus, as shown for the independently evaluated sources, the HAC limits will be met.

5.2.2 Gamma Source

SCALE models of the 10-160B cask are evaluated with a Co-60 source. The resulting equivalent source, approximately 13.4 Ci, gives a gamma dose rate of approximately 9.96 mrem/hr at 2m from the 8' wide trailer.

5.2.3 Neutron Source

SCALE models of the 10-160B cask are evaluated with a Pu-Be neutron source. A ^{239}Pu-Be source produces neutrons at a rate of approximately 1.4E+06 n/sec per Ci (Ref. 5.6.3). A 325 FGE (approximately 20 Ci) ^{239}Pu-Be source will produce approximately 2.8E+07 n/sec. The equivalent neutron source, which produces a dose rate of 9.4 mrem/hr at 2m from the 8' wide trailer, has an emission rate of 1.1 E+08 n/sec. Thus, the equivalent source used for the dose rate calculation is larger than the fissile gram limit imposed by the criticality evaluation of Chapter 6 and gives a conservative dose rate result. The neutron energy spectrum for a Pu-Be source is shown below.

Neutron Energy Spectrum for a Pu-Be Source (Ref. 5.6.3)

Energy Interval, E_i (MeV)	Fraction of neutrons in E_i
0-0.5	0.038
0.5-1	0.049
1-1.5	0.045
1.5-2	0.042
2-2.5	0.046
2.5-3	0.062
3-6.5	0.459

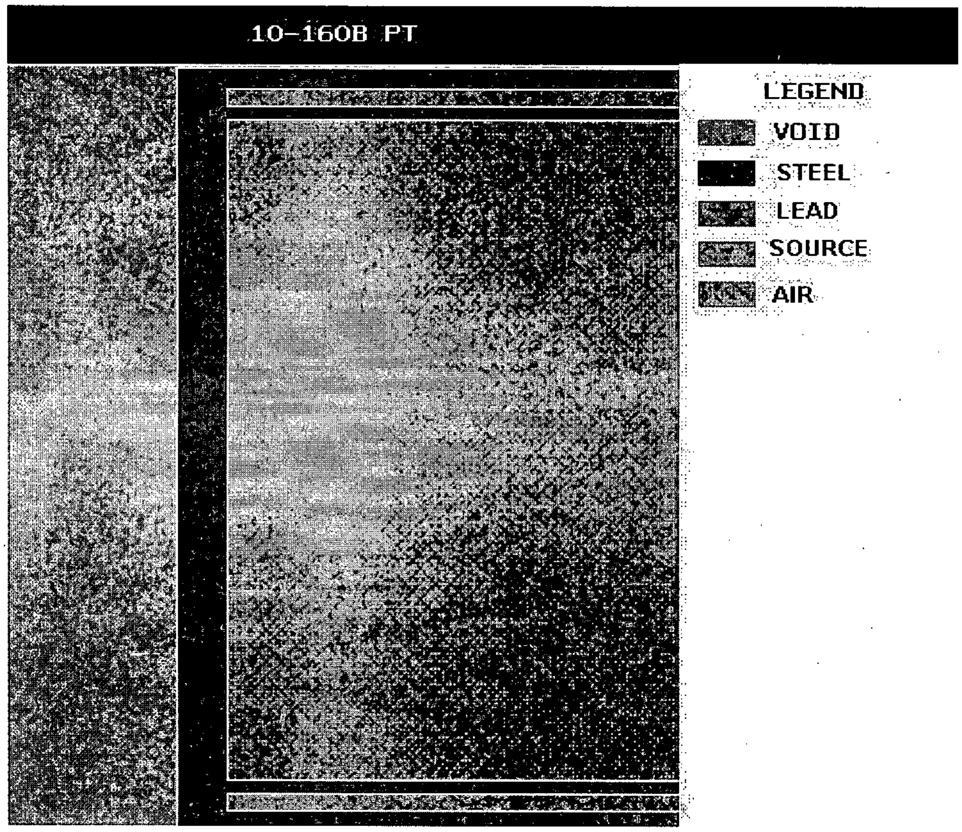
6.5-10.5	0.259
Total	1.000

5.3 Model Specification

5.3.1 Description of Radial and Axial Shielding Configuration

Normal Conditions of Transport (NCT)
The walls of the 10-160B cask, 1.125" inner and 2" outer steel walls with a 1.875" lead layer between, are modeled as cylindrical shells around the cavity cylinder. The base and lid of the cask is a 5.5" steel plate. Impact limiters are conservatively ignored. This geometry is shown in Figure 5.1. In terms of shielding, the cask lid and bottom are the same so only one end is modeled. The cask is transported upright, i.e., with the axis of the cylinder vertical. Doses are evaluated at contact with the cask sidewall, with the cask lid, and at 2m from the 8' wide trailer.

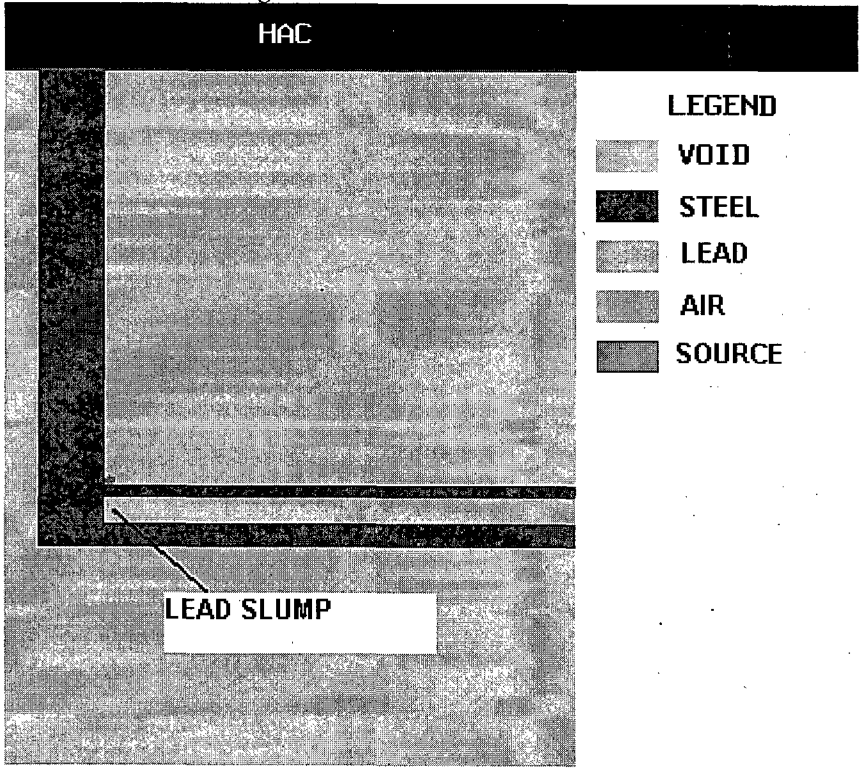
Figure 5.1 NCT Cask Model



Hypothetical Accident Conditions (HAC)
As discussed in Section 2, the hypothetical accident conditions do not affect the geometry of the steel shells or the base or lid (see Section 5.3.1, above). The HAC model is shown in Figure 5.3. The lead slump

resulting from the 30' drop (< 0.02") discussed in Section 2.7.1.1, is included in the HAC model as a void 0.05 cm high at the top of the lead shell. Doses are determined at 1 m from the sidewall and the lid.

Figure 5.2 HAC Cask Model



5.3.2 Material Properties

The properties of the cask materials are shown in Table 5.2

Table 5.2 Material Properties

Material	Composition	Density (g/cm^3)
Source	beryllium / cobalt	1.85 / 8.9
Cask inner wall	Steel	7.82
Cask outer wall	Steel	7.82
Cask shield layer	Lead	11.34

5.4. Shielding Evaluation

5.4.1. Methods

The gamma and neutron dose rates were calculated using SCALE, Module SAS4 (Ref.3), using the geometry described in Section 5.3. The dose locations are surface or point detectors at the cask surface or at 2m from the trailer for NCT and at 1m from the cask surface for HAC.

5.4.2. Input and Output Data

The SCALE input and output files are provided in 5.7. The input file lists the inputs that define the source dimensions, shield dimensions, materials and density, and source spectrum.

5.4.3. Flux-to-Dose-Rate Conversion

The flux to exposure rate conversion factors are listed in Table 5.3 and Table 5.4 (Ref. 5.6.2). These are the default conversion factors in SCALE.

Table 5.3 Gamma-Ray-Flux-To-Dose-Rate Conversion Factors

Photon Energy-E (MeV)	$DF_g(E)$ Rem/hr)/(photons/cm^2-s)
0.01	3.96-06
0.03	5.82-07
0.05	2.90-07
0.07	2.58-07
0.1	2.83-07
0.15	3.79-07
0.2	5.01-07
0.25	6.31-07
0.3	7.59-07
0.35	8.78-07
0.4	9.85-07
0.45	1.08-06
0.5	1.17-06
0.55	1.27-06
0.6	1.36-06
0.65	1.44-06
0.7	1.52-06
0.8	1.68-06
1.0	1.98-06
1.4	2.51-06
1.8	2.99-06
2.2	3.42-06
2.6	3.82-06
2.8	4.01-06
3.25	4.41-06
3.75	4.83-06
4.25	5.23-06
4.75	5.60-06
5.0	5.80-06
5.25	6.01-06
5.75	6.37-06
6.25	6.74-06
6.75	7.11-06
7.5	7.66-06
9.0	8.77-06
11.0	1.03-05
13.0	1.18-05
15.0	1.33-05

Table 5.4 Neutron Flux-To-Dose-Rate Conversion Factors And Mean Quality Factors ($\overline{QF}$)

Neutron Energy-E (MeV)	$\overline{QF}$*	$DF_n(E)$ (rem/hr) (n/cm^2-s)
2.5-08	2	3.67-06
1.0-07	2	3.67-06
1.0-06	2	4.46-06
10.-05	2	4.54-06
1.0-04	2	4.18-06
1.0-03	2	3.76-06
1.0-02	2.5	3.56-06
1.0-01	7.5	2.17-05
5.0-01	11	9.26-05
1.0	11	1.32-04
2.5	9	1.25-04
5.0	8	1.56-04
7.0	7	1.47-04
10.0	6.5	1.47-04
14.0	75	2.08-04
20.0	8	2.27-04

*Maximum value of QF in a 30-cm phantom.
#Read as 2.5 x 10^{-8}

5.4.4. External Radiation Levels

The SCALE model used to determine external radiation levels uses point or surface detectors to calculate the dose rates at various distances from the cask surface either radially or axially. The point detectors are aligned with the point sources, thus normally giving the maximum dose rates. The highest dose rate from the point or surface detectors is reported. Table 5.5 contains the maximum neutron and gamma dose rates found for each of the four cases, i.e., NCT radial, NCT axial, HAC radial, and HAC axial for each of the sources, neutron and gamma.

Table 5.5 Maximum External Radiation Levels

Normal Conditions of Transport	**Package Surface (mrem/h)**			**2 Meters from Trailer (mrem/h)**
Radiation	Top	Side	Bottom	Side
Neutron Source	86.3	114	86.3	9.44
Gamma Source	179	126	179	9.96
10 CFR 71.47 Limit[1]	200	200	200	10

1. shipped as "exclusive use"

Hypothetical Accident Conditions	**1 Meter from Package Surface mSv/h (mrem/h)**		
Radiation	Top	Side	Bottom
Neutron Source	39.5	82.7	39.5
Gamma Source	99.9	143.6	99.9

10 CFR 71.51(a)(2) Limit	1000	1000	1000

5.5 Conclusion

The cask shielding must be able to limit the dose rate to 1000 mrem/hr at 1 meter from any surface of the cask after the cask goes through the hypothetical accident. This section demonstrates compliance with this requirement. Structural analysis (Section 2.0) demonstrates that the cask wall will not fail during the hypothetical accident. However, lead slump may occur during a drop giving an isolated region in the sidewall without lead. Lead slump cannot occur in the lid or bottom of the cask since lead is not present in these parts of the cask. The dose rate at 1 meter from the cask in the slumped region (assuming a localized lead void) was determined to be less than the 1000 mrem/hr limit for a source at the NCT dose rate limit. Normally, a shipper will apply a degree of conservatism to the NCT limits, typically 10-20%, to ensure compliance. Thus, the activity of the contents will be less than that assumed in the in the preceding analysis and dose rates under HAC will be less than the values predicted above.

5.6. References

5.6.1. SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluations, NUREG/CR-0200, Rev.6 (ORNL/NUREG/CSD-2/R6), Vols. I, II, III, May 2000
5.6.2. ANSI/ANS 6.1.1-1977, "Neutron and Gamma-Ray Flux-to-Dose-Rate Factors."
5.6.3. Cember, H, *Introduction to Health Physics,* Pergamon Press, New York, 1987

5.7. SCALE Input Files for 10-160B Consolidated SAR Rev. 0

5.7.1. 10-160b-pt-axial-HAC.inp

```
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 lead 2 1 293 end
 beryllium 3 1 293 end
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 cobalt 5 1 293 end
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 soe 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 22 78 0 0 0 0 0 0 0 0 end
 det 199.06 0 76.79 199.06 0 81.79 199.06 0 86.79 199.06 0 91.79 199.06
 0 96.79 199.06 0 101.79 199.06 0 106.79 199.06 0 111.79 199.06 0
 116.79 199.06 0 121.79 199.06 0 126.79 199.06 0 131.79 199.06 0
 136.79 199.06 0 141.79 199.06 0 146.79 199.06 0 151.79 end
 sdl 99.06 199.06 299.06 399.06 end
 sdr 70 120 70 140 70 90 70 90 end
 sds 10 0 14 36 0 0 0 0 end
 sxy 5 84.36 86.36 -1 1 95.79 97.79 86.36 97.79 99.06 111.76   end
gend
10-160b pt hac
 0 0 0 0
 sph 85.36 0 96.79 1
 rcc 0 0 -97.79 0 0 195.58 86.36
 rcc 0 0 -98.79 0 0 197.58 89.218
 rcc 0 0 -97.79 0 0 195.53 93.98
 rcc 0 0 -111.76 0 0 223.52 99.06
 sph 0 0 0 300
 sph 0 0 0 500
 rcc 0 0 -97.79 0 0 195.58 93.98
 rcc 0 0 -211.76 0 0 423.52 199.06
  end
 src +1
 cav +2 -1
 inn +3 -2
 shd +4 -3
 our +5 -8
 inv +6 -9
 exv +7 -6
 slp +8 -3 -4
 det +9 -5
  end
 1 1 1 1 1 1 1 1 1
 0 0 0 0 0 0 0 0 0
 5 4 1 2 1 1000 0 4 4
 0

end
```

5.7.2. 10-160b-pt-axial-igo0.inp

```
'Input generated by Espn 89 Compiled on 06-07-2002
=sas4     parm=size=500000
10-160B pt
27n-18couple  infhommedium
 carbonsteel 1 1 293 end
 lead 2 1 293 end
 beryllium 3 1 293 end
 arbm-air 0.0002 2 0 0 0 7014 82 8016 18 4 1 293 end
 cobalt 5 1 293 end
end comp
 idr=1 ity=2 izm=3 isn=8 irf=9504 ifs=1 mhw=4 frd=1 szf=1  end
 1 97.79 111.76   end
 5 4 1   end
xend
 ran=000000111507 tim=120 nst=1000 nmt=4000 nit=1500 nco=4 ist=0 ipr=0
 iso=0 nod=0 sfa=1e+12 igo=0 inb=0 ine=0 mfu=5 isp=0 ipf=0 isd=4
 nda=1000  end
 soe 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 22 78 0 0 0 0 0 0 0 0 end
 sds 10 0 18 0 10 0 10 0 end
gend
point source
 fue 1 97.78 end
fend
 inn 1 89.218 98.79 end
 rs1 2 93.98 97.79 end
 our 1 99.06 111.76 end
 as1 1 89.218 99.79 end
 hol 1 end
 cav 4 86.36 97.79 end
cend
end
```

5.7.3. 10-160b-pt-HAC.inp

```
'Input generated by Espn 89 Compiled on 06-07-2002
=sas4     parm=size=500000
10-160B pt axial
27n-18couple  infhommedium
 carbonsteel 1 1 293 end
 lead 2 1 293 end
 beryllium 3 1 293 end
 arbm-air 0.0002 2 0 0 0 7014 82 8016 18 4 1 293 end
 cobalt 5 1 293 end
end comp
 idr=0 ity=2 izm=5 isn=8 irf=9504 ifs=1 mhw=5 frd=86.36 szf=1  end
 86.36 89.218 93.98 99.06 199.06   end
 4 1 2 1 4   end
xend
 ran=000000091807 tim=120 nst=1000 nmt=4000 nit=1000 nco=4 ist=0 ipr=0
 iso=0 nod=16 sfa=1e+12 igo=4 inb=0 ine=0 mfu=5 isp=0 ipf=0 isd=4
 nda=1000  end
 soe 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 22 78 0 0 0 0 0 0 0 0 end
 det 199.06 0 76.79 199.06 0 81.79 199.06 0 86.79 199.06 0 91.79 199.06
 0 96.79 199.06 0 101.79 199.06 0 106.79 199.06 0 111.79 199.06 0
 116.79 199.06 0 121.79 199.06 0 126.79 199.06 0 131.79 199.06 0
 136.79 199.06 0 141.79 199.06 0 146.79 199.06 0 151.79 end
 sdl 99.06 199.06 299.06 399.06 end
 sdr 70 120 70 140 70 90 70 90 end
```

```
 sds 10 0 14 36 0 0 0 0 end
 sxy 5 84.36 86.36 -1 1 95.79 97.79 86.36 97.79 99.06 111.76   end
gend
10-160b pt hac
 0 0 0 0
 sph 85.36 0 96.79 1
 rcc 0 0 -97.79 0 0 195.58 86.36
 rcc 0 0 -98.79 0 0 197.58 89.218
 rcc 0 0 -97.79 0 0 195.53 93.98
 rcc 0 0 -111.76 0 0 223.52 99.06
 sph 0 0 0 300
 sph 0 0 0 500
 rcc 0 0 -97.79 0 0 195.58 93.98
 rcc 0 0 -211.76 0 0 423.52 199.06
  end
 src +1
 cav +2 -1
 inn +3 -2
 shd +4 -3
 our +5 -8
 inv +6 -9
 exv +7 -6
 slp +8 -3 -4
 det +9 -5
  end
 1 1 1 1 1 1 1 1 1
 0 0 0 0 0 0 0 0 0
 5 4 1 2 1 1000 0 4 4
 0

end
```

5.7.4. 10-160b-pt-igo0.inp

```
'Input generated by Espn 89 Compiled on 06-07-2002
=sas4     parm=size=500000
10-160B pt
27n-18couple  infhommedium
 carbonsteel 1 1 293 end
 lead 2 1 293 end
 beryllium 3 1 293 end
 arbm-air 0.0002 2 0 0 0 7014 82 8016 18 4 1 293 end
 cobalt 5 1 293 end
end comp
 idr=0 ity=2 izm=5 isn=8 irf=9504 ifs=1 mhw=4 frd=1 szf=1  end
 1 86.36 89.218 93.98 99.06   end
 5 4 1 2 1   end
xend
 ran=000000111207 tim=120 nst=1000 nmt=4000 nit=10000 nco=4 ist=0 ipr=0
 iso=0 nod=0 sfa=1e+12 igo=0 inb=0 ine=0 mfu=5 isp=0 ipf=0 isd=4
 nda=1000  end
 soe 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 22 78 0 0 0 0 0 0 0 0 end
 sdl 99.06 199.06 322 344 end
 sdr 0 20 0 100 0 100 0 10 end
 sds 5 1 10 1 10 1 1 1 end
gend
point source
 fue 1 97.78 end
fend
 inn 1 89.218 98.79 end
```

```
 rs1 2 93.98 97.79 end
 our 1 99.06 111.76 end
 as1 1 89.218 99.79 end
 hol 1 end
 cav 4 86.36 97.79 end
cend
end
```

5.7.5. 10-160b-pt-n-axial-HAC.inp

```
'Input generated by Espn 89 Compiled on 06-07-2002
=sas4     parm=size=500000
10-160B pt neutron
27n-18couple  infhommedium
 carbonsteel 1 1 293 end
 lead 2 1 293 end
 beryllium 3 1 293 end
 arbm-air 0.0002 2 0 0 0 7014 82 8016 18 4 1 293 end
 cobalt 5 1 293 end
end comp
 idr=1 ity=1 izm=4 isn=8 irf=9029 ifs=1 mhw=3 frd=86.36 szf=1  end
 97.79 98.79 111.76 211.76   end
 4 1 1 4   end
xend
 ran=000000111607 tim=120 nst=1000 nmt=4000 nit=500 nco=4 ist=0 ipr=0
 iso=0 nod=9 sfa=1.1e+08 igo=4 inb=0 ine=0 mfu=3 isp=0 ipf=0 isd=4
 nda=1000  end
 soe 0.259 0.459 0.108 0.042 0.045 0.049 0.038 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 end
 det 45.36 0 211.76 55.36 0 211.76 65.36 0 211.76 75.36 0 211.76 85.36
 0 211.76 95.36 0 211.76 105.36 0 211.76 115.36 0 211.76 125.36 0
 211.76 end
 sdl 111.76 211.76 311.76 411.76 end
 sdr 80 90 0 150 80 90 80 90 end
 sds 0 0 15 36 0 0 0 0 end
 sxy 3 84.36 86.36 -1 1 95.79 97.79 86.36 97.79 99.06 111.76   end
gend
10-160b pt hac
 0 0 0 0
 sph 85.36 0 96.79 1
 rcc 0 0 -97.79 0 0 195.58 86.36
 rcc 0 0 -98.79 0 0 197.58 89.218
 rcc 0 0 -97.79 0 0 195.53 93.98
 rcc 0 0 -111.76 0 0 223.52 99.06
 sph 0 0 0 400
 sph 0 0 0 500
 rcc 0 0 -97.79 0 0 195.58 93.98
 rcc 0 0 -211.76 0 0 423.52 199.06
  end
 src +1
 cav +2 -1
 inn +3 -2
 shd +4 -3
 our +5 -8
 inv +6 -9
 exv +7 -6
 slp +8 -3 -4
 det +9 -5
  end
 1 1 1 1 1 1 1 1 1
 0 0 0 0 0 0 0 0 0
```

```
 3 4 1 2 1 1000 0 4 4
 0
 end
```

5.7.6. 10-160b-pt-n-axial-igo0.inp

```
'Input generated by Espn 89 Compiled on 06-07-2002
=sas4     parm=size=500000
10-160B pt
27n-18couple  infhommedium
 carbonsteel 1 1 293 end
 lead 2 1 293 end
 beryllium 3 1 293 end
 arbm-air 0.0002 2 0 0 0 7014 82 8016 18 4 1 293 end
end comp
 idr=1 ity=1 izm=3 isn=8 irf=9029 ifs=1 mhw=4 frd=1 szf=1  end
 1 97.78 111.76   end
 3 4 1   end
xend
 ran=000000091807 tim=120 nst=1000 nmt=4000 nit=500 nco=4 ist=0 ipr=0
 iso=0 nod=0 sfa=1.1e+08 igo=0 inb=0 ine=0 mfu=3 isp=0 ipf=0 isd=4
 nda=1000  end
 soe 26 46 11 4 5 5 4 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 end
 sdr 0 100 0 100 0 10 0 10 end
 sds 10 0 10 0 1 0 1 0 end
gend
point source
 fue 1 97.78 end
fend
 inn 1 89.218 98.79 end
 rs1 2 93.98 97.79 end
 our 1 99.06 111.76 end
 as1 1 89.218 99.79 end
 hol 1 end
 cav 4 86.36 97.79 end
cend
end
```

5.7.7. 10-160b-pt-n-HAC.inp

```
'Input generated by Espn 89 Compiled on 06-07-2002
=sas4     parm=size=500000
10-160B pt neutron
27n-18couple  infhommedium
 carbonsteel 1 1 293 end
 lead 2 1 293 end
 beryllium 3 1 293 end
 arbm-air 0.0002 2 0 0 0 7014 82 8016 18 4 1 293 end
 cobalt 5 1 293 end
end comp
 idr=0 ity=1 izm=5 isn=8 irf=9029 ifs=1 mhw=3 frd=86.36 szf=1  end
 86.36 89.218 93.98 99.06 199.06   end
 4 1 2 1 4   end
xend
 ran=000000091807 tim=120 nst=1000 nmt=4000 nit=1000 nco=4 ist=0 ipr=0
 iso=0 nod=10 sfa=1.1e+08 igo=4 inb=0 ine=0 mfu=3 isp=0 ipf=0 isd=4
 nda=1000  end
 soe 0.259 0.459 0.108 0.042 0.045 0.049 0.038 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 end
 det 199.06 0 57.79 199.06 0 67.79 199.06 0 77.79 199.06 0 87.79 199.06
 0 97.79 199.06 0 107.79 199.06 0 117.79 199.06 0 127.79 199.06 0
 137.79 199.06 0 147.79 end
```

```
 sdl 99.06 199.06 322 344 end
 sdr 70 120 0 140 80 100 80 100 end
 sds 10 0 14 36 10 0 10 0 end
 sxy 3 84.36 86.36 -1 1 95.79 97.79 86.36 97.79 99.06 111.76   end
gend
10-160b pt hac
 0 0 0 0
 sph 85.36 0 96.79 1
 rcc 0 0 -97.79 0 0 195.58 86.36
 rcc 0 0 -98.79 0 0 197.58 89.218
 rcc 0 0 -97.79 0 0 195.53 93.98
 rcc 0 0 -111.76 0 0 223.52 99.06
 sph 0 0 0 400
 sph 0 0 0 500
 rcc 0 0 -97.79 0 0 195.58 93.98
 rcc 0 0 -211.76 0 0 423.52 199.06
  end
 src +1
 cav +2 -1
 inn +3 -2
 shd +4 -3
 our +5 -8
 inv +6 -9
 exv +7 -6
 slp +8 -3 -4
 det +9 -5
  end
 1 1 1 1 1 1 1 1 1
 0 0 0 0 0 0 0 0 0
 3 4 1 2 1 1000 0 4 4
 0

end
```

5.7.8. 10-160b-pt-n-igo0.inp

```
'Input generated by Espn 89 Compiled on 06-07-2002
=sas4     parm=size=500000
10-160B pt
27n-18couple  infhommedium
 carbonsteel 1 1 293 end
 lead 2 1 293 end
 beryllium 3 1 293 end
 arbm-air 0.0002 2 0 0 0 7014 82 8016 18 4 1 293 end
 cobalt 5 1 293 end
end comp
 idr=0 ity=1 izm=5 isn=8 irf=9029 ifs=1 mhw=4 frd=1 szf=1  end
 1 86.36 89.218 93.98 99.06   end
 3 4 1 2 1   end
xend
 ran=000000111307 tim=120 nst=1000 nmt=4000 nit=100 nco=4 ist=0 ipr=0
 iso=0 nod=0 sfa=1.1e+08 igo=0 inb=0 ine=0 mfu=3 isp=0 ipf=0 isd=4
 nda=1000  end
 soe 26 46 11 4 5 5 4 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 end
 sdl 99.06 199.06 322 344 end
 sdr 0 20 0 100 0 100 0 10 end
 sds 5 1 10 1 10 1 1 1 end
gend
point source
 fue 1 97.78 end
fend
```

```
 inn 1 89.218 98.79 end
 rsl 2 93.98 97.79 end
 our 1 99.06 111.76 end
 asl 1 89.218 99.79 end
 hol 1 end
 cav 4 86.36 97.79 end
cend
end
```

7.0 OPERATING PROCEDURE

This chapter describes the general procedure for loading and unloading of the 10-160B cask.

An optional steel insert may be used to shield the contents of the cask. The appropriate thickness of insert that should be used is determined from calculations and experience with previous, similar shipments. However, the insert must be thick enough so that dose rates on the exterior of the cask do not exceed the limits of 10 CFR 71.47, but must be no thicker than the maximum permissible size described in section 1.0.

The maximum permissible payload of the cask is 14,500 pounds, including contents, secondary containers, shoring, and optional steel insert (if used).

For contents that could radiolytically generate combustible gases, the criteria of Section 4.8 must be addressed. For DOE TRU waste, compliance with the 5% hydrogen concentration limit shall be demonstrated by the methods discussed in Appendix 4.10.2. For other contents, which exceed the 5% concentration limit, the procedures in Section 7.4 can be used to satisfy the criteria of Section 4.8.

7.1 Procedure for Loading the Package

7.1.1 Determine if cask must be removed from trailer for loading purposes. To remove cask from trailer:

7.1.1.1 Loosen and disconnect ratchet binders from upper impact limiter.

7.1.1.2 Using suitable lifting equipment, remove upper impact limiter. Care should be taken to prevent damage to impact limiter during handling and storage.

7.1.1.3 Disconnect cask to trailer tie-down equipment.

7.1.1.4 Attach cask lifting ears and torque bolts to 200 ft-lbs ± 20 ft-lbs lubricated.

7.1.1.5 Using suitable lifting equipment, remove cask from trailer and lower impact limiter and place cask in level loading position.

NOTE **THE CABLES USED FOR LIFTING THE CASK MUST HAVE A TRUE ANGLE, WITH RESPECT TO THE HORIZONTAL OF NOT LESS THAN 60°.**

7.1.2 Loosen and remove the twenty-four bolts (24, 1¾" – 8 UN) which secure the primary lid to cask body.

7.1.3 Remove primary lid from cask body using suitable lifting equipment and the three lifting lugs on the secondary lid. Care should be taken during lid handling operations to prevent damage to cask or lid seal surfaces.

NOTE **THE CABLES USED FOR LIFTING THE LID MUST HAVE A TRUE ANGLE, WITH RESPECT TO THE HORIZONTAL OF NOT LESS THAN 45°.**

NOTE **IN CERTAIN CIRCUMSTANCES, LOADING MAY BE ACCOMPLISHED THROUGH THE SECONDARY LID AND THE PRIMARY LID WILL REMAIN ON. IN THIS CASE, THE FOLLOWING ALTERNATE (A) STEPS WILL BE USED:**

7.1.1.A (ALTERNATE) REMOVE THE IMPACT LIMITER CENTER COVER PLATE. THIS WILL PROVIDE ACCESS TO THE SECONDARY LID AND LIFTING LUGS.

7.1.2.A (ALTERNATE) WORKING THROUGH THE CENTER HOLE IN THE UPPER IMPACT LIMITER, LOOSEN AND REMOVE THE 12 1¾" – 8 UN LID BOLTS WHICH SECURE THE SECONDARY LID TO THE PRIMARY LID.

7.1.3.A (ALTERNATE) REMOVE THE SECONDARY LID USING SUITABLE LIFTING EQUIPMENT AND THE THREE LUGS ON THE LID. CARE SHOULD BE TAKEN DURING LID HANDLING

OPERATIONS TO PREVENT DAMAGES TO SEAL SURFACES OR THE LID

7.1.4 Visually inspect accessible areas of the cask interior for damage, loose materials, or moisture. Clean and inspect seal surfaces. Replace seals when defects or damage is noted which may preclude proper sealing.

NOTE **RADIOACTIVELY CONTAMINATED LIQUIDS MAY BE PUMPED OUT, REMOVED BY USE OF AN ABSORBENT MATERIAL, OR VIA DRAIN LINE. REMOVAL OF ANY MATERIAL FLOW INSIDE THE CASK SHALL BE PERFORMED UNDER THE SUPERVISION OF QUALIFIED HEALTH PHYSICS (HP) PERSONNEL WITH THE NECESSARY HP MONITORING AND RADIOLOGICAL HEALTH SAFETY PRECAUTIONS AND SAFEGUARDS.**

NOTE **WHEN SEALS ARE REPLACED (INCLUDING SEALS ON THE OPTIONAL VENT AND DRAIN PORTS), LEAK TESTING IS REQUIRED AS SPECIFIED IN SECTION 8.2.2.1.**

7.1.5 Check the torques on the cavity vent and drain line cap screws to determine that the cap screws are properly installed using O-rings. This step is not required if the cask does not have the optional vent and drain lines, or if the tamper seals on the vent or drain lines have not been removed. Torque the cap screws to 20 ± 2 ft-lbs.

7.1.6 Place radwaste material, disposable liners, drums, or other containers into cask and install shoring or bracing, if necessary to restrict movement of contents during transport.

7.1.7 Clean and inspect lid seal surfaces.

7.1.8 Replace the primary lid and secure the lid to the cask body by installing the 24 lid bolts. Ensure that the lid orientation stripe is in alignment with the cask stripe. Torque bolts to 300 ± 30 ft-lbs.

7.1.8.A (Alternate) Replace secondary lid (if removed) and secure to the primary lid with 12 bolts. Ensure that the lid orientation stripe is in alignment with the stripe on the primary lid. Torque the bolts to 300 ± 30 ft-lbs.

NOTE **PERFORM PRESSURE DROP LEAK TEST OF THE CASK PRIMARY LID, SECONDARY LID, VENT LINE, OR DRAIN LINE (AS APPLICABLE) IN ACCORDANCE WITH SECTION 8.2.2.2 PRIOR TO SHIPMENT OF PACKAGE LOADED WITH LARGE QUANTITIES OF LSA MATERIALS OR TYPE B QUANTITIES OF NON-LSA MATERIAL.**

7.1.9 Install anti-tamper seals to the designated lid bolts, or to vent and/or drain line plugs (if applicable).

7.1.10 If cask has been removed from trailer, proceed as follows to return cask to trailer:

7.1.10.1 Using suitable lifting equipment, lift and position cask into lower impact limiter on trailer in the same orientation as removed.

7.1.10.2 Unbolt and remove cask lifting ears.

7.1.10.3 Reconnect cask to trailer using tie-down equipment.

7.1.11 Using suitable lifting equipment, lift, inspect for damage and install upper impact limiter on cask in the same orientation as removed.

7.1.12 Attach and hand tighten ratchet binders between upper and lower impact limiters.

7.1.13 Cover lift lugs as required.

7.1.14 Install anti-tamper seals to the designated ratchet binder.

7.1.15 Replace center plate on the upper impact limiter.

7.1.16 Inspect package for proper placards and labeling.

7.1.17 Complete required shipping documentation.

7.1.18 Prior to shipment of a loaded package the following shall be confirmed:

(a) That the licensee who expects to receive the package containing materials in excess of Type A quantities specified in 10 CFR 20.1906(b) meets and follows the requirements of 10 CFR 20.1906 as applicable.

(b) That trailer placarding and cask labeling meet DOT specifications (49 CRF 172).

(c) That the external radiation dose rates of the 10-160B are less than or equal to 200 millirem per hour (mrem/hr) at the surface and less than or equal to 10 mrem/hr at 2 meters in accordance with 10 CFR 71.47.

(d) That all anti-tamper seals are properly installed.

7.2 Procedure for Unloading Package

In addition to the following sequence of events for unloading a package, packages containing quantities of radioactive material in excess of Type A quantities specified in 10 CFR 20.1906(b) shall be received, monitored, and handled by the licensee receiving the package in accordance with the requirements of 10 CFR 20.1906 as applicable.

7.2.1 Move the unopened package to an appropriate level unloading area.

7.2.2 Perform an external examination of the unopened package. Record any significant observations.

7.2.3 Remove anti-tamper seals.

7.2.4 Loosen and disconnect ratchet binders from the upper overpack assembly.

7.2.5 Remove upper overpack assembly using caution not to damage the cask or overpack assembly.

7.2.6 If cask must be removed from trailer, refer to Step 7.1.1.

7.2.7 (Optional if vent port installed). Vent cask cavity removing plugs from the vent line.

7.2.8 Loosen and remove the twenty-four (24) 1¾" – 8 UN primary lid bolts.

7.2.9 Using suitable lifting equipment, lift lid from cask using care during handling operations to prevent damage to cask and lid seal surfaces.

<u>NOTE</u>: THE CABLES USED FOR LIFTING THE LID MUST HAVE A TRUE ANGLE WITH RESPECT TO THE HORIZONTAL OF NOT LESS THAN 45°.

7.2.10 Remove contents to disposal area.

<u>NOTE</u>: RADIOACTIVELY CONTAMINATED LIQUIDS MAY BE PUMPED OUT, REMOVED BY USE OF AN ABSORBENT MATERIAL, OR VIA DRAIN LINE. REMOVAL OF ANY MATERIAL FROM INSIDE THE CASK SHALL BE PERFORMED UNDER THE SUPERVISION OF QUALIFIED HEALTH PHYSICS (HP) PERSONNEL WITH THE NECESSARY HP MONITORING AND RADIOLOGICAL HEALTH SAFETY PRECAUTIONS AND SAFEGUARDS.

7.2.11 Assemble package in accordance with loading procedure (7.1.7 through 7.1.17).

7.3 Preparation of Empty Packages for Transport

The Model 10-160B cask requires no special transport preparation when empty. Loading and unloading procedures outlined in this chapter shall be followed as applicable for empty packages. The requirements of 49 CFR 173.428 shall be complied with.

NOTE: EACH PACKAGE USER WILL BE SUPPLIED WITH A COMPLETE DETAILED OPERATING PROCEDURE FOR USE WITH THE PACKAGE.

7.4 Procedures for Shipment of Packages Which Generate Combustible Gases

Procedures for preparing packages for shipment which radiolytically generate combustible gases are outlined below. These procedures are divided into two categories:

a. Combustible gas control by inerting, and

b. Combustible gas suppression.

7.4.1 Combustible Gas Control by Inerting

7.4.1.1 Dewater the secondary container. The bulk of the free water is removed from the secondary container by displacing the water with nitrogen gas.

7.4.1.2 Inert the secondary container (and, if necessary, the cask). The inerting operation is done at the dewatering station just before the cask is loaded. Inerting is performed if the hydrogen generated will be greater than 5% in any portion of the package for a time period that is twice the expected shipping time. Inerting is intended to limit the oxygen concentration to less than 5% including any oxygen that is radiolytically generated over the same period considered for hydrogen generation. If a leak path can develop between the secondary container and the cask, the cask will also be inerted.

7.4.1.3 Inerting of the secondary container and / or the cask cavity, to achieve an oxygen concentration of less than 5%, can be performed per the following:

- Connect a nitrogen supply.
- Pressurize with nitrogen to 15 ±1 psig. for fifteen minutes.
- Depressurize to ~ 0 psig.
- Repeat this pressurization / depressurization cycle two more times

7.4.2 Combustible Gas Suppression

7.4.2.1 Dewater the secondary container. See paragraph 7.4.1.1.

7.4.2.2 Install the previously qualified* combustible gas suppression system (e.g., a vapor pressure catalytic recombiner).

*Previous qualification means that the catalytic recombiner design to be used has been tested for a period of twice the expected shipping time under conditions expected in transport and has proven satisfactory.

7.4.2.3 Sample the gas in the secondary container and measure static pressure. This will assure that the combustible gas control method is working properly and that the combustible gas criteria specified in Section 4.4 will be met.

7.4.2.4 Load the secondary container.

Attachment 3