

## 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 ~~the 10CFR71, the 1998 version~~. The package is designated the Model CNS-10-160B package. ~~The Transport Index number for the package is 3.0.~~

### 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 5 1/2 inch thickness of flat circular steel plates (2 1/2 and 3 inches) which are welded together. The cask primary lid also consists of a 5 1/2 inch thickness flat circular steel plates (2 1/2 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 ~~stainless 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 47 1/2 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<sub>2</sub>) 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<sub>2</sub>) 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<sub>2</sub> and which does not generate spontaneously more than 100 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<sub>2</sub>.

#### 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). ~~TRU wastes are limited as described in Appendix 4.10.2, Transuranic (TRU) Waste Compliance Methodology for Hydrogen Gas Generation. Contents containing greater than 20 Ci of plutonium must be in solid form.~~
- 2) Neutron activated metals or metal oxides in solid form.
- ~~3) 3)–Miscellaneous radioactive solid waste 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.~~

CNS-10-160B GENERAL ARRANGEMENT

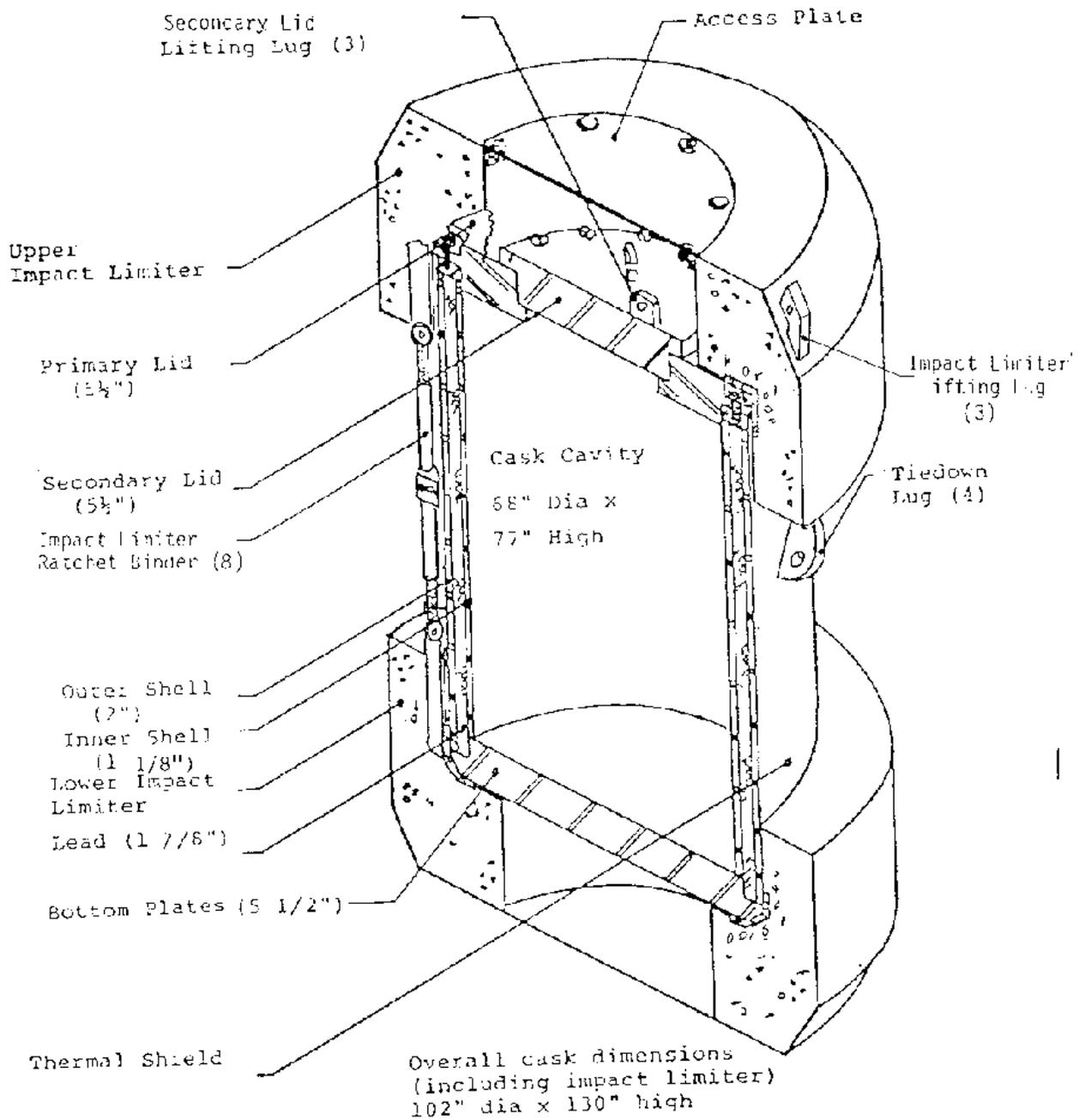


Figure 1-1

CNS 10-160B GENERAL ARRANGEMENT

Figure 1-1

1.3 Appendix

CNS-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 CNS 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 0.105 inch thick stainless-steel plate with a 0.16 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 Table 3.1. Initial conditions and assumptions are listed in Table 3.2.

The results summarized in Table 3.1 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  
Summary of Thermal Results

Condition	Normal Conditions		Hypothetical Accident		
	Calculated <sup>(1)</sup> Value	Maximum Allowable	Calculated <sup>(1)</sup> Value	Analyzed <sup>(2)</sup>	Maximum Allowable
Maximum temperature difference across the cask body (°F)	0.4617	<sup>(3)</sup>	30.3	45	<sup>(3)</sup>
Maximum temperature difference across the outer shell (°F)	0.05	<sup>(3)</sup>	15.3	24	<sup>(3)</sup>
Maximum temperature difference across the inner shell (°F)	0.03	<sup>(3)</sup>	1.7	2	<sup>(3)</sup>
Maximum average wall temperature (°F)	168	<sup>(3)</sup>	243	334	<sup>(3)</sup>
Maximum lead temperature (°F)	168	622	243	335	622
Maximum seal (or cask body) temperature (°F)	168	250 <sup>(4)</sup>	252	352	400 <sup>(5)</sup>
Maximum internal pressure (PSIG)	2.7	<sup>(3)</sup>	4.8	7.3	<sup>(3)</sup>

## 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 obtained by conservatively increasing the results from the analyses presented in this chapter.
- (3) Set by stress considerations.
- (4) See Section 3.4.2
- (5) See Section 3.5.3

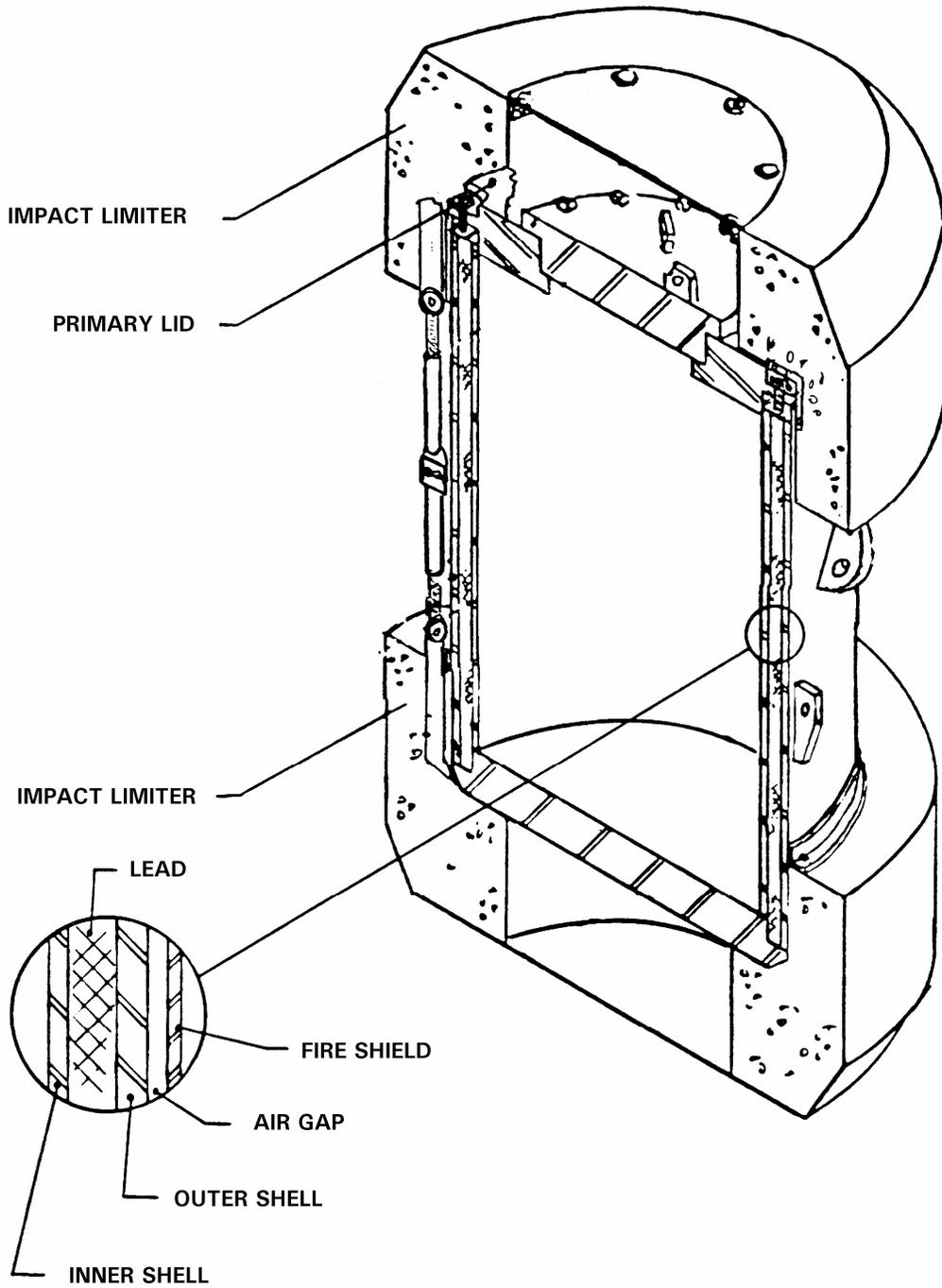


Figure 3.1  
Location of Components Analyzed in Thermal Design

Table 3.2

## Summary of Initial Conditions and Assumptions

<b>Condition or Assumption</b>	<b>Normal Conditions</b>	<b>Hypothetical Accident</b>
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,  $\epsilon$ , 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

<b>Material</b>	<b>Property</b>	<b>Ref.:Page</b>	<b>Value</b>
Steel	Density	2:536	488 lb/ft <sup>3</sup>
	$\epsilon$ (Outside)	3:648	0.8
	$\epsilon$ (Inside)	4:133	0.15
Lead	Density	2:535	710 lb/ft <sup>3</sup>
	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).

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

where:

C = 0.19 (assumes the cask is vertical)  
 h = Heat transfer coefficient (BTU/hr-sq ft-F)  
 T<sub>s</sub> = cask surface temperature (Degrees F)  
 T<sub>a</sub> = 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.

$$\text{(Equation 2)} \quad q = \sigma \epsilon F A (T_I^4 - T_J^4)$$

where:

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

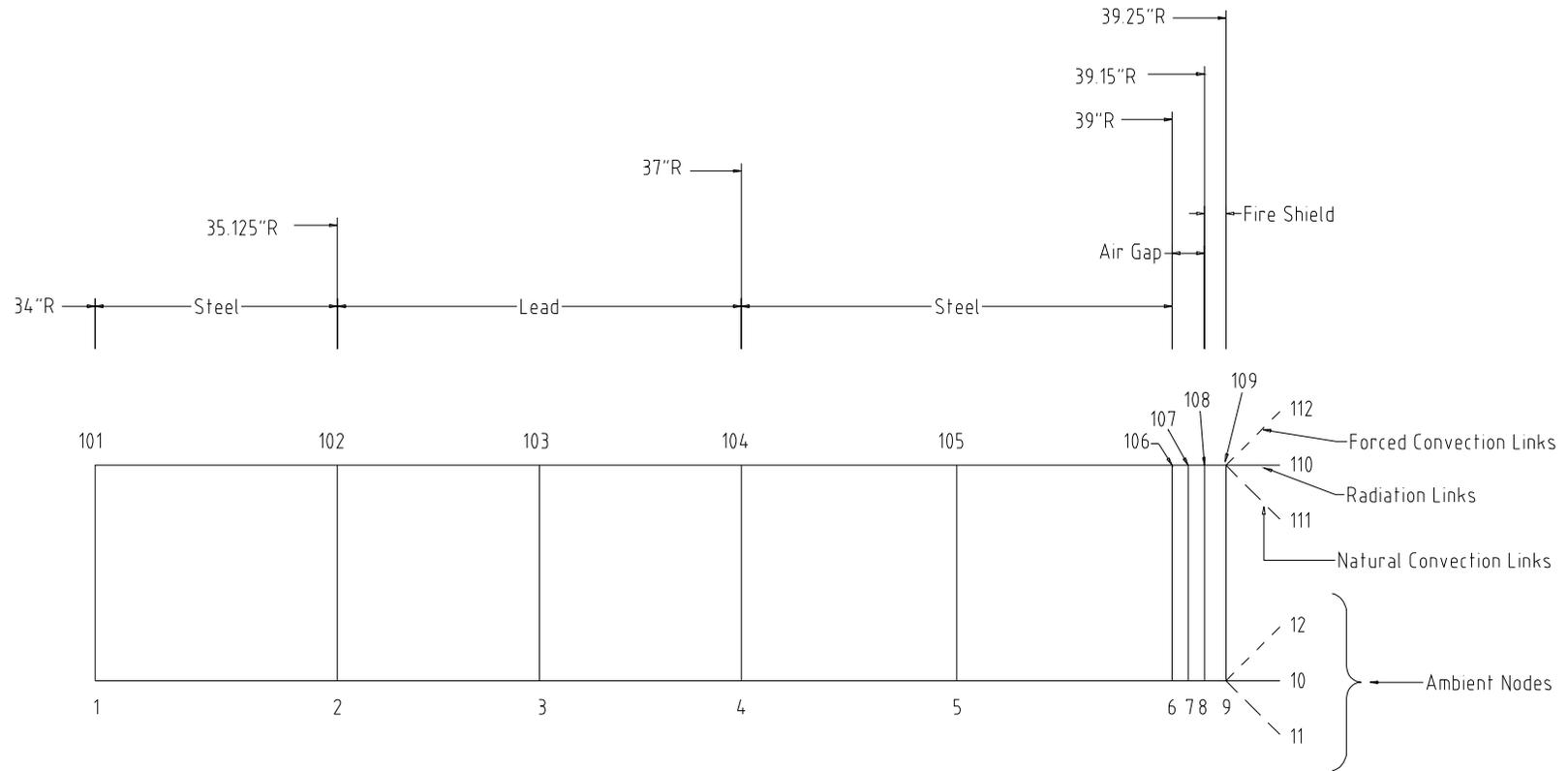


Figure 3.2

Node and Element Locations in the CNS 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,  $\epsilon$ , for heat transfer between two infinite parallel planes as given by equation 3 (Reference 2, page 336).

$$\text{(Equation 3)} \quad \epsilon = \frac{\epsilon_1 \epsilon_2}{\epsilon_2 + \epsilon_1 - \epsilon_1 \epsilon_2}$$

where:

$\epsilon$  = overall emissivity  
 $\epsilon_1$  = surface 1 emissivity  
 $\epsilon_2$  = 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).

$$\text{(Equation 4)} \quad q = \frac{\sigma A_1 (T_1^4 - T_2^4)}{\frac{1}{\epsilon_1} + \frac{(A_1)(1/\epsilon_2 - 1)}{A_2}}$$

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  $\epsilon = \epsilon_1 = \epsilon_2$ , a form factor may be defined by equation 5 to put equation 4 in the same form as equation 2.

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

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 surface of the inside wall of the cask (nodes 1 and 101), and is calculated to be 168°F. 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 is at the outside surface of the fire shield (nodes 9 and 109), and is equal to 161°F. The maximum temperature of the contents depends on the physical characteristics of the particular contents carried. Based on the small temperature gradient within the cask itself (only 0.4617°F between inside and outside surfaces), the maximum contents temperature can be considered to be 168°F. This temperature is well below that at which damage to the waste might occur.

#### 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 set equal to the maximum inside surface temperature of the cask. The maximum inside surface temperature of the cask is 168°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 168°F,  $P_1$ , may be calculated by the ideal gas relationship given in equation 6.

(Equation 6)

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

$$P_1 = \frac{(460 + 168 \text{ }^\circ\text{R})}{(460 + 70 \text{ }^\circ\text{R})} * 14.70 \text{ PSIA}$$

$$P_1 = 17.4 \text{ PSIA}$$

The vapor pressure contributed by water in the cavity at 168°F is 5.7 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)                     $17.4 \text{ PSIA} + 5.7 \text{ PSIA} - 14.7 \text{ PSIA} = 8.4 \text{ PSIG}$

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  $0.4617^\circ\text{F}$  on the  $100^\circ\text{F}$  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  $168^\circ\text{F}$  and are within the required elastomer seal operating region of  $-40$  to  $250^\circ\text{F}$ . 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  $0.4617^\circ\text{F}$ . 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  $168^\circ\text{F}$ . 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:

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

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

$$1 m = 39.37 \text{ inch}$$

$$1^\circ C = 1.8^\circ F$$

Therefore,

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

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

$$\text{(Equation 8)} \quad q = hA (T_s - T_a)$$

where:

h = Heat transfer coefficient (BTU/hr-sq ft-F)

A = Area (sq ft)

T<sub>s</sub> = cask surface temperature (Degrees F)

T<sub>a</sub> = 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.

### 3.5.2 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. However, the maximum seal temperature will not exceed the maximum temperature of the cask body, 252°F. Thus, the seal temperature is conservatively set equal to the maximum calculated temperature of the cask body plus 100°F for an analyzed maximum of 352°F. The HAC temperature criterion (maximum allowable) for the seal material is conservatively set at 400°F with a duration of 1 hour.

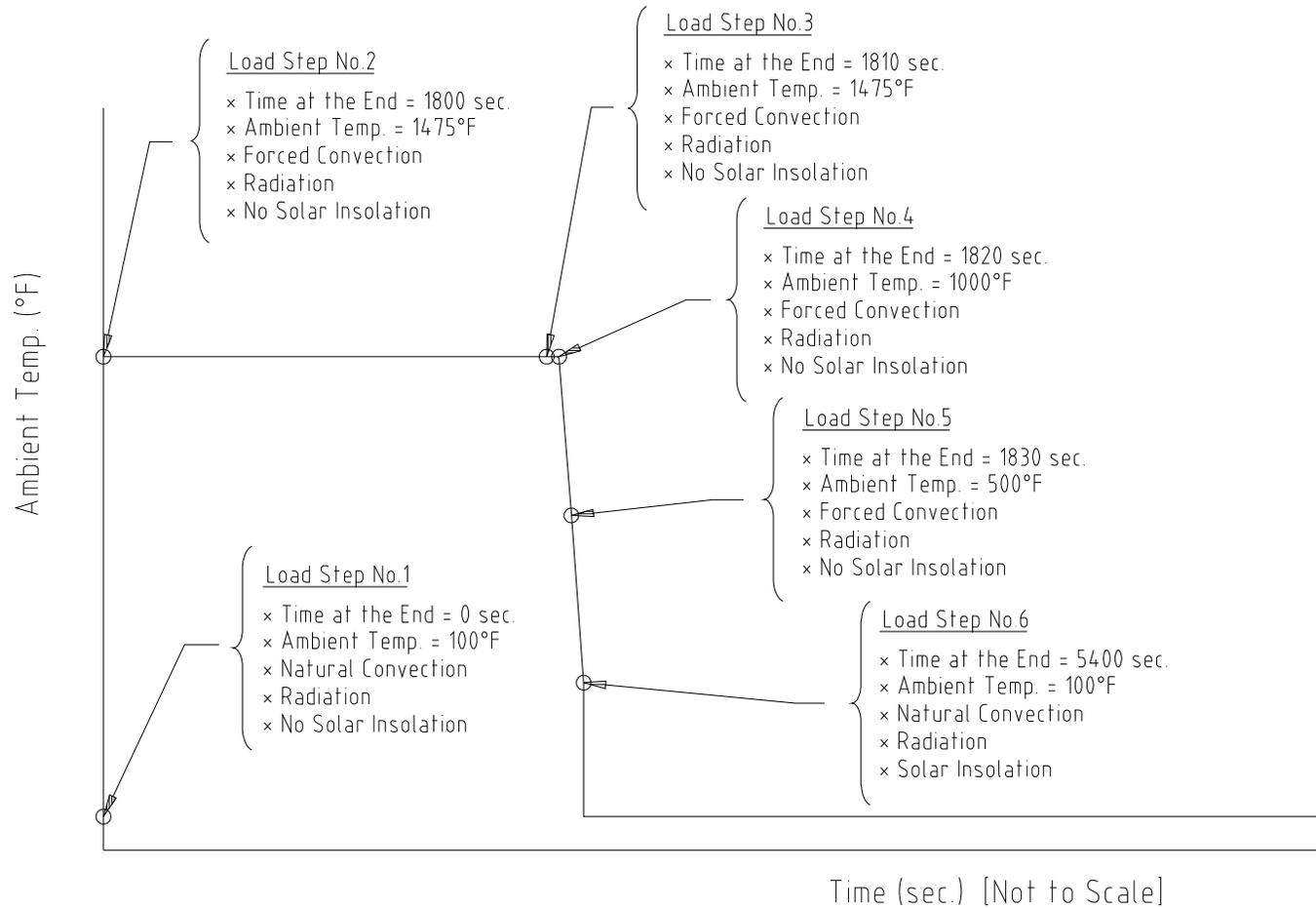


Figure 3.3  
Transient Fire Analysis - Load Step and Boundary Conditions Schematic

Table 3.4

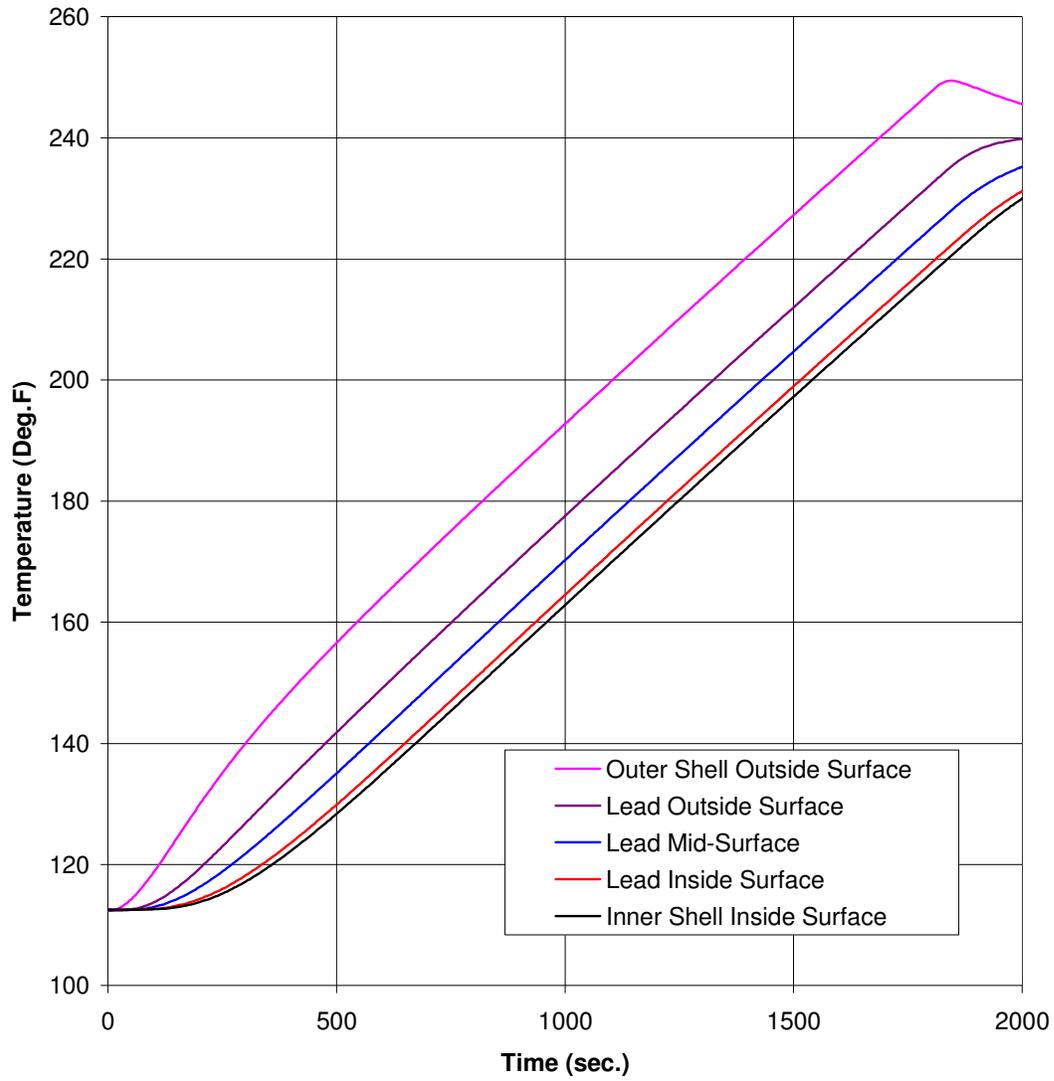
## Summary of Maximum Hypothetical Accident Temperatures

Component	Maximum Calculated Temp.			Maximum Allowable Temperature (°F)
	Location (Node No.)	Time (Hr. <u>sec</u> )	Value (°F)	
Fire Shield	9, 109	<u>0.501810</u>	<u>13601361</u>	N.A.
Structural Shell	6, 106	<u>0.511845</u>	<u>252249</u>	800
Lead	4, 104	<u>0.742705</u>	<u>243240</u>	622
Seals	N.A.	<u>0.511845</u>	<u>252249</u>	400

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.



### 10-160B Cask Hypothetical Fire Accident Analysis



### 10-160B Cask Hypothetical Fire Accident Analysis

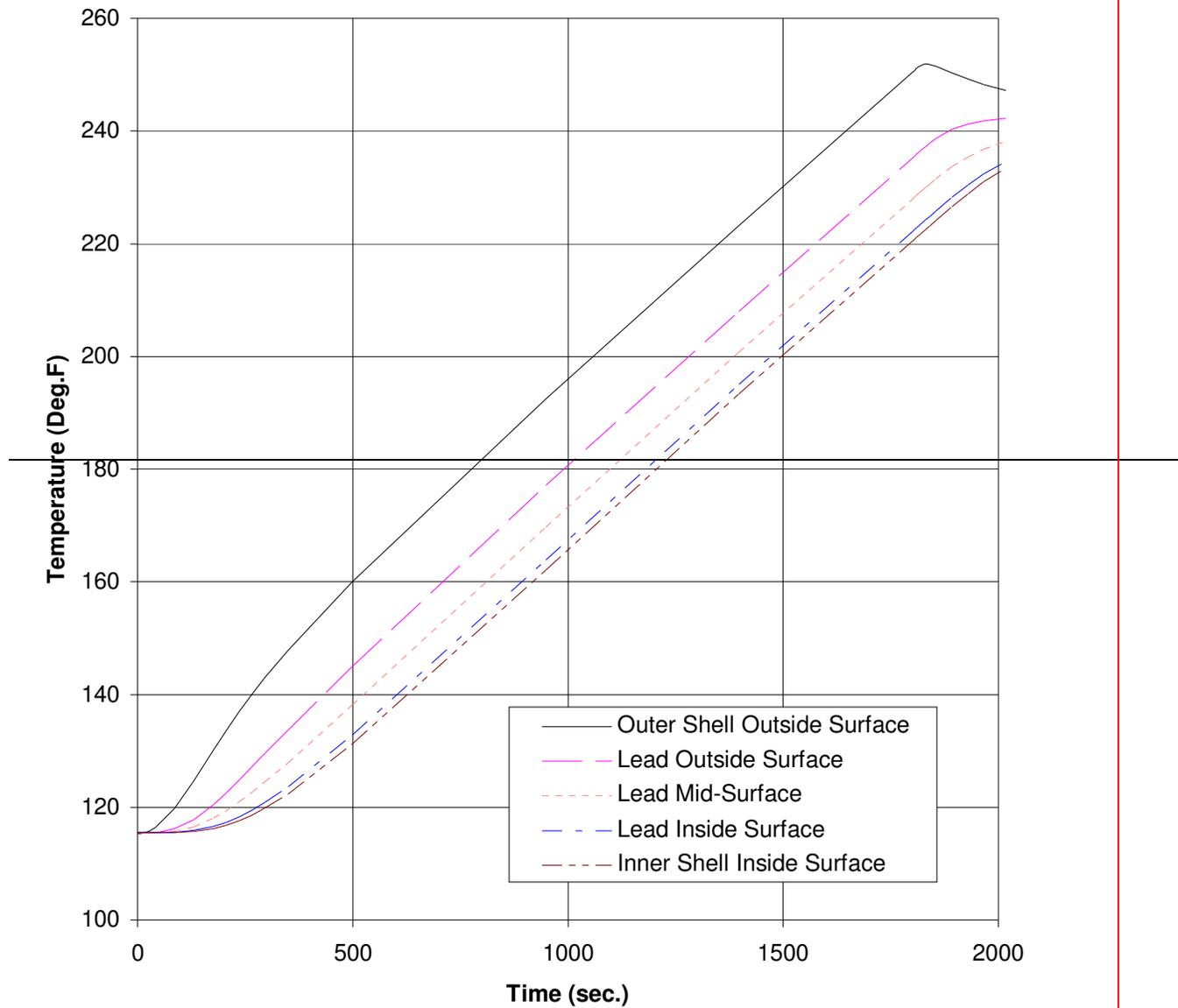
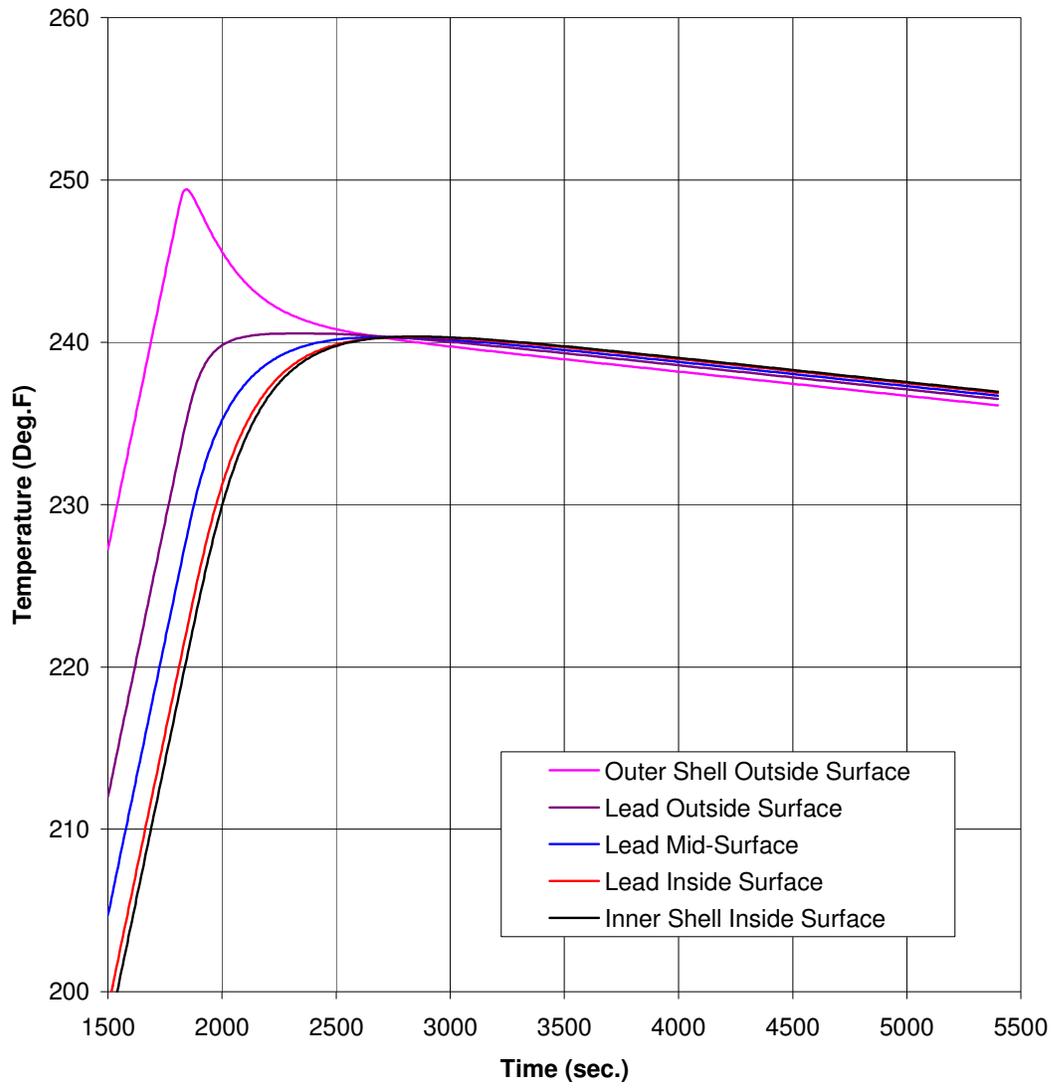


Figure 3.4

Hypothetical Accident - Fire Transient:  
Temperature Versus Time



### 10-160B Cask Hypothetical Fire Accident Analysis



### 10-160B Cask Hypothetical Fire Accident Analysis

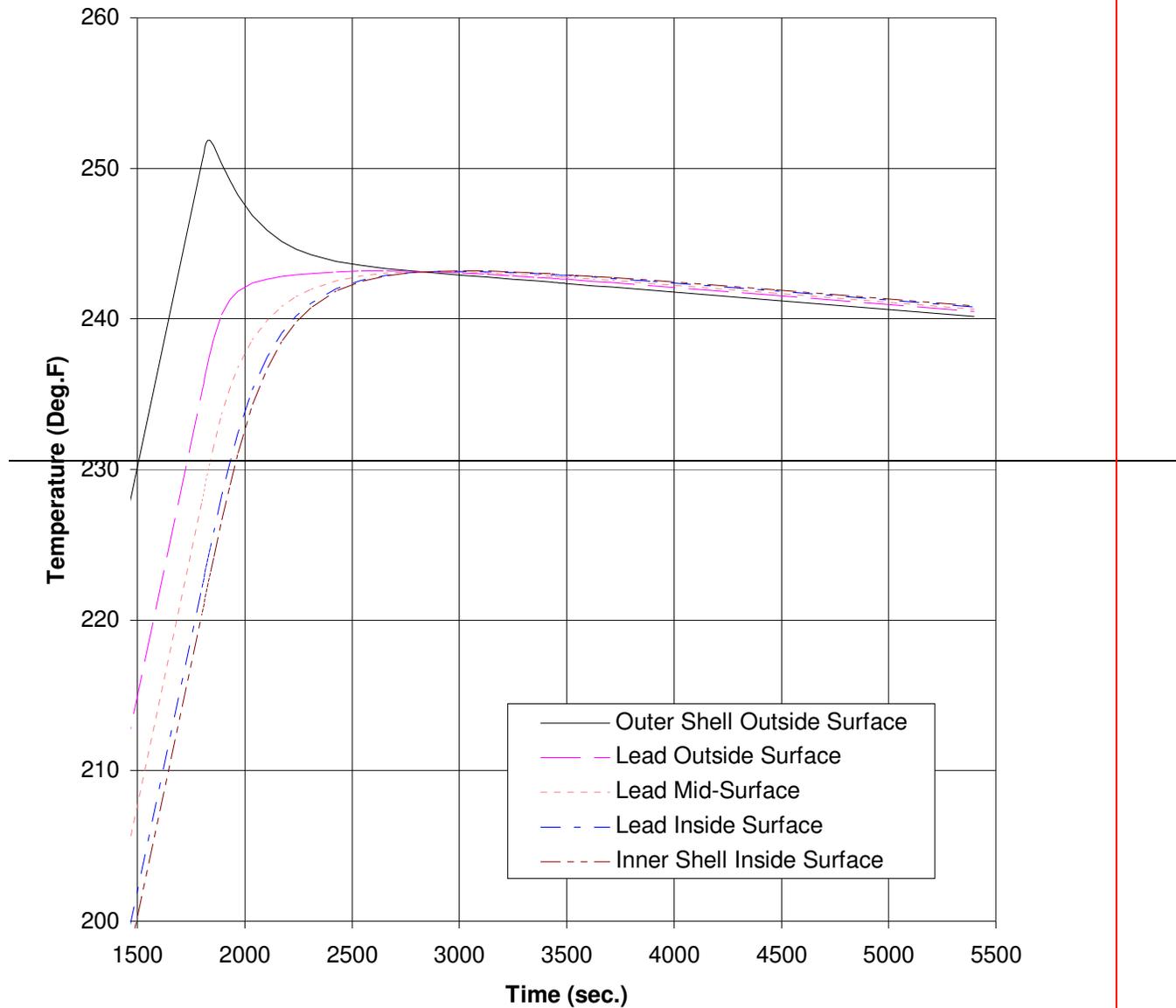


Figure 3.5

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 set at least equal to the maximum inside surface temperature of the cask. The maximum inside surface temperature of the cask occurs at 0.84-79 hours after the start of the hypothetical accident, ~~and~~ The calculation gives the maximum temperature as 240°F but the gas temperature is conservatively set as equal to 243°F. Assuming that atmospheric pressure exists inside the cask at 70°F, the partial pressure of the gas mixture in the cask at 243°F,  $P_1$ , may be calculated by the ideal gas relationship given in equation 8.

(Equation 9)

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

$$P_1 = \frac{(460 + 243 \text{ }^\circ\text{R})}{(460 + 70 \text{ }^\circ\text{R})} * 14.70 \text{ PSIA}$$

$$P_1 = 19.5 \text{ PSIA}$$

The vapor pressure contributed by water in the cavity at 243°F is 26.4 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)             $19.5 \text{ PSIA} + 26.4 \text{ PSIA} - 14.7 \text{ PSIA} = 31.2 \text{ PSIG}$

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.

### 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 30.3° F and occurs 15.830 minutes after the start of the fire. The maximum temperature difference across the outer shell is 15.3°F (occurring 15.830 minutes after the start of the fire) and the maximum temperature difference across the inner shell is 1.7°F (occurring 15.830.5 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 243.240°F and occurs at 48.45 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 within the package due to the hypothetical accident thermal conditions are below maximum allowable limits. Seal temperature is conservatively set equal to the maximum wall temperature of 252°F which occurs at 30 minutes after the start of the fire. This temperature is below the required 400°F HAC temperature limit for the elastomer seals. The maximum lead temperature of 243°F occurs at 0.74 hours after the start of the fire. The maximum lead temperature is well below the 622°F melting point of lead. 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. 5.2 Computer Software, ANSYS Inc., Cannonsburgh, Pennsylvania, 1996.
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.

## 4. CONTAINMENT

This chapter describes the containment configuration and test requirements for the CNS 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 3/4 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, 1 3/4 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 1/2 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 CNS 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  $3.25 \times 10^{-6}$  ref-cm<sup>3</sup>/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<sub>2</sub> 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):

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

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 168 degrees-F and 8.4 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<sub>2</sub> or less
- Free water is limited to restriction of one-percent of solid volume
- Hence the curie content = 0.01 x 3000 A<sub>2</sub>
- The minimum void volume occurs when the largest liner is shipped

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

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

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

$$\begin{aligned} \text{Void Volume} &= 269,064 - 252,103 = 16,961 \text{ in}^3 \\ &= 16,961 \text{ in}^3 \times 16.4 \text{ cm}^3/\text{in}^3 \\ &= 278,161 \text{ cm}^3 \end{aligned}$$

Hence,

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

And,

$$\begin{aligned} \text{(Equation 5)} \quad L_n &= \frac{R_n}{C} = \frac{2.78 \times 10^{-10} A_2 \text{ Ci/sec}}{1.08 \times 10^{-4} A_2 \text{ Ci/cm}^3} \quad \text{Eqn. 3, Ref. 4} \\ &= 2.57 \times 10^{-6} \text{ cm}^3/\text{sec} \end{aligned}$$

A leak rate at standard conditions will be calculated which is equivalent to a volumetric leak rate of  $2.57 \times 10^{-6} \text{ cm}^3/\text{sec}$ .

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

$$L_u = (F_c + F_m)(P_u - P_d) \left( \frac{P_a}{P_u} \right) \quad \text{Eqn. B.5, Reference 4}$$

$$F_m = \frac{3.81 \times 10^3 D^3 \sqrt{\frac{T}{M}}}{a P_a} \quad \text{Eqn. B.4, Reference 4}$$

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

where:

$L_u$  = upstream leakage rate,  $\text{cm}^3/\text{sec}$

$$\mu_{\text{air}} = 0.0185 \text{ cP}$$

$$T = 168^\circ\text{F} = 349^\circ\text{K} \quad \text{Section 3.4.4}$$

$$P_u = 8.4 \text{ psig} = 1.57 \text{ atm}$$

$$P_d = 1.0 \text{ atm}$$

$$P_a = (1.57 + 1.0)/2 = 1.28 \text{ atm}$$

$$M_{\text{water}} = 18 \text{ g/gmole}$$

$a$  = 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:

$$F_c = \frac{2.49 \times 10^6 D^4}{(0.6)(0.0185)} = 2.24 \times 10^8 D^4$$

$$F_m = \frac{3.81 \times 10^3 D^3 \sqrt{\frac{349}{18}}}{(0.6)(1.28)} = 2.18 \times 10^4 D^3$$

$$2.57 \times 10^{-6} = (2.24 \times 10^8 D^4 + 2.18 \times 10^4 D^3)(1.57 - 1.0) \left( \frac{1.28}{1.57} \right) \quad \text{Solve for } D$$

$$D = 3.74 \times 10^{-4} \text{ cm}$$

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

$$a = 0.6 \text{ cm}$$

$$M_{\text{air}} = 29 \text{ g/gmole}$$

$$\mu_{\text{air}} = 0.0185 \text{ cP}$$

$$P_u = 1.0 \text{ atm}$$

$$P_d = 0.01 \text{ atm}$$

$$P_a = (1.0 + 0.01)/2 = 0.505 \text{ atm}$$

$$T = 298^\circ\text{K}$$

$$F_c = \frac{(2.49 \times 10^6)(3.74 \times 10^{-4})^4}{(0.6)(0.0185)} = 4.38 \times 10^{-6} \frac{\text{cm}^3}{\text{atm} - \text{sec}}$$

$$F_m = \frac{(3.81 \times 10^3)(3.74 \times 10^{-4})^3 \sqrt{\frac{298}{29}}}{(0.60)(0.505)} = 2.11 \times 10^{-6} = \frac{\text{cm}^3}{\text{atm} - \text{sec}}$$

Substituting into B.5:

$$L_{std} = (4.38 \times 10^{-6} + 2.11 \times 10^{-6})(1.0 - 0.01) \left( \frac{0.505}{1.0} \right) = 3.25 \times 10^{-6} \frac{\text{ref} - \text{cm}^3}{\text{sec}}$$

#### 4.2.2 Pressurization of the Containment Vessel

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 CNS 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 CNS 10-160B package.

#### 4.2.4 Coolant Loss

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

### 4.3 Containment Requirements for Hypothetical Accident Conditions

#### 4.3.1 Leak Test Requirements

Section 2.7 demonstrates that the CNS 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 CNS 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.

$$\begin{aligned} \text{(Equation 9)} \quad R_a &= (A_2/\text{week})(1 \text{ week}/168 \text{ hr}) \\ &= 5.952 \times 10^{-3} A_2 / \text{hr} \end{aligned}$$

In Section 3.5.4, it is noted that the saturated water vapor in equilibrium at 243 degrees-F and 31.2 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 =  $3000 \times A_2$  or less
- Free water is limited to restriction of one-percent of solid volume
- Hence the curie content =  $0.01 \times 3000 A_2$
- The minimum void volume occurs when the largest liner is shipped

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

The largest liner will have at least  $\frac{3}{4}$  inch of radial clearance and a  $1\frac{1}{2}$  inch of height difference, giving a volume

$$\begin{aligned}
 \text{(Equation 11)} \quad V(\text{liner}) &= \frac{\pi}{4} \times (67.25 - 2 \times 0.75)^2 \times (75.75 - 1.5) \text{ in}^3 \\
 &= 252,103 \text{ in}^3
 \end{aligned}$$

$$\begin{aligned}
 \text{Void Volume} &= 269,064 - 252,103 = 16,961 \\
 &= 16,961 \text{ in}^3 \times 16.4 \text{ cm}^3/\text{in}^3 \\
 &= 278,161 \text{ cm}^3
 \end{aligned}$$

Hence,

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

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.

$$\begin{aligned}
 \text{(Equation 13)} \quad L_a &= \frac{5.952 \times 10^{-3} A_2 \text{ Ci/hr}}{1.08 \times 10^{-4} A_2 \text{ Ci/cm}^3} \frac{1 \text{ hr}}{3600 \text{ sec}} \\
 &= 1.53 \times 10^{-2} \text{ cm}^3/\text{sec}
 \end{aligned}$$

The allowable leak rate during the hypothetical accident is larger than during the normal conditions of transport,  $3.25 \times 10^{-6}$  ref-cm<sup>3</sup>/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 CNS 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  $1 \times 10^{-3}$  ref-cm<sup>3</sup>/sec. This section will show that the requirement of ANSI N14.5 is met by testing to a sensitivity of  $1 \times 10^{-3}$  ref-cm<sup>3</sup>/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<sup>3</sup>.

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<sup>3</sup>, the test sensitivity will be greater than the primary lid's.

$$\text{(Equation 15)} \quad L_R = \frac{V T_s}{3600 HP_s} \left[ \frac{P_1}{T_1} - \frac{P_2}{T_2} \right] \quad \text{Eqn B.14, Reference 4}$$

where:

$L_R$  = atm-cm<sup>3</sup>/sec of air at standard conditions

$V$  = gas volume in the test annulus cm<sup>3</sup>

$T_s$  = 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 Required Hold Time at the Test Pressure

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<sup>-3</sup> ref-cm<sup>3</sup>/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:

$$L \leq S/2 \quad \text{Equation B-17, Reference 4}$$

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

$$V = 55 \text{ cm}^3$$

$$T_s = T_1 = T_2 = 298^\circ\text{K}$$

$$P_1 - P_2 = \text{pressure instrument sensitivity} = 0.1 \text{ psig}$$

$$5 \times 10^{-4} = \frac{(55 \text{ cm}^3)(298^\circ \text{K})}{3600(H \text{ hr})(1 \text{ atm})} \left( \frac{0.007 \text{ atm}}{298^\circ \text{K}} \right)$$

Solve for H:

$$H = 0.214 \text{ hr} = 12.8 \text{ min.}$$

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 ~~CNS~~ 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 it 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 ( $L_{std} = 3.25 \times 10^{-6}$ ) is:

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

$$D_{\max} := 3.74 \cdot 10^{-4} \cdot \text{cm} \quad \text{From Section 4.2.1}$$

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

Determine the equivalent air/R12 mixture ( $L_{\text{mix}}$ ) 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.

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

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

$$P_{\text{air}} = 0.33 \cdot \text{atm}$$

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

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

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

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

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

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

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

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

$$\Rightarrow \mu_{\text{mix}} = 0.0131 \cdot \text{cP}$$

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

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

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

then,

$$F_c = 6.175 \times 10^{-6} \frac{\text{cm}^3}{\text{sec} \cdot \text{atm}}$$

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

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

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

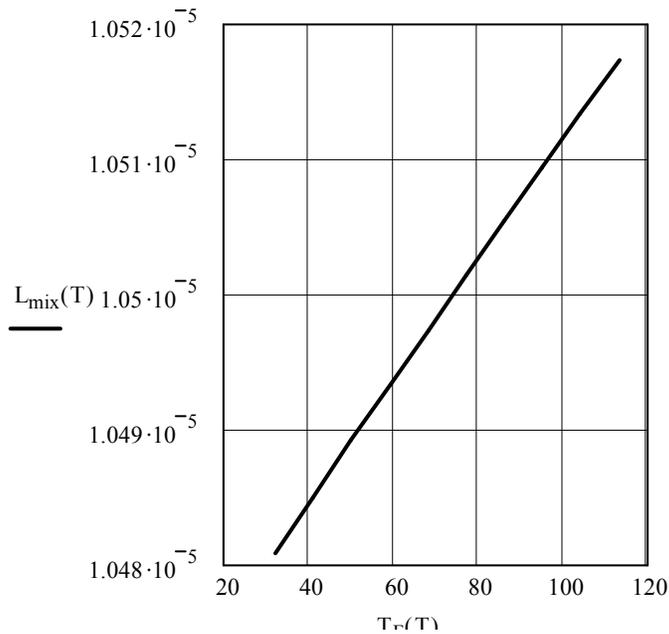


Fig.4.1 - Allowable R-12 Gas/Air Mixture Test Leakage, cm<sup>3</sup>/sec, versus test temperature, deg.F

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.

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

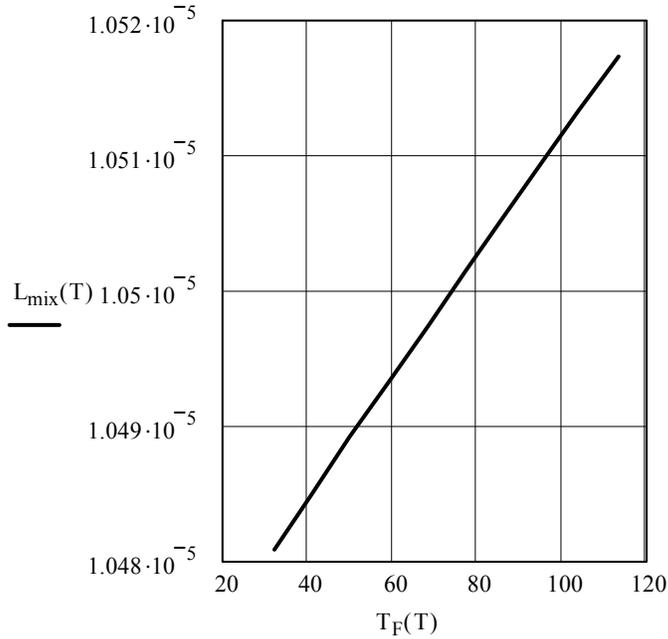


Fig.4.2 - Allowable R-12 test leakage, cm<sup>3</sup>/sec versus test temperature, deg.F

Determine the equivalent mass flow rate for L<sub>R12</sub> in oz/yr:

$$N(T) := \frac{P_{R12} \cdot V}{R_0 \cdot T} \quad \text{Ideal Gas Law}$$

where,

$$R_0 := \frac{82.05 \text{ cm}^3 \cdot \text{atm}}{\text{mole} \cdot \text{K}}$$

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.

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

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

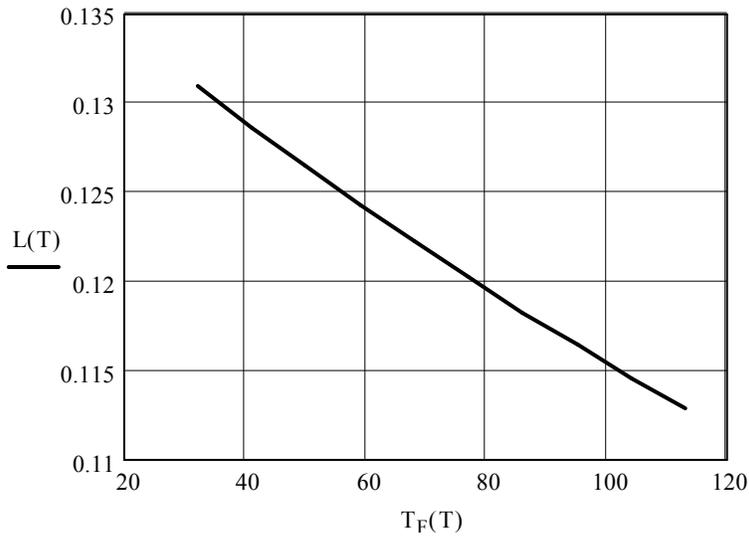


Fig.4.3 - Allowable R-12 test leakage, oz/yr, versus test temperature, deg.F

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:

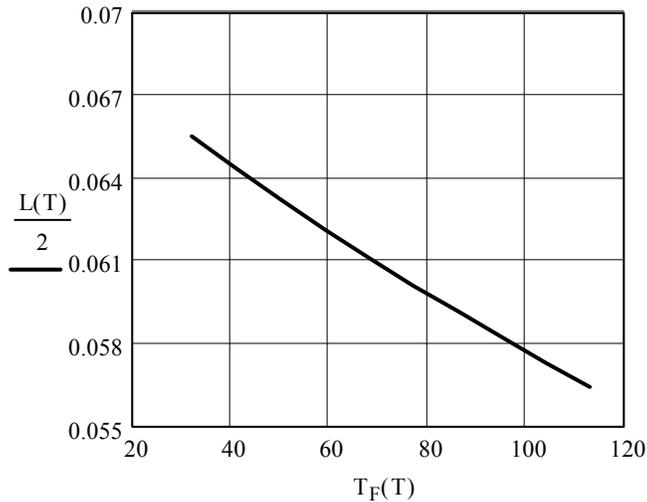


Fig.4.4 - Allowable R-12 test leakage sensitivity, oz/yr, versus test temperature, deg.F

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 CNS 10-160B cask.

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 it 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 4.6 have been verified by hand calculations.

##### 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 ( $L_{\text{std}} = 3.25 \times 10^{-6}$  ref-  $\text{cm}^3/\text{sec}$ ) is:

$$D_{\max} := 3.74 \cdot 10^{-4} \cdot \text{cm}$$

Next, determine the equivalent air/He mixture ( $L_{\text{mix}}$ ) 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.

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

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

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

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

$$P_a = 1.85 \cdot \text{atm}$$

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

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

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

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

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

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

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

$$T := 273\text{-K}, 278\text{-K}.. 318\text{-K} \quad \text{Temperature range for test: } 32^{\circ}\text{F to approx. } 113^{\circ}\text{F}$$

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

$$\Rightarrow F_c = 4.203 \cdot 10^{-6} \cdot \frac{\text{cm}^3}{\text{sec} \cdot \text{atm}}$$

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

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

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

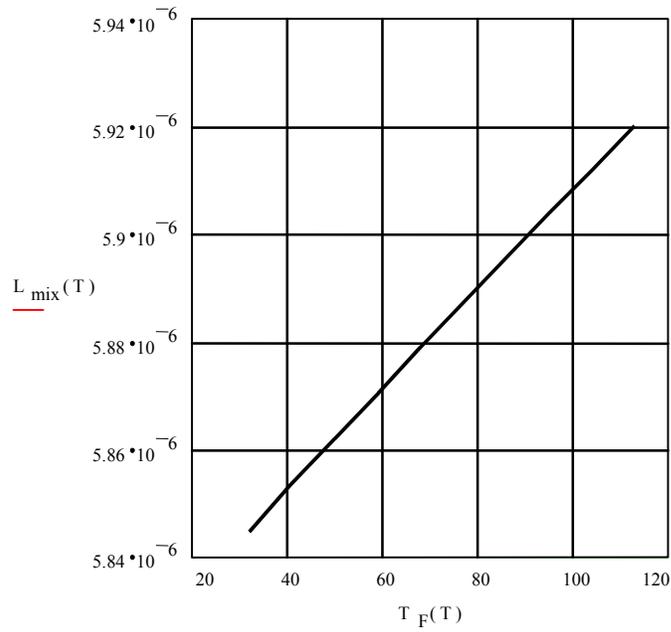


Fig.4.5 - Allowable He/Air Mixture Test Leakage, cm<sup>3</sup>/sec, versus test temperature, deg.F

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.

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

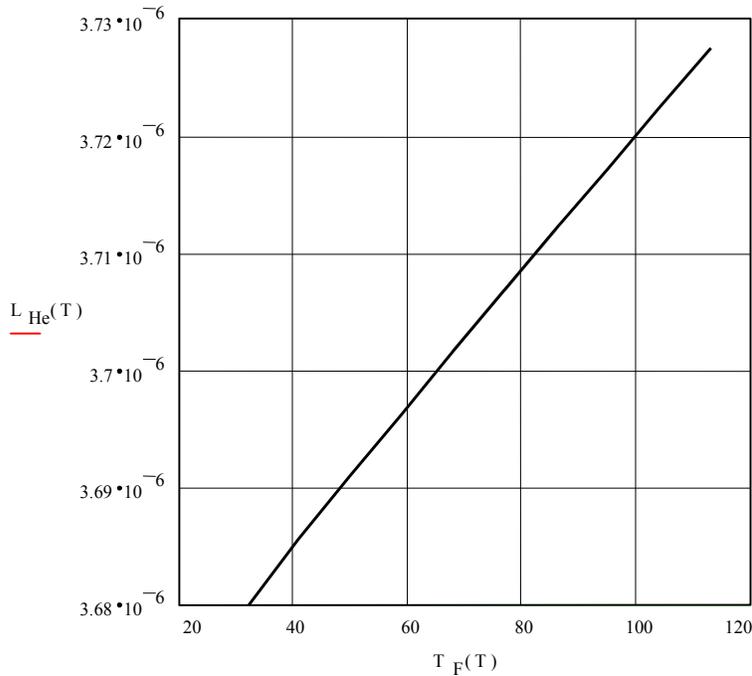


Fig.4.6 - Allowable Helium test leakage, cm<sup>3</sup>/sec versus test temperature, deg.F

Determine the equivalent mass flow rate for L<sub>He</sub> in oz/yr:

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

where,

$$R_o := \frac{82.05 \text{ cm}^3 \cdot \text{atm}}{\text{moleK}}$$

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.

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

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

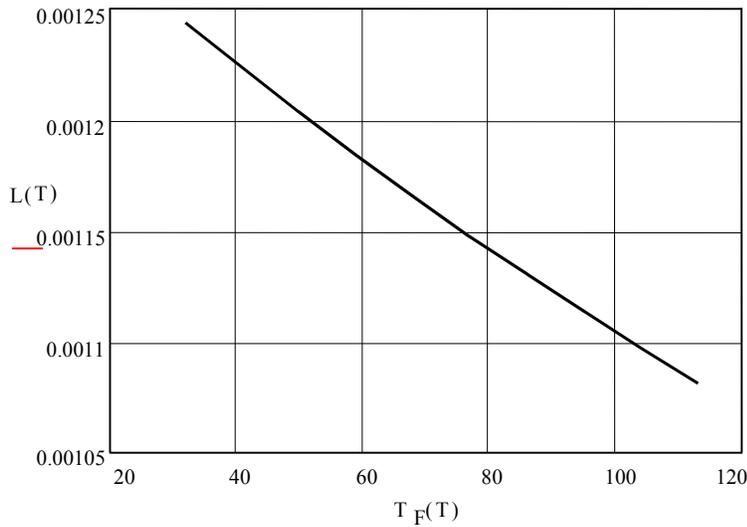


Fig.4.7 - Allowable helium test leakage, oz/yr, versus test temperature, deg.F

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:

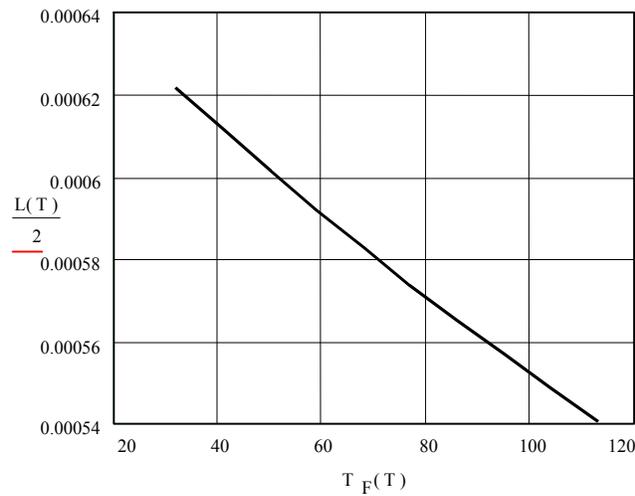


Fig.4.8 - Allowable helium test leakage sensitivity, oz/yr, versus test temperature, deg.F

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 CNS 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.

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 it 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 4.7 have been verified by hand calculations.

##### 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 ( $L_{std} = 3.25 \times 10^{-6}$ ) is:

$$D_{max} := 3.74 \cdot 10^{-4} \cdot \text{cm}$$

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.

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

$$P_{air} := 9.92 \text{ in}_\text{Hg}$$

$$P_{air} = 0.33 \text{ atm}$$

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

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

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

$$P_a = 1.85 \text{ atm}$$

The properties of R134a are given in the attached literature:

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

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

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

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

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

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

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

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

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

$$\Rightarrow F_c = 6.344 \times 10^{-6} \frac{\text{cm}^3}{\text{sec} \cdot \text{atm}}$$

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

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

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

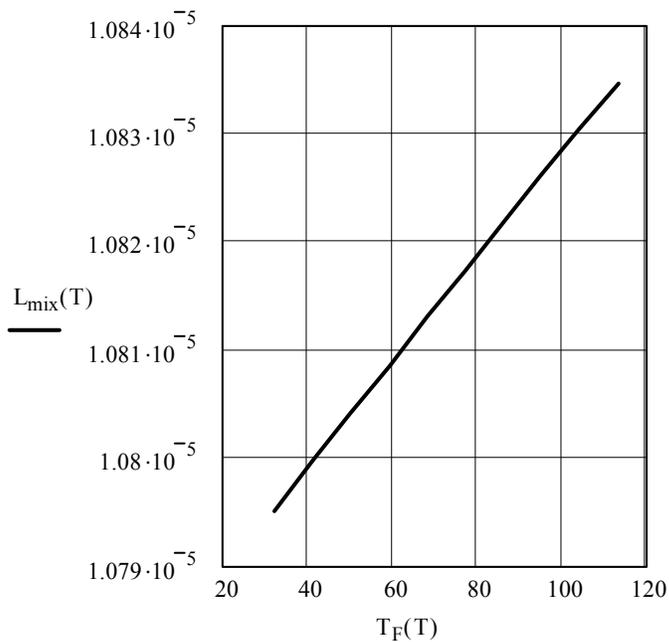


Fig.4.9 - Allowable R134a/Air Mixture Test Leakage, cm<sup>3</sup>/sec, versus test temperature, deg.F

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.

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

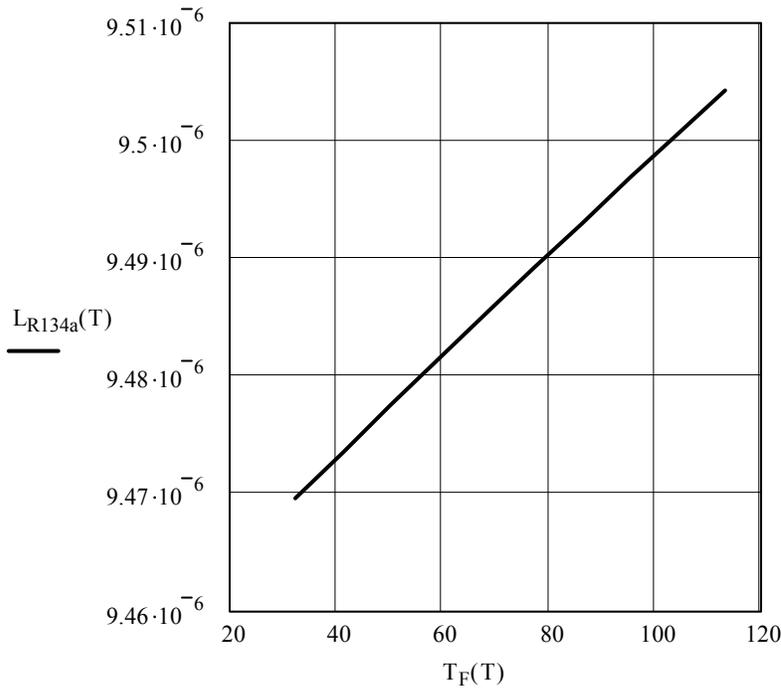


Fig.4.10 - Allowable R-134a test leakage, cm<sup>3</sup>/sec versus test temperature, deg.F

Determine the equivalent mass flow rate for L<sub>R134a</sub> in oz/yr, the measurement used by the detector:

$$N(T) := \frac{P_{R134a} \cdot V}{R_0 \cdot T} \quad \text{Ideal Gas Law}$$

where,

$$R_0 := \frac{82.05 \text{ cm}^3 \cdot \text{atm}}{\text{mole} \cdot \text{K}} \quad \text{Universal Gas Constant}$$

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.

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

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

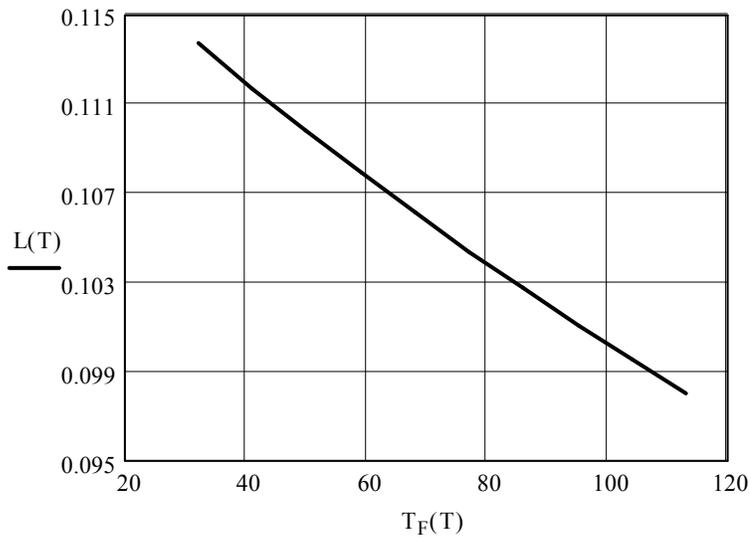


Fig.4.11 - Allowable R134a test leakage, oz/yr, versus test temperature, deg.F

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:

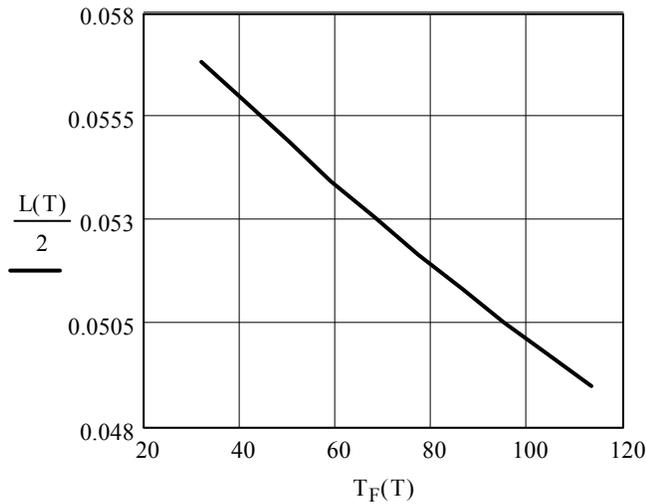


Fig.4.12 - Allowable R134a test leakage sensitivity, oz/yr, versus test temperature, deg.F

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%.

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 0.063 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.

##### 4.9.2 Test Conditions

The test is performed with a mass spectrometer leak detector. The test is conducted on the ~~CNS~~ 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  $1.0 \times 10^{-7}$  atm-cm<sup>3</sup>/sec of air (leaktight). The detector sensitivity must be less than or equal to  $5.0 \times 10^{-8}$  atm-cm<sup>3</sup>/sec. Similar tests are performed on the vent and drain ports, if so equipped.

4.11 References

1. Hansen Couplings, The Hansen Manufacturing Company, Cleveland, Ohio.
2. Mark's Standard Handbook for Mechanical Engineers, Theodore Baumeister, et. al., Eighth Edition, McGraw-Hill Book Company, New York, 1979.
3. Basic Engineering Thermodynamics, M. W. Zemansky and H. C. Van Ness, McGraw-Hill Book Company, New York, 1966.
4. American National Standard for Leakage Tests on Packages for Shipment of Radioactive Materials, American National Standards Institute, Inc., New York, ANSI N14.5-1997, 1998.
5. CRC Handbook of Chemistry and Physics, Robert C. Weast and Melvin J. Astle, eds., 62nd Edition, CRC Press, Inc., Boca Ration, Florida, 1981.
6. Flame and Detonation Initiation Area Propagation in Various Hydrogen - Air Mixtures With and Without Water Spray, L. W. Carlson, et. al., Atomic International Division of Rockwell International, Canoga Park, California, May 11, 1973.
7. Combustion, Flames and Explosions of Gases, B. Lewis and G. von Elbe, Academic Press, New York, 1961, Second Edition, Appendix B.
8. Nondestructive Testing Handbook, 2<sup>nd</sup> Ed., Vol. One, American National Standards Institute, Inc., New York, 1982.

4.10 Appendices

Appendix 4.10.1

Properties of R-134a

Appendix 4.10.2

Transuranic (TRU) Waste Compliance  
Methodology for Hydrogen Gas Generation



P134a



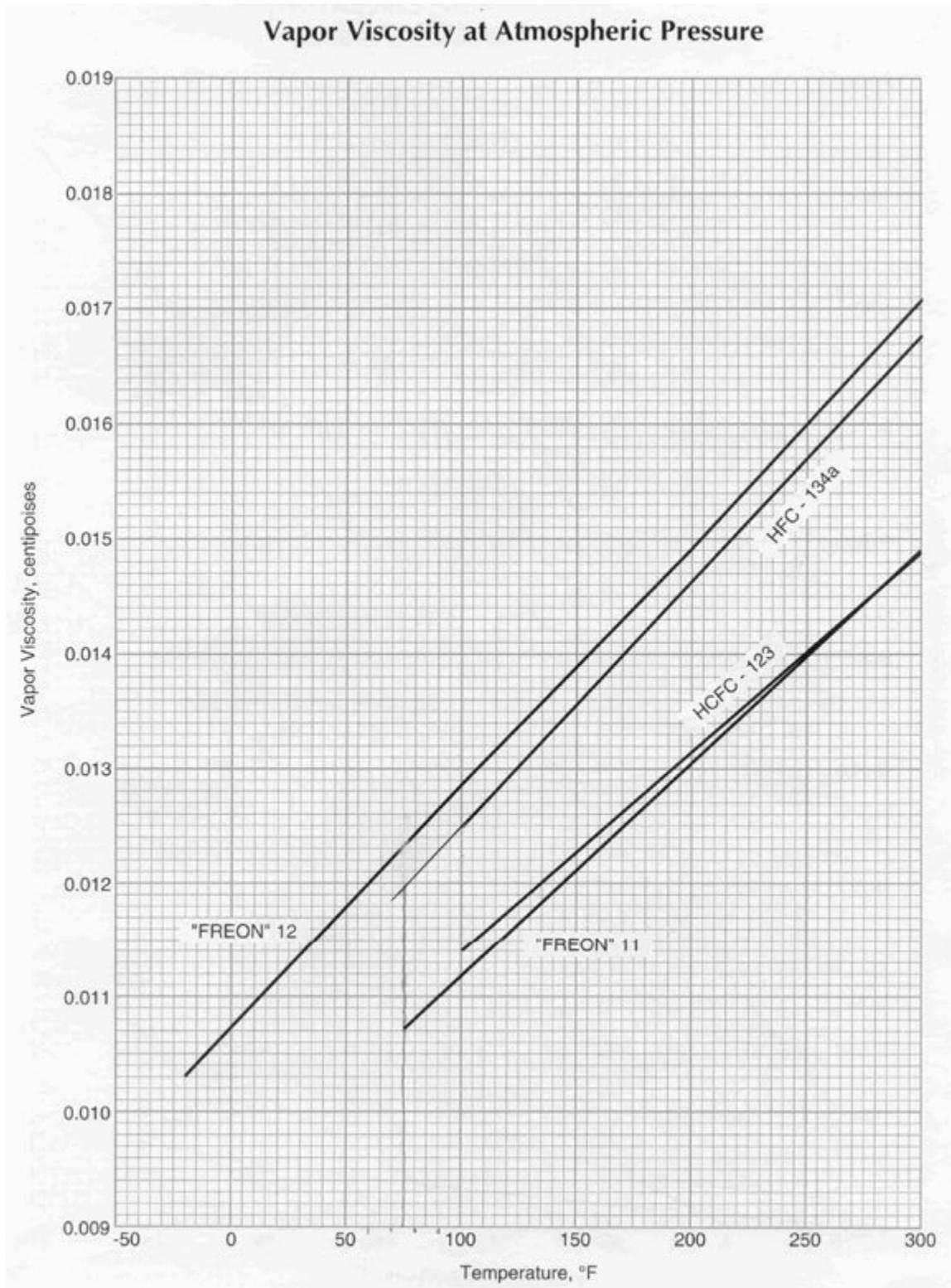
**Suva**<sup>®</sup>  
refrigerants

HFC-134a

Properties, Uses, Storage, and Handling

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# SUVA®

## REFRIGERANTS

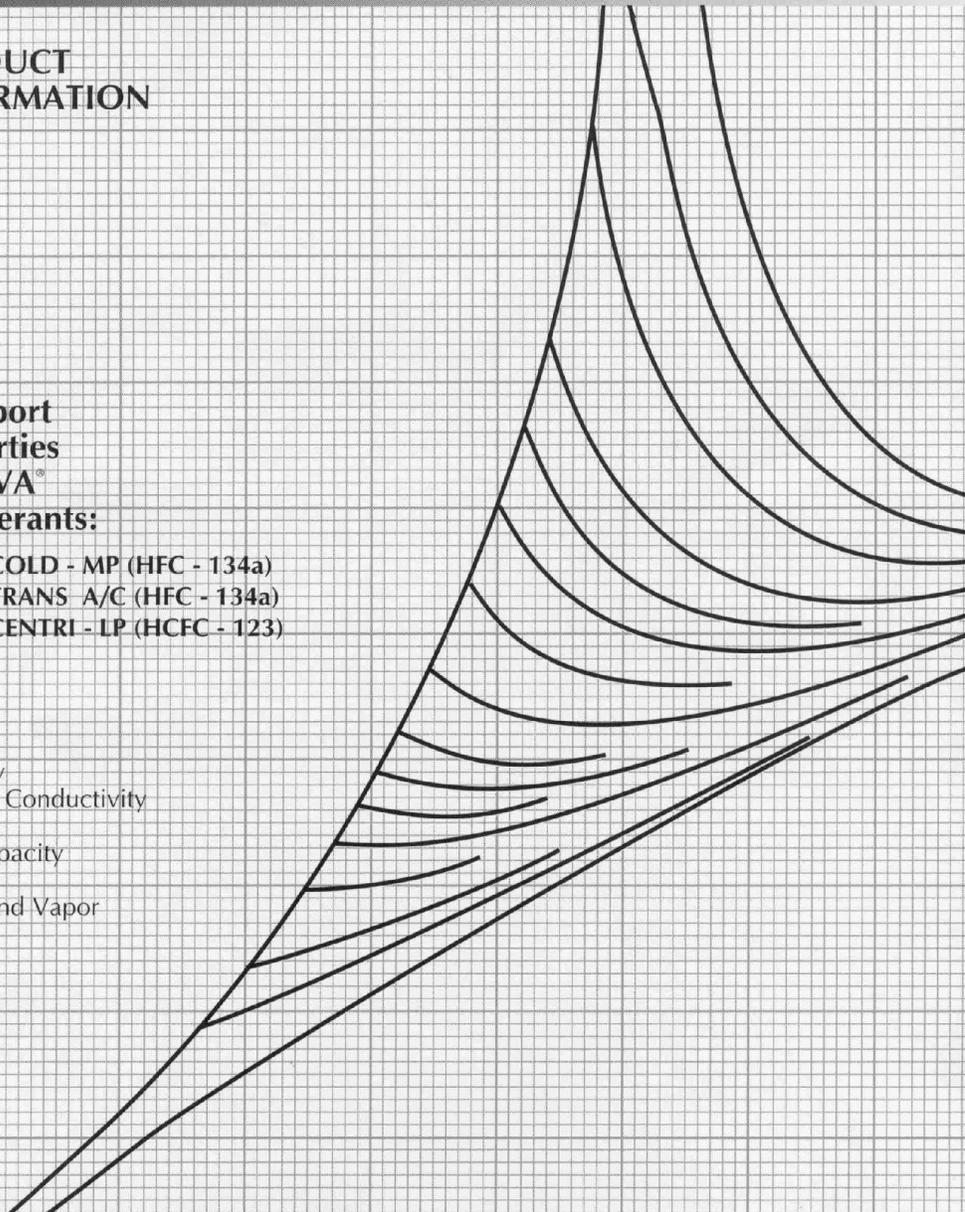
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### PRODUCT INFORMATION

#### Transport Properties of SUVA® Refrigerants:

- SUVA® COLD - MP (HFC - 134a)
- SUVA® TRANS A/C (HFC - 134a)
- SUVA® CENTRI - LP (HCFC - 123)

Viscosity  
Thermal Conductivity  
and  
Heat Capacity  
for the  
Liquid and Vapor



**Table 2**  
**Physical Properties of HFC-134a**

Physical Properties	Units	HFC-134a
Chemical Name	—	Ethane, 1,1,1,2-Tetrafluoro
Chemical Formula	—	CH <sub>2</sub> FCF <sub>3</sub>
Molecular Weight	—	102.03
Boiling Point at 1 atm (101.3 kPa or 1.013 bar)	°C	-26.1
	°F	-14.9
Freezing Point	°C	-103.3
	°F	-153.9
Critical Temperature	°C	101.1
	°F	213.9
Critical Pressure	kPa	4060
	lb/in. <sup>2</sup> abs	588.9
Critical Volume	m <sup>3</sup> /kg	1.94 × 10 <sup>-3</sup>
	ft <sup>3</sup> /lb	0.031
Critical Density	kg/m <sup>3</sup>	515.3
	lb/ft <sup>3</sup>	32.17
Density (Liquid) at 25°C (77°F)	kg/m <sup>3</sup>	1206
	lb/ft <sup>3</sup>	75.28
Density (Saturated Vapor) at Boiling Point	kg/m <sup>3</sup>	5.25
	lb/ft <sup>3</sup>	0.328
Heat Capacity (Liquid) at 25°C (77°F)	kJ/kg·K	1.44
	or Btu/(lb) (°F)	0.339
Heat Capacity (Vapor) at Constant Pressure at 25°C (77°F) and 1 atm (101.3 kPa or 1.013 bar)	kJ/kg·K	0.852
	or Btu/(lb) (°F)	0.204
Vapor Pressure at 25°C (77°F)	kPa	666.1
	bar	6.661
	psia	96.61
Heat of Vaporization at Boiling Point	kJ/kg	217.2
	Btu/lb	93.4
Thermal Conductivity at 25°C (77°F)		
Liquid	W/m·K	0.0824
	Btu/hr·ft·°F	0.0478
Vapor at 1 atm (101.3 kPa or 1.013 bar)	W/m·K	0.0145
	Btu/hr·ft·°F	0.00836
Viscosity at 25°C (77°F)		
Liquid	mPa·S (cP)	0.202
Vapor at 1 atm (101.3 kPa or 1.013 bar)	mPa·S (cP)	0.012
Solubility of HFC-134a in Water at 25°C (77°F) and 1 atm (101.3 kPa or 1.013 bar)	wt %	0.15
Solubility of Water in HFC-134a at 25°C (77°F)	wt %	0.11
Flammability Limits in Air at 1 atm (101.3 kPa or 1.013 bar)	vol %	None
Autoignition Temperature	°C	770
	°F	1418
Ozone Depletion Potential	—	0
Halocarbon Global Warming Potential (HGWP) (For CFC-11, HGWP = 1)	—	0.28
Global Warming Potential (GWP) (100 yr. ITH. For CO <sub>2</sub> , GWP = 1)	—	1200
TSCA Inventory Status	—	Reported/Included
Toxicity AEL <sup>(a)</sup> (8- and 12-hr TWA)	ppm (v/v)	1000

<sup>(a)</sup>AEL (Acceptable Exposure Limit) is an airborne inhalation exposure limit established by DuPont that specifies time-weighted average concentrations to which nearly all workers may be repeatedly exposed without adverse effects.

Note: kPa is absolute pressure.

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 CNS 10-160B cask.

The payload parameters that are controlled in order to ensure safe transport of the TRU waste in the CNS 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 CNS 10-160B cask (including the parts of the cask that might be affected by the payload).
- Restrictions on the maximum pressure in the CNS 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, through Revision 22 of the SAR, were provided in the site-specific sub tier appendices (Appendices 4.10.2.1 through 4.10.2.5). 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.

As of Revision 0 of the Consolidated SAR, site-specific compliance methodologies for additional 10-160B cask TRU waste payloads are approved by the 10-160B TRU Payload Engineer provided that compliance with the transportation requirements of this appendix can be demonstrated. The 10-160B TRU Payload Engineer does not have the authority to change the transportation requirements for the 10-160B cask as specified in this appendix without approval from the U.S. Nuclear Regulatory Commission. The 10-160B TRU Payload Engineer may approve only contents meeting the requirements of this appendix. The 10-160B TRU Payload Engineer will perform the site-specific waste evaluation against the 10-160B payload parameters of this appendix and document the assessment in the "10-160B TRU Waste Payload Assessment" document. The documentation of the site-specific waste evaluations will be modeled on the previously-approved site-specific compliance methodologies documented in Appendices 4.10.2.1 through 4.10.2.5. The 10-160B user shall retain copies of the payload evaluation and the Payload Engineer approval.

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 CNS 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 CNS-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 CNS 10-160B cask payload content codes. Sections 4.0 through 11.0 discuss each payload parameter requirements for the CNS 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 or in the compliance methodologies approved in the 10-160B TRU Waste Payload Assessment.

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 CNS 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 or in the compliance methodologies approved by the 10-160B TRU Payload Engineer in the 10-160B TRU Waste Payload Assessment. 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 CNS 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 CNS 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 ~~CNS~~ 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 ~~CNS~~ 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 ~~CNS~~ 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 CNS 10-160B.

## 9.0 ISOTOPIC CHARACTERIZATION AND FISSILE CONTENT

### 9.1 Requirements

The CNS 10-160B cask payload allows 325 FGE of fissile materials, ~~provided the mass limits of Title 10, Code of Federal Regulations, Section 71.15 (10 CFR 71.15) are not exceeded.~~ Plutonium content ~~must not exceed~~ 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 ~~10 CFR 71.15 limits~~ 325 FGE limit
- Calculation of plutonium content and ~~comparison~~ confirmation of solid form if exceeding the ~~with~~ 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 ~~meet the requirements of 10 CFR 71.15~~ demonstrate compliance with the 325 FGE limit.

#### 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. ~~to demonstrate compliance with the 20 curie limit.~~

## 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 CNS 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 CNS 10-160B cask. In addition, potentially flammable VOCs are restricted to 500 ppm in the headspace of the CNS 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 methodology approved in the 10-160B TRU Waste Payloads Assessment or in the sub tier 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 methodology. Conservative assumptions may be used in site-specific sub tier 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 site-specific sub-tier appendices or in the compliance methodology approved in the 10-160B TRU Waste Payloads Assessment ~~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 CNS 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 CNS 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:

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

Where:

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

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

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

Where:

$X_{\text{fh}}$	=	maximum mole fraction of hydrogen in the CNS 10-160B IV cavity
$N_{\text{tg}}$	=	total moles of gas inside the CNS 10-160B IV cavity
P	=	pressure inside the CNS 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
$V_{\text{void}}$	=	void volume inside the CNS 10-160B IV cavity (liters)
R	=	gas constant = 62.361 mm Hg-liter/mole-K
T	=	absolute temperature of air in the CNS 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:

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

Where:

$X_{\text{inner}}$	=	mole fraction of hydrogen in innermost confinement layer (a value of 0.05 has been used
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$R_{\text{eff}}$  = for this parameter since this is the maximum permissible concentration)  
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  $X_{\text{inner}}$  and solving for the gas generation rate the following results:

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

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:

$$Q = [(CG)(N_A)/(G_{\text{eff}} \text{ molecules}/100\text{eV})][1.602 \times 10^{-19} \text{ watt-sec/eV}]$$

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 =  $6.023 \times 10^{23}$  molecules/mole  
 $G_{\text{eff}}$  = 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:

$$D_{\text{total}}(t) = \Gamma A C_i \sum_{i=1}^{\text{NR}} (0.82 E_i^{\forall} + E_i^{\exists} + E_i^{\exists} + E_i^{\times}) [1 - \exp(-\lambda_i t)]$$

where,

$D_{\text{total}}(t)$	=	Total cumulative absorbed dose at time, $t$ (rad)
$A$	=	A proportionality constant equal to $1.84 \times 10^{10}$ rad gram MeV <sup>-1</sup> yr <sup>-1</sup> Ci <sup>-1</sup>
$C_i$	=	The specific activity of the “ $i$ ”th nuclide in Curies/gram of waste
$\lambda_i$	=	The decay constant of the “ $i$ ”th radionuclide (yr <sup>-1</sup> )
$\text{NR}$	=	Number of radionuclides
$E_i^{\forall}$	=	$\forall$ 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).
$E_i^{\times}$	=	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).

$E_{i\gamma}$  = 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:

$$E_{i\gamma} = \Gamma_j n_{ij} f_{ij} E_{ij}$$

where,

$\Gamma_j$  = 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  
 $f_{ij}$  = the fraction of energy, of the “j”th gamma ray of the “i”th nuclide that is absorbed in the waste.  
 $E_{ij}$  = 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 CNS 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 CNS cask is used to represent the payload container in the RadCalc input file as the RadCalc database does not include the CNS cask. The package void volume for a CNS 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<sup>3</sup>

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 ~~CNS~~ 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 or in the compliance methodologies approved in the 10-160B TRU Waste Payload Assessment.

#### 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 ~~CNS~~ 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 ~~CNS~~ 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.  
~~U.S. Department of Energy, "Safety Analysis Report for the TRUPACT-II Shipping Package," Current Revision, U.S. Department of Energy Carlsbad Area 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 Breisemeister, 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.
- ~~12.9 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.~~

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.

<b>Table A-1. Experimental Dose-Dependent G Values</b>					
<b>Matrix</b>	<b>Current Waste Material Type G Value</b>	<b>Number of Observations</b>	<b>Mean</b>	<b>Standard Deviation</b>	<b>95% Upper Tolerance Limit</b>
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 cellulose were higher than those for dry cellulose 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 ( $^{238}\text{Pu}$  and  $^{239}\text{Pu}$ ).

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<sup>3</sup> stainless steel pressure cylinders, each loaded with 52.5 grams of a single or a combination of TRU waste matrix materials. Materials tested included cellulose, 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 <sup>238</sup>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 <sup>238</sup>PuO<sub>2</sub> 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 <sup>238</sup>PuO<sub>2</sub> 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  $^{238}\text{PuO}_2$  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 ( $\text{H}_2$ ) for containers meeting a watt\*year criteria of 0.012 is governed by assuming polyethylene as the packaging material, with a G value ( $\text{H}_2$ ) 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 ( $\text{H}_2$ ) 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  $\alpha$  and  $\beta$  dose-dependent G values and non-dose-dependent G values for  $\gamma$  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:

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

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 ( $6.023 \times 10^{23}$  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 ~~CNS~~-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 ~~CNS~~ 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 ~~CNS~~ 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<sup>a</sup>**

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<sup>a</sup>**  
(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

<sup>a</sup>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.

<sup>b</sup>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 CNS 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 CNS 10-160B Cask payload.

Chemical lists provided for site-specific TRU waste content codes identified for shipment in the CNS 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 CNS 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

<b>Lists of Allowable Materials and Associated Reactivity Groups</b>		
<b>Allowable Chemical/Material<sup>a</sup></b>	<b>Reactivity Group<sup>b</sup></b>	
	<b>Name</b>	<b>Number<sup>c</sup></b>
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
<b>Acids, inorganic</b>	Acids, Mineral, Non-oxidizing	1
<b>Acids, inorganic</b>	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
<b>Detergent, solid (e.g., emulsifiers, surfactants)</b>	Esters	13
<b>Detergent, solid (e.g., emulsifiers, surfactants)</b>	Hydrocarbons, aromatic	16
<b>Detergent, solid (e.g., emulsifiers, surfactants)</b>	Hydrocarbons, aliphatic, unsaturated	28
<b>Detergent, solid (e.g., emulsifiers, surfactants)</b>	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

<b>Lists of Allowable Materials and Associated Reactivity Groups</b>		
<b>Allowable Chemical/Material<sup>a</sup></b>	<b>Reactivity Group<sup>b</sup></b>	
	<b>Name</b>	<b>Number<sup>c</sup></b>
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
<b><i>Hydrocarbons, aliphatic (e.g., cyclohexane, n-paraffin hydrocarbons)</i></b>	Hydrocarbon, aliphatic, unsaturated	28
<b><i>Hydrocarbons, aliphatic (e.g., cyclohexane, n-paraffin hydrocarbons)</i></b>	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
<b><i>Leaded rubber (e.g., gloves, aprons, sheet material)</i></b>	Metals, Other elemental, and alloy, as sheets, rods, moldings, vapors, or sponges	23
<b><i>Leaded rubber (e.g., gloves, aprons, sheet material)</i></b>	Metals and metal compounds, toxic	24
<b><i>Leaded rubber (e.g., gloves, aprons, sheet material)</i></b>	Combustible and flammable materials, miscellaneous	101
Leather	Combustible and flammable materials, miscellaneous	101
Magnesia cement (e.g., Ramcote® cement)	Water reactive substance	107

<b>Lists of Allowable Materials and Associated Reactivity Groups</b>		
<b>Allowable Chemical/Material<sup>a</sup></b>	<b>Reactivity Group<sup>b</sup></b>	
	<b>Name</b>	<b>Number<sup>c</sup></b>
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
<b>Metals (e.g., aluminum, cadmium, copper, steel, tantalum, tungsten, zinc)</b>	Metals, alkali and alkaline earth, elemental	21
<b>Metals (e.g., aluminum, cadmium, copper, steel, tantalum, tungsten, zinc)</b>	Metals, Other elemental and alloy in the form of powders, vapors, or sponges	22
<b>Metals (e.g., aluminum, cadmium, copper, steel, tantalum, tungsten, zinc)</b>	Metals, Other elemental, and alloy, as sheets, rods, moldings, vapors, or sponges	23
<b>Metals (e.g., aluminum, cadmium, copper, steel, tantalum, tungsten, zinc)</b>	Metals and metal compounds, toxic	24
<b>Metals (e.g., aluminum, cadmium, copper, steel, tantalum, tungsten, zinc)</b>	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
<b>Polyamides (nylon)</b>	Amides	6
<b>Polyamides (nylon)</b>	Combustible and flammable materials, miscellaneous	101
Polychlorotrifluoroethylene (e.g., Kel-F®)	Combustible and flammable materials, miscellaneous	101
<b>Polyesters (e.g., Dacron®, Mylar®)</b>	Esters	13
<b>Polyesters (e.g., Dacron®, Mylar®)</b>	Combustible and flammable materials, miscellaneous	101
<b>Polyethylene glycol (e.g., Carbowax®)</b>	Alcohols and Glycols	4
<b>Polyethylene glycol (e.g., Carbowax®)</b>	Combustible and flammable materials, miscellaneous	101
Polyimides	Hydrocarbons, aromatic	16
Polyphenyl methacrylate	Combustible and flammable materials, miscellaneous	101

<b>Lists of Allowable Materials and Associated Reactivity Groups</b>		
<b>Allowable Chemical/Material<sup>a</sup></b>	<b>Reactivity Group<sup>b</sup></b>	
	<b>Name</b>	<b>Number<sup>c</sup></b>
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
<b>Portland cement</b>	Caustics	10
<b>Portland cement</b>	Water reactive substance	107
<b>Resins (e.g., aniline-formaldehyde, melamine-formaldehyde, organic resins, phenol-formaldehyde, phenolic resins, urea-formaldehyde)</b>	Aldehydes	5
<b>Resins (e.g., aniline-formaldehyde, melamine-formaldehyde, organic resins, phenol-formaldehyde, phenolic resins, urea-formaldehyde)</b>	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
<b>Salts (e.g., calcium chloride, calcium fluoride, sodium chloride)</b>	Other Inorganics (non-reactive)	0
<b>Salts (e.g., calcium chloride, calcium fluoride, sodium chloride)</b>	Fluorides, inorganic	15
Sand/soil, inorganic	Other Inorganics (non-reactive)	0
<b>Sand/soil, organic</b>	Combustible and flammable materials, miscellaneous	101
Triocetyl 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

<sup>a</sup>Chemicals in **bold italic** have been assigned to more than one reactivity group.

<sup>b</sup>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.

<sup>c</sup>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

<b>List of Unique Reactivity Group Numbers in Lists of Allowable Materials</b>		
<b>Allowable Chemical/Material<sup>a</sup></b>	<b>Reactivity Group<sup>b</sup></b>	
	<b>Name</b>	<b>Number</b>
Absorbents/adsorbents (e.g., Celite®, diatomaceous earth, diatomite, Florco®, Oil-Dri®, perlite, vermiculite)	Other solidification materials and absorbents/adsorbents	0
<b>Acids, inorganic</b>	Acids, Mineral, Non-oxidizing	1
<b>Acids, inorganic</b>	Acids, Mineral, Oxidizing	2
Acids, solid, organic	Acids, Organic	3
<b>Polyethylene glycol (e.g., Carbowax®)</b>	Alcohols and Glycols	4
<b>Resins (e.g., aniline-formaldehyde, melamine-formaldehyde, organic resins, phenol-formaldehyde, phenolic resins, urea-formaldehyde)</b>	Aldehydes	5
<b>Polyamides (nylon)</b>	Amides	6
<b>Portland cement</b>	Caustics	10
Esters (e.g., ethyl acetate, polyethylene glycol ester)	Esters	13
Ethers (e.g., ethyl ether)	Ethers	14
<b>Salts (e.g., calcium chloride, calcium fluoride, sodium chloride)</b>	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
<b>Metals (e.g., aluminum, cadmium, copper, steel, tantalum, tungsten, zinc)</b>	Metals, Other elemental and alloy in the form of powders, vapors, or sponges	22
<b>Metals (e.g., aluminum, cadmium, copper, steel, tantalum, tungsten, zinc)</b>	Metals, Other elemental, and alloy, as sheets, rods, moldings, vapors, or sponges	23
<b>Leaded rubber (e.g., gloves, aprons, sheet material)</b>	Metals and metal compounds, toxic	24
<b>Hydrocarbons, aliphatic (e.g., cyclohexane, n-paraffin hydrocarbons)</b>	Hydrocarbon, aliphatic, unsaturated	28
<b>Hydrocarbons, aliphatic (e.g., cyclohexane, n-paraffin hydrocarbons)</b>	Hydrocarbon, aliphatic, saturated	29

<b>List of Unique Reactivity Group Numbers in Lists of Allowable Materials</b>		
<b>Allowable Chemical/Material<sup>a</sup></b>	<b>Reactivity Group<sup>b</sup></b>	
	<b>Name</b>	<b>Number</b>
<b><i>Resins (e.g., aniline-formaldehyde, melamine-formaldehyde, organic resins, phenol-formaldehyde, phenolic resins, urea-formaldehyde)</i></b>	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
<b><i>Metals (e.g., aluminum, cadmium, copper, steel, tantalum, tungsten, zinc)</i></b>	Reducing agents, strong	105
Aqueous solutions/water	Water and Mixtures containing water	106
<b><i>Portland cement</i></b>	Water reactive substances	107

<sup>a</sup>Chemicals in ***bold italic*** have been assigned to more than one reactivity group.

<sup>b</sup>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

Group No.	Reactivity Group Name	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
1	Acids, Mineral, Non-Oxidizing																											
2	Acids, Mineral, Oxidizing																											
3	Acids, Organic																											
4	Alcohols and Glycols																											
5	Aldehydes																											
6	Amides																											
10	Caustics																											
13	Esters																											
14	Ethers																											
15	Fluorides, Inorganic																											
16	Hydrocarbons, Aromatic																											
17	Halogenated Organics																											
19	Ketones																											
21	Metals, Alkali and Alkaline Earth, Elemental																											
22	Metals, Other Elemental Alloys as Powders, Vapors, or Sponges																											
23	Metals, Other Elemental Alloys as Sheets, Rods, Moldings, Etc.																											
24	Metals and Metal Compounds, Toxic																											
28	Hydrocarbons, Aliphatic, Unsaturated																											
29	Hydrocarbons, Aliphatic, Saturated																											
31	Phenols and Cresols																											
32	Organophosphates, Phosphothioates, Phosphodithioates																											
101	Combustible and Flammable Materials, Miscellaneous																											
103	Polymerizable Compounds																											
104	Oxidizing Agents, Strong																											
105	Reducing Agents, Strong																											
106	Water and Mixtures Containing Water																											
107	Water Reactive Substances																											
<b>Reactivity Group No.</b>		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 Polymerization
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

<b>Potential Chemical Incompatibilities</b>			
<b>Combination of Reactivity Groups</b>		<b>Reaction Result (A x B)</b>	<b>Explanation of Potential Incompatibility</b>
<b>Group A</b>	<b>Group B</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

<b>Potential Chemical Incompatibilities</b>			
<b>Combination of Reactivity Groups</b>		<b>Reaction Result (A x B)</b>	<b>Explanation of Potential Incompatibility</b>
<b>Group A</b>	<b>Group B</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.

<b>Potential Chemical Incompatibilities</b>			
<b>Combination of Reactivity Groups</b>		<b>Reaction Result (A x B)</b>	<b>Explanation of Potential Incompatibility</b>
<b>Group A</b>	<b>Group B</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

<b>Potential Chemical Incompatibilities</b>			
<b>Combination of Reactivity Groups</b>		<b>Reaction Result (A x B)</b>	<b>Explanation of Potential Incompatibility</b>
<b>Group A</b>	<b>Group B</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

<b>Potential Chemical Incompatibilities</b>			
<b>Combination of Reactivity Groups</b>		<b>Reaction Result (A x B)</b>	<b>Explanation of Potential Incompatibility</b>
<b>Group A</b>	<b>Group B</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

<b>Potential Chemical Incompatibilities</b>			
<b>Combination of Reactivity Groups</b>		<b>Reaction Result (A x B)</b>	<b>Explanation of Potential Incompatibility</b>
<b>Group A</b>	<b>Group B</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

<b>Potential Chemical Incompatibilities</b>			
<b>Combination of Reactivity Groups</b>		<b>Reaction Result (A x B)</b>	<b>Explanation of Potential Incompatibility</b>
<b>Group A</b>	<b>Group B</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

<b>Potential Chemical Incompatibilities</b>			
<b>Combination of Reactivity Groups</b>		<b>Reaction Result (A x B)</b>	<b>Explanation of Potential Incompatibility</b>
<b>Group A</b>	<b>Group B</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.

<b>Potential Chemical Incompatibilities</b>			
<b>Combination of Reactivity Groups</b>		<b>Reaction Result (A x B)</b>	<b>Explanation of Potential Incompatibility</b>
<b>Group A</b>	<b>Group B</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

<b>Potential Chemical Incompatibilities</b>			
<b>Combination of Reactivity Groups</b>		<b>Reaction Result (A x B)</b>	<b>Explanation of Potential Incompatibility</b>
<b>Group A</b>	<b>Group B</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.

<b>Potential Chemical Incompatibilities</b>			
<b>Combination of Reactivity Groups</b>		<b>Reaction Result (A x B)</b>	<b>Explanation of Potential Incompatibility</b>
<b>Group A</b>	<b>Group B</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.

<b>Potential Chemical Incompatibilities</b>			
<b>Combination of Reactivity Groups</b>		<b>Reaction Result (A x B)</b>	<b>Explanation of Potential Incompatibility</b>
<b>Group A</b>	<b>Group B</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.

<b>Potential Chemical Incompatibilities</b>			
<b>Combination of Reactivity Groups</b>		<b>Reaction Result (A x B)</b>	<b>Explanation of Potential Incompatibility</b>
<b>Group A</b>	<b>Group B</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

<b>Potential Chemical Incompatibilities</b>			
<b>Combination of Reactivity Groups</b>		<b>Reaction Result (A x B)</b>	<b>Explanation of Potential Incompatibility</b>
<b>Group A</b>	<b>Group B</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

<b>Potential Chemical Incompatibilities</b>			
<b>Combination of Reactivity Groups</b>		<b>Reaction Result (A x B)</b>	<b>Explanation of Potential Incompatibility</b>
<b>Group A</b>	<b>Group B</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

<b>Potential Chemical Incompatibilities</b>			
<b>Combination of Reactivity Groups</b>		<b>Reaction Result (A x B)</b>	<b>Explanation of Potential Incompatibility</b>
<b>Group A</b>	<b>Group B</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

<b>Potential Chemical Incompatibilities</b>			
<b>Combination of Reactivity Groups</b>		<b>Reaction Result (A x B)</b>	<b>Explanation of Potential Incompatibility</b>
<b>Group A</b>	<b>Group B</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

<b>Potential Chemical Incompatibilities</b>			
<b>Combination of Reactivity Groups</b>		<b>Reaction Result (A x B)</b>	<b>Explanation of Potential Incompatibility</b>
<b>Group A</b>	<b>Group B</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

<b>Potential Chemical Incompatibilities</b>			
<b>Combination of Reactivity Groups</b>		<b>Reaction Result (A x B)</b>	<b>Explanation of Potential Incompatibility</b>
<b>Group A</b>	<b>Group B</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

<b>Potential Chemical Incompatibilities</b>			
<b>Combination of Reactivity Groups</b>		<b>Reaction Result (A x B)</b>	<b>Explanation of Potential Incompatibility</b>
<b>Group A</b>	<b>Group B</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 is 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.~~ As documented in Attachment C of sub-tier Appendix 4.10.2.1, a 10-day controlled shipping period may be used when the shipping distance between shipping site and receiving site is less than or equal to 2,283 miles. The use of a 10-day controlled shipment is an option only for sites that impose the administrative controls specified by Attachment C of sub-tier Appendix 4.10.2.1. The implementation of these controls ensures that the 10-160B cask is loaded at the shipping site, transported from the shipping site to the receiving site, and vented within a maximum of 10 days from the closure (or sealing) of the 10-160B cask inner vessel. ~~This~~ site-specific shipping period may be used in the gas generation analysis for the site's waste.

5. SHIELDING EVALUATION5.1 Discussion and Results5.1.1 Operating Design

The Model CNS 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 CNS 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 cask surface. 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. ~~Total shield thickness is conservatively evaluated as 3” of steel and 1 5/8” of lead.~~

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~~ Normal Conditions of Transport (NCT) and ~~accident condition~~ 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 ~~which can exist on any~~ centered in the cask cavity.  
~~interior cask surface.~~

5.1.3.2 Accident Conditions

- The source is modeled as a point source ~~which can exist on any interior cask surface~~ 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)

<u>Condition</u>	<u>Package Surface</u>		<u>1 m from Surface</u>		<u>2m from</u>
	<u>Side</u>	<u>Top/Bottom</u>	<u>Side</u>	<u>Top/Bottom</u>	<u>8' trailer</u>
<del>Normal</del> <u>NCT</u>					
<u>Neutron Source</u>	<u>114</u>	<u>86.3</u>	<u>N.A.</u>	<u>N.A.</u>	<u>9.44</u>
<del>Calculated</del> <u>Gamma</u>	<u>200</u> <u>126</u>	<u>200</u> <u>179</u>	<u>2.2</u> <u>N.A.</u>	<u>3.0</u> <u>N.A.</u>	<u>0.69</u> <u>96</u>
<u>ma Source</u>					
Allowable	200	200	N.A.	N.A.	10.0
<del>Hyp-</del> <u>Accident</u> <u>HAC</u>					
<u>Neutron Source</u>	<u>N.A.</u>	<u>N.A.</u>	<u>82.7</u>	<u>39.5</u>	<u>N.A.</u>
<del>Calculated</del> <u>Gamma</u>	<u>200</u> <u>N.A.</u>	<u>200</u> <u>N.A.</u>	<u>31.4</u> <u>144</u>	<u>3.0</u> <u>99.9</u>	<u>N.A.</u>
<u>Source</u>					
Allowable	N.A.	N.A.	1000.0	1000.0	<u>N.A.</u>

5.1.4 Transport Index

~~————~~ The Transport Index is defined in 10CFR71.4 as being equivalent to the maximum radiation level in millirem per hour at one meter (3.3 ft). Based on Table 5.1, the TI for the 10-160B is 3.0.

5.2 Source Specification

5.2.1 Gamma Source Methodology

~~The equivalent A unit point source, assuming a Co-60 source (1.25 Mev average energy), is determined for the normal geometry 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.~~

~~The dose rate from a point source is given by equation 1.~~

$$\text{(Equation 1)} \quad D = \frac{KBSe^{-b}}{4\pi r^2}$$

where:

~~D = dose rate (r/hr)~~

~~K = flux to dose rate conversion factor~~

$$\frac{r/hr}{2.20 \times 10^{-6} \text{ gammas/cm}^2 \text{-sec}} \text{ at 1.25 Mev (Ref. 1, p. 132)}$$

~~S = gamma source strength (gammas/sec)~~

~~n~~

$$b = \sum_i \mu_i t_i$$

~~$\mu_i$  = macroscopic cross section of material i (cm<sup>-1</sup>)~~

~~$t_i$  = thickness of material i (cm)~~

~~B = buildup factor~~

~~r = distance from the source to the dose point (cm)~~

Solving equation 1 for the source, S, yields equation 2.

$$\text{(Equation 1)} \quad S = \frac{4\pi r^2 D}{KBe^{-b}} \quad \text{5.2.2 Gamma Source}$$

SCALE models of the 10-160B cask is 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.

5.2.32 Neutron Sources

There are no sources of neutron radiation in the radioactive materials to be carried in the CNS 10-160B cask. SCALE models of the 10-160B cask are evaluated with a Pu-Be neutron source. A <sup>239</sup>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) <sup>239</sup>Pu-Be

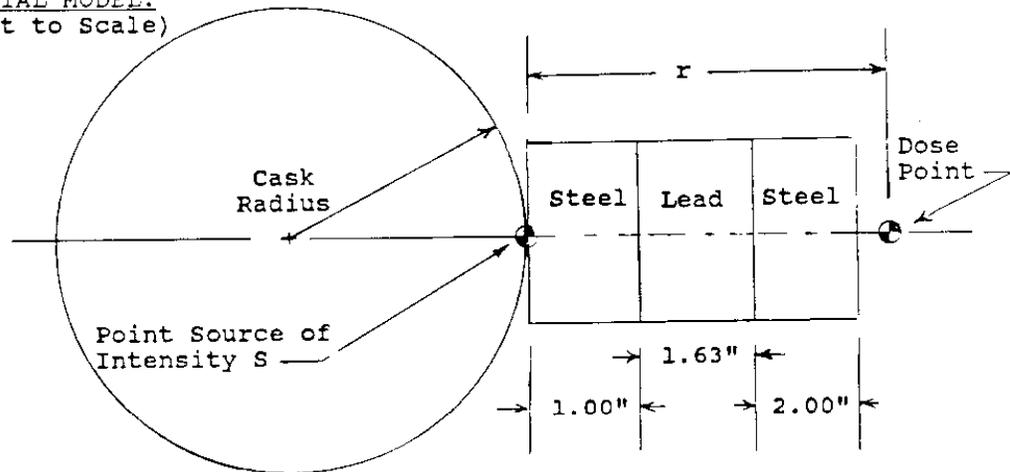
source will produce approximately 2.8E+07 n/sec. The equivalent neutron source, which produces a dose rate of 9.4 mrem/hr at 2m from the 8' wide trailer, has an emission rate of 1.1 E+08 n/sec. Thus, the equivalent source used for the dose rate calculation is larger than the fissile gram limit imposed 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)

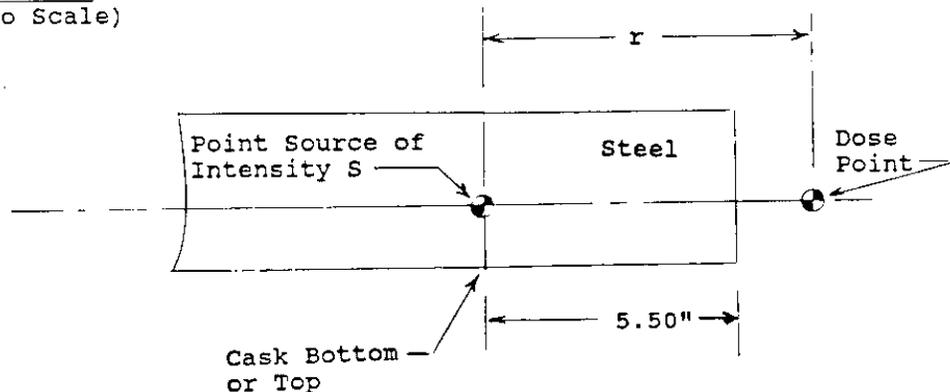
<u>Energy Interval, E<sub>i</sub></u> <u>(MeV)</u>	<u>Fraction of</u> <u>neutrons in E<sub>i</sub></u>
<u>0-0.5</u>	<u>0.038</u>
<u>0.5-1</u>	<u>0.049</u>
<u>1-1.5</u>	<u>0.045</u>
<u>1.5-2</u>	<u>0.042</u>
<u>2-2.5</u>	<u>0.046</u>
<u>2.5-3</u>	<u>0.062</u>
<u>3-6.5</u>	<u>0.459</u>
<u>6.5-10.5</u>	<u>0.259</u>
<u>Total</u>	<u>1.000</u>

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RADIAL MODEL:  
(Not to Scale)



AXIAL MODEL:  
(Not to Scale)



5.3 Model Specification

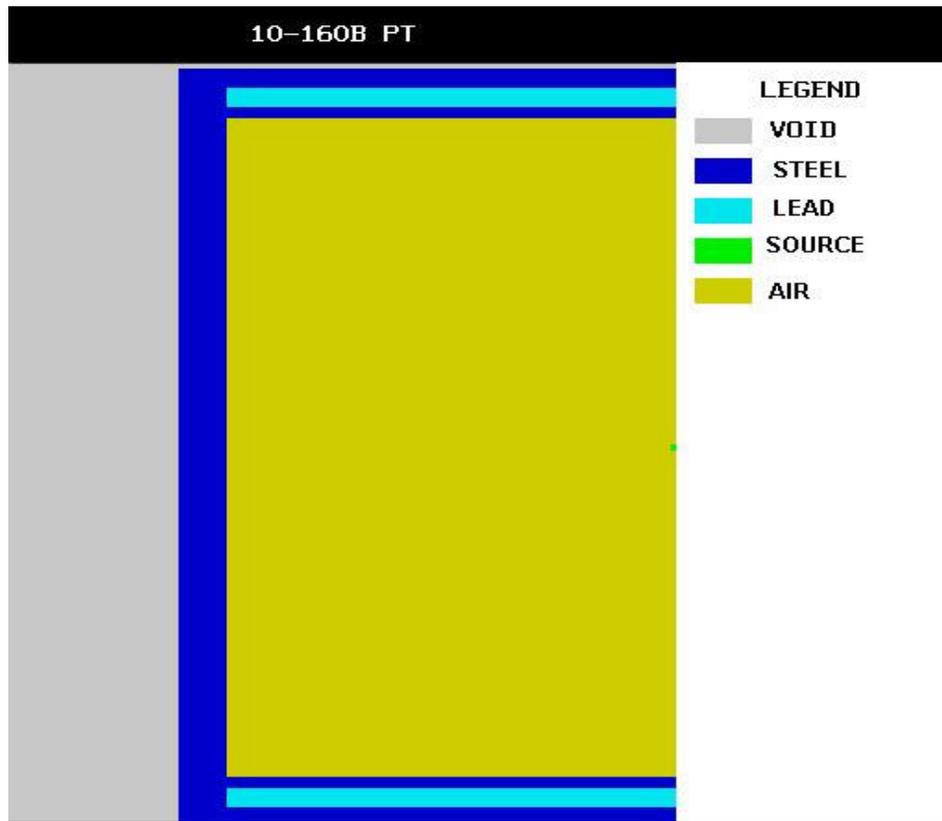
5.3.1 Description of Radial and Axial Shielding Configuration

Normal Conditions of Transport (NCT)

Description of the radial and axial shielding models are shown in Figure 5.2.

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.

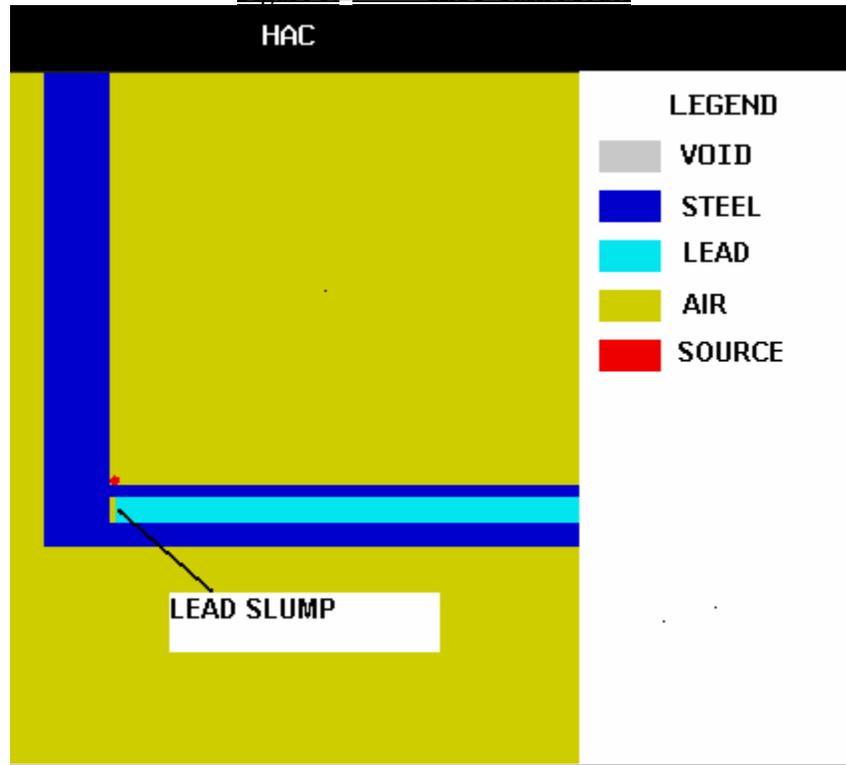
**Figure 5.1 NCT Cask Model**



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**

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

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**

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

**Table 5.4 Neutron Flux-To-Dose-Rate Conversion Factors And Mean Quality Factors (QF)**

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

\*Maximum value of QF in a 30-cm phantom.  
#Read as 2.5 x 10<sup>-8</sup>

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**

<u>Normal Conditions of Transport</u>	<u>Package Surface (mrem/h)</u>			<u>2 Meters from Cask (mrem/h)</u>
	<u>Top</u>	<u>Side</u>	<u>Bottom</u>	
<u>Radiation</u>				<u>Side</u>
<u>Neutron Source</u>	<u>86.3</u>	<u>114</u>	<u>86.3</u>	<u>9.44</u>
<u>Gamma Source</u>	<u>179</u>	<u>126</u>	<u>179</u>	<u>9.96</u>
<u>10 CFR 71.47 Limit<sup>1</sup></u>	<u>200</u>	<u>200</u>	<u>200</u>	<u>10</u>

1. shipped as “exclusive use”

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

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

<u>Material</u>	<u>Density (g/cm<sup>3</sup>)</u>	<u>Mass Atten. Coeff. At 1.25 Mev (cm<sup>2</sup>/g)</u>	<u>Macro. Cross Section (cm<sup>-1</sup>)</u>
Carbon Steel	8.03 (2:6-44)	0.0544 (1:138)	0.437
Lead	11.35 (1:65)	0.0613 (1:138)	0.696

5.5

Notes:

- 1. (x:xx) indicates (Reference:Page).
- 2. (Macro. Cross Section) = (Density) (Mass Atten. Coeff.)

5.4 Shielding Evaluation

5.4.1 Radial Model

The gamma radiation sources that correspond to regulatory dose rate limits for the cask in a radial direction were calculated assuming a point source. This gives the most conservative approach and allows for the wide variety of source geometries that could be encountered. The dose model used for this calculation is shown in Figure 5.2.

The point source producing a dose rate of 10 mr/hr at 2 meters from the cask and the point source producing a dose rate of 200 mr/hr at the cask outside surface are determined in the following analysis. The relaxation length, b, is determined through the side of the cask by equation 3.

$$\begin{aligned}
 \text{(Equation 3)} \quad b &= \mu_{cs} t_{cs} + \mu_{pb} t_{pb} \\
 &= (0.437 \text{ cm}^{-1})(3.00 \text{ in})(2.54 \text{ cm/in}) + \\
 &\quad (0.696 \text{ cm}^{-1})(1.63 \text{ in})(2.54 \text{ cm/in}) \\
 &= 3.33 + 2.88 \\
 &= 6.21
 \end{aligned}$$

The buildup factor,  $B$ , is calculated by weighting the buildup factors for iron and lead according to the number of relaxation lengths of each present in the side wall (Equation 4).

$$\text{(Equation 4)} \quad B = \frac{(\mu_{cs} t_{cs})(B_{cs}) + (\mu_{pb} t_{pb})(B_{pb})}{\mu_{cs} t_{cs} + \mu_{pb} t_{pb}}$$

Substituting buildup factors evaluated at  $b = 6.21$  and at 1.25 Mev for lead and steel (approximated by iron) from Reference 1, page 147 yields equation 5.

$$\begin{aligned}
 \text{(Equation 5)} \quad B &= \frac{(3.33)(6.59) + (2.88)(2.76)}{3.33 + 2.88} \\
 &= 4.81
 \end{aligned}$$

Finally, substituting  $b$ ,  $B$ , and the dose rate limit of  $D = 10 \text{ mr/hr}$  at 2 meters into equation 2 yields equation 6 expressing the point source strength producing  $10 \text{ mr/hr}$  at 2 meters.

$$\begin{aligned}
 \text{(Equation 6)} \quad S &= \frac{4\pi (211.8 \text{ cm})^2 (0.010 \text{ r/hr})}{\left[ 2.20 * 10^{-6} \frac{\text{r/hr}}{\text{gammas/cm}^2 \text{ - sec}} \right] (4.81)e^{-6.21}} \\
 &= 2.65 * 10^{11} \text{ gammas/see}
 \end{aligned}$$

Similarly, the point source which yields 200 mr/hr at the cask surface is given by equation 7.

$$(Equation 7) \quad S = \frac{4\pi(11.8 \text{ cm})^2 (0.200 \text{ r/hr})}{\left[ \frac{2.20 * 10^{-6} \text{ r/hr}}{1.65 * 10^{10} \text{ gammas/sec}} \right] (4.81)e^{-6.21}}$$

The limiting point source strength in contact with the side wall, then, is  $1.65 * 10^{10}$  gammas/sec. Equation 8, derived from equation 1, gives the dose rate as a function of distance from the cask side surface, a, and of point source strength, S.

$$(Equation 8) \quad D = \frac{\left[ \frac{2.20 * 10^{-6} \text{ r/hr}}{\text{gammas/cm}^2 - \text{sec}} \right] (4.81)(S)(e^{-6.21})}{4\pi(a + 11.8 \text{ cm})^2}$$

$$= \frac{(1.692 * 10^{-9})(S) \text{ r - cm}^2 - \text{sec/gammas - hr}}{(a + 11.8 \text{ cm})^2}$$

Figure 5.3 shows dose rates at 0, 1, and 2 meters from the cask side surface for various source strengths. Substituting the limiting source strength  $S = 1.65 * 10^{10}$  gammas/sec into equation 8 yields equation 9 which gives the maximum dose rate at any distance from the cask side surface.

$$(Equation 9) \quad D = \frac{27.92 \text{ r - cm}^2 / \text{hr}}{(a + 11.8 \text{ cm})^2}$$

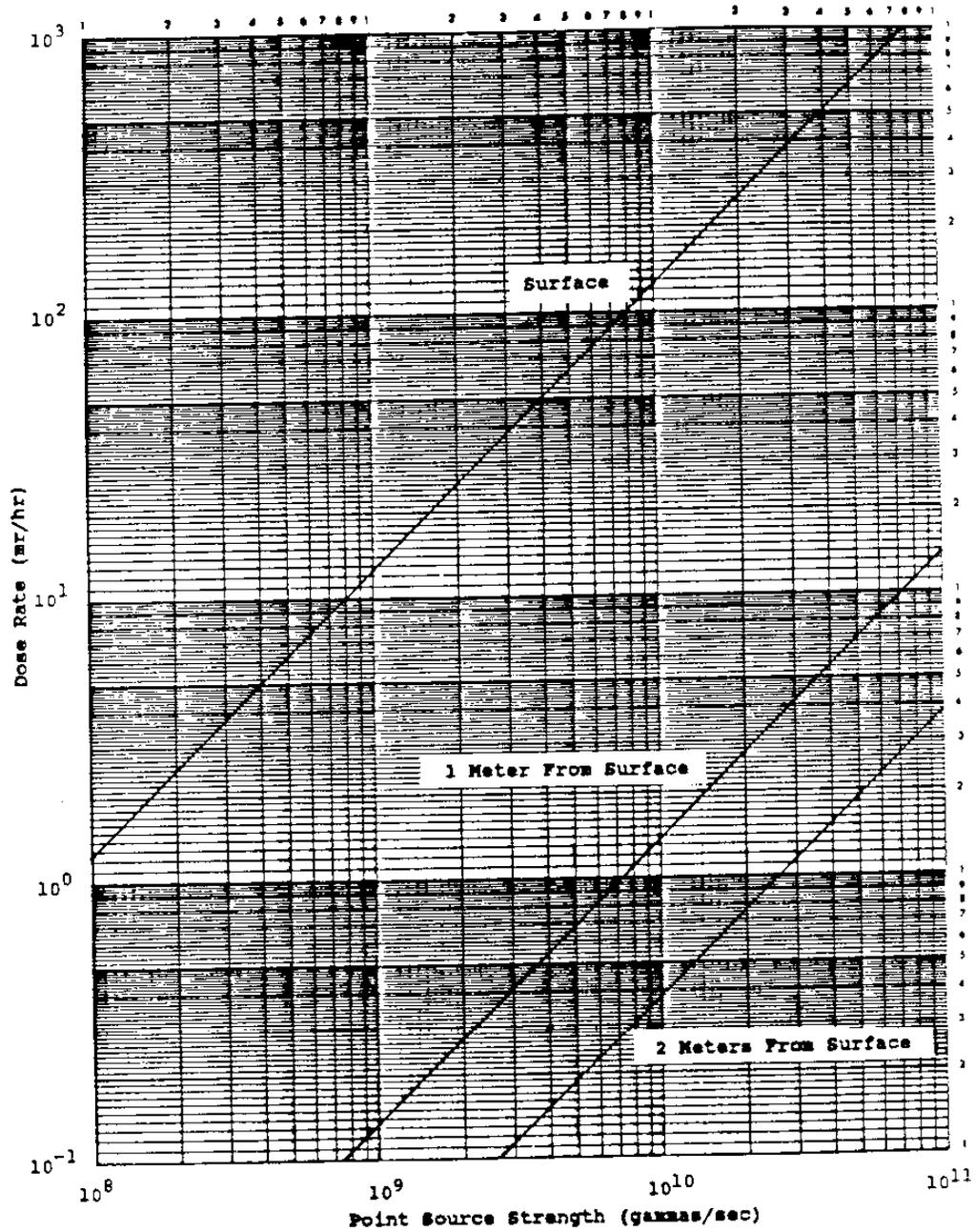


Figure 5.3  
Dose Rate Versus Point Source Strength—Side of Cask

5.4.2 Axial Model

The gamma radiation sources that correspond to regulatory dose rate limits for the cask in an axial direction were calculated assuming a point source. This gives the most conservative approach and allows for the wide variety of source geometries that could be encountered. The dose model used for this calculation is shown in Figure 5.2.

The point source which would result in a dose rate of 10 mr/hr at 2 meters from the cask and the point source resulting in a dose rate of 200 mr/hr at the cask outside surface are determined in the following analysis. The number of relaxation lengths,  $b$ , is determined through the top or bottom of the cask by equation 10.

$$\begin{aligned} \text{(Equation 10)} \quad b &= \mu_{es} t_{es} \\ &= (0.437 \text{ cm}^{-1}) (5.50 \text{ in}) (2.54 \text{ cm/in}) \\ &= 6.11 \end{aligned}$$

The buildup factor,  $B$ , is approximated by the buildup factor for iron. It is equal to 6.49 at  $b = 6.11$  and an energy of 1.25 Mev (Reference 1, page 147). Finally, substituting  $b$ ,  $B$ , and the dose rate limit of  $D = 10$  mr/hr at 2 meters into equation 2 yields equation 11 for the source producing 10 mr/hr at 2 meters.

$$\begin{aligned} \text{(Equation 11)} \quad S &= \frac{4\pi(214.0 \text{ cm})^2 (0.010 \text{ r/hr})}{\left[ \frac{2.20 * 10^{-6} \text{ r/hr}}{\text{gammas/cm}^2 \text{ - sec}} \right] (6.49)e^{-6.11}} \\ &= 1.82 * 10^{11} \text{ gammas/sec} \end{aligned}$$

Similarly, the point source which yields 200 mr/hr at the cask surface is given by equation 12.

$$\begin{aligned} \text{(Equation 12)} \quad S &= \frac{4\pi(14.0\text{ cm})^2 (0.200\text{ r/hr})}{2.20 * 10^{-6} \frac{\text{r/hr}}{\text{gammas/cm}^2 - \text{sec}} (6.49)e^{-6.11}} \\ &= 1.55 * 10^{10} \text{ gammas/sec} \end{aligned}$$

The limiting source strength, then, is  $1.55 * 10^{10}$  gammas/sec. Equation 13, derived from equation 1, gives the dose rate as a function of distance from the cask side surface,  $a$ , and of point source strength,  $S$ .

$$\begin{aligned} \text{(Equation 13)} \quad D &= \frac{\left[ 2.20 * 10^{-6} \frac{\text{r/hr}}{\text{gammas/cm}^2 - \text{sec}} \right] (6.49)(S)e^{-6.21}}{4\pi(a + 14.0\text{ cm})^2} \\ &= \frac{(2.523 * 10^{-9})(S)\text{ r - cm}^2 - \text{sec/gammas - hr}}{(a + 14.0\text{ cm})^2} \end{aligned}$$

Figure 5.4 shows dose rates at 0, 1, and 2 meters from the cask top or bottom surfaces for various source strengths. Substituting the limiting source strength  $S = 1.55 * 10^{10}$  gammas/sec into equation 13 yields equation 14 which gives the maximum dose rate at any distance from the cask top or bottom surfaces.

$$\text{(Equation 14)} \quad D = \frac{39.11 \text{ r - cm}^2 / \text{hr}}{(a + 14.0\text{ cm})^2}$$

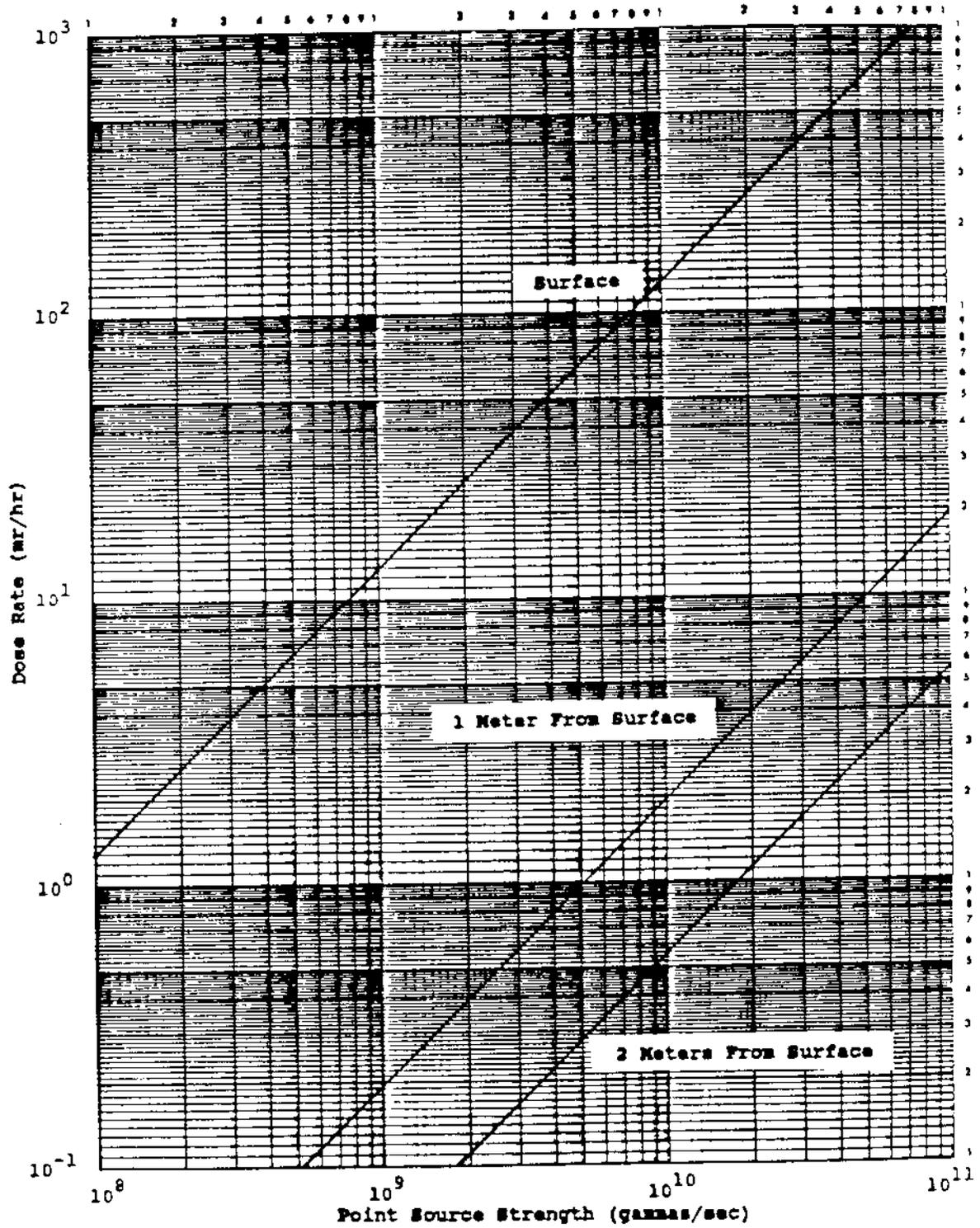


Figure 5.4  
Dose Rate Versus Point Source Strength—Top/Bottom of Cask

5.4.3 Accident Conditions 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) is was determined in the following analysis and is compared with 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.

~~\_\_\_\_\_ The number of relaxation lengths, b, is determined through the slumped region (side wall without lead) by equation 15.~~

(Equation 15) ~~\_\_\_\_\_~~

$$b = \mu_{es} t_{es}$$

$$= (0.437 \text{ cm}^{-1})(3.00 \text{ in})(2.54 \text{ cm/in})$$

$$= 3.33$$

~~\_\_\_\_\_ The buildup factor, B, is approximated by the buildup factor for iron. It is equal to 3.79 at b = 3.33 and at an energy of 1.25 Mev (Reference 1, page 147). Substituting b, B, and the maximum point source that may be transported in contact with the side wall,  $1.65 * 10^{10}$  gammas/sec (equation 7), gives equation 16 for the maximum dose rate at 1 meter from the side wall after lead slump.~~

(Equation 16)

$$D = \frac{\left[ 2.20 * 10^{-6} \frac{\text{r/hr}}{\text{gammas/cm}^2 \text{ - sec}} \right] (3.79)(1.65 * 10^{10} \text{ gammas/sec}) e^{-3.33}}{4\pi(111.8 \text{ cm})^2}$$

~~\_\_\_\_\_~~  $= 3.14 * 10^{-2} \text{ r/hr or } 31.4 \text{ mr/hr} \ll 1000 \text{ mr/hr}$

~~\_\_\_\_\_ The maximum dose rate calculated at 1 meter from the lead slump region, 31 mr/hr, is a factor of 32 lower than the 1000 mr/hr limit.~~

~~\_\_\_\_\_ Lead slump cannot occur in the top or bottom of the cask since lead is not present in these parts of the cask.~~

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. 05.7.1. 10-160b-pt-axial-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
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 1
0 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 0 22 78 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
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 0 22 78 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
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
sd1 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

```



```

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 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

```





hol 1 end  
cav 4 86.36 97.79 end  
cend  
end

- ~~5.7.~~
- ~~5.8.~~
- ~~5.9.~~
- ~~5.10.~~
- ~~5.11.~~
- ~~5.12.~~
- ~~5.13.~~
- ~~5.14.~~
- ~~5.15.~~
- ~~5.16.~~
- ~~5.17.~~
- ~~5.18.~~
- ~~5.19.~~
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- ~~5.21.~~
- ~~5.22.~~
- ~~5.23.~~
- ~~5.24.~~
- ~~5.25.~~
- ~~5.26.~~
- ~~5.27.~~
- ~~5.28.~~
- ~~5.29.~~
- ~~5.30.~~
- ~~5.31.~~
- ~~5.32.~~
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- ~~5.34.~~
- ~~5.35.~~
- ~~5.36.~~
- ~~5.37.~~
- ~~5.38.~~
- ~~5.39.~~
- ~~5.40.~~
- ~~5.41.~~
- ~~5.42.~~
- ~~5.43.~~
- ~~5.44.~~
- ~~5.45.~~
- 5.46. Figure 5.2
- 5.47. Radial and Axial Shielding Models

~~5.3.2 Shield Region Densities~~

~~5.48.~~

~~5.49. The mass densities, attenuation coefficients, and macroscopic cross sections,  $\mu$ , for each material in the model are shown in Table 5.2. The mass attenuation coefficient for carbon steel (CS) is approximated by the mass attenuation coefficient of its primary constituent, iron.~~

~~5.50.~~

~~5.51. Table 5.2~~

~~5.52. Shielding Material Properties~~

~~5.53.~~

~~5.54.5.5~~ REFERENCES

~~5.55.~~

~~5.56.1. Radiological Health Handbook, John C. Villforth and George R. Shultz, eds., U. S. Department of Health, Education, and Welfare, Rockville, MD, January 1970.~~

~~5.57.~~

## 6.0 CRITICALITY EVALUATION

### 6.1 DESCRIPTION OF CRITICALITY DESIGN

This criticality safety evaluation supports shipment of up to ten TRU waste drums per 10-160B Cask. This criticality safety evaluation establishes a general payload for the 10-160B Cask. The maximum fissile mass limit for the 10-160B Cask is 325 fissile-gram-equivalent (FGE). The waste drums will be filled with manually compacted waste (i.e., not machine compacted) containing a maximum of 1% by weight of special reflectors.

#### 6.1.1 Design Features

The Model CNS 10-160B packaging consists of a lead and steel containment vessel which provides the necessary shielding for the various radioactive payloads. (Refer to Section 1.2.3 for packaging contents.) Tests and analysis performed and documented within chapters 2.0 and 3.0 have demonstrated the ability of the containment vessel to maintain its shielding integrity under normal conditions of transport.

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.

Figures 6-1 and 6-2 present representative views of a single 10-160B Cask with ten 55-gallon drums for a normal as-loaded configuration.

#### 6.1.2 Summary Table of Criticality Evaluation

Table 6.1 summarizes the results of the criticality evaluation for single packages and arrays of packages for the conditions defined in 10 CFR 71.55 and 71.59. These results indicate that the 10-160B Cask with any of the payloads described in Section 6.2 remains safely subcritical under NCT and HAC even with the extremely conservative assumptions used in the analysis.

#### 6.1.3 Criticality Safety Index

As shown in Table 6.1, the maximum calculated  $k_{\text{eff}}$  value is 0.93873 (Case f022flat02) for an infinite array of fully flooded 10-160B Casks containing an optimally moderated sphere with 325 g of Pu-239. This is below the  $k_{\text{eff}}$  limit of 0.94 after allowing for bias and uncertainties. Because an infinite array of casks is safely subcritical, Nequals infinity and the CSI is zero.

Table 1. Summary of Criticality Safety Evaluation Results.

<b>Single Package Results [10 CFR 71.55(b), (d), (e)]</b>	
Package calculated to be subcritical under conditions for maximum reactivity	Maximum $k_{\text{eff}}^a = 0.93252$ , $\sigma = 0.00020$ (case f033)
Most reactive configuration	Compact sphere containing 325 g of $\text{Pu}^{239}$ homogenized with 25% by volume of $\text{CH}_2$ and 1% by weight of Be based on $\text{CH}_2$ and $\text{Pu}^{239}$ with the remaining volume filled with $\text{H}_2\text{O}$
Moderation for most reactive configuration	Cask flooded
Reflection for most reactive configuration (package materials and/or 30 cm water)	30 cm water around the cask
<b>Array Results</b>	
NCT array [10 CFR 71.59(a)(1)]	Maximum $k_{\text{eff}}^a = 0.45328$ , $\sigma = 0.00015$ (case f369a)
Number of packages	Analyzed: infinite array (CSI = 0)
Most reactive fissile content	Compact sphere containing 325 g of $\text{Pu}^{239}$ homogenized with 25% by volume of $\text{CH}_2$ and 1% by weight of Be based on $\text{CH}_2$ and $\text{Pu}^{239}$
Interstitial moderation	No interstitial moderation
Reflection surrounding array	No reflector since infinite array
HAC array [10 CFR 71.59(a)(2)]	Maximum $k_{\text{eff}}^a = 0.93873$ , $\sigma = 0.00020$ (case f022flat02)
Number of packages	Analyzed: infinite array (CSI = 0)
Most reactive fissile content:	Compact sphere containing 325 g of $\text{Pu}^{239}$ homogenized with 25% by volume of $\text{CH}_2$ and 1% by weight of Be based on $\text{CH}_2$ and $\text{Pu}^{239}$ with the remaining volume filled with $\text{H}_2\text{O}$
Interstitial moderation	0.001 g/cm <sup>3</sup> water interstitial moderation
Reflection surrounding array	No reflector since infinite array

<sup>a</sup> The effective criticality limit for this evaluation is  $k_{\text{eff}} < 0.94$  which accounts for bias and uncertainties (see Section 6.8).

## 6.2 FISSILE MATERIAL CONTENTS

The 10-160B payload is conservatively assumed to contain 325 g of pure  $\text{Pu}^{239}$ . The quantities of all fissile isotopes other than  $\text{Pu}^{239}$  present in the RH-TRU waste matrix may be converted to a FGE using the conversion factors outlined in the *Remote-Handling Transuranic Waste Authorization Methods for Payload Control (RH-TRAMPAC)* (Reference 6). In addition, the  $\text{Pu}^{239}$  is conservatively assumed to be contained within a sphere moderated and reflected by

polyethylene (CH<sub>2</sub>) with the total CH<sub>2</sub> comprising up to a maximum of 25% by volume of the 550 gallons. Beryllium is added as a special reflector/moderator with the total beryllium comprising up to a maximum of 1% by weight of the total masses of CH<sub>2</sub> and Pu<sup>239</sup>.

The use of polyethylene as the bounding hydrogenous moderating material is justified by the SAIC-1322-001 (Reference 7) study which concludes that polyethylene is the most reactive moderator that could credibly moderate the transuranic waste in a pure form. A 25% volumetric packing fraction for polyethylene is used as a conservative value which is based on physical testing that bounds the packing fraction of polyethylene in manually compacted TRU waste of 13.36% (Reference 8).

This evaluation also addresses the addition of special reflectors in the waste matrix. Materials that can credibly provide better than 25% polyethylene/75% water equivalent reflection are termed "special reflectors" and are not authorized for shipment in quantities that exceed 1% by weight. Based on the studies of reflector material documented in SAIC-1322-001 (Reference 7), Be, BeO, C, D<sub>2</sub>O, MgO, and depleted uranium (less than 0.72 wt% and greater than or equal to 0.3 wt% <sup>235</sup>U) are the only materials considered special reflectors. SAIC-1322-001 found that beryllium is the bounding special reflector as it provides the best reflection of the system and results in the highest  $k_{\text{eff}}$ .

For the NCT cases, the total amount of CH<sub>2</sub> is based on 25% by volume of 10 drums. The total amount of beryllium is based upon 1% by weight of the total mass of the CH<sub>2</sub> and the Pu<sup>239</sup> in the 10 drums. The NCT configurations are assumed to not contain water. Therefore, the remaining volume not filled with polyethylene, Pu<sup>239</sup> and beryllium is considered to be void. Densities are based upon smearing the materials with the void in the fissile sphere and the reflector.

For the NCT cases, the fissile sphere contains 325 g Pu<sup>239</sup> uniformly distributed with 25% by volume of CH<sub>2</sub>. Beryllium, added to the fissile sphere as a special reflector/moderator, is uniformly distributed throughout the sphere in the amount of 1% by mass of the total CH<sub>2</sub> and Pu<sup>239</sup> mass. H/Pu ratios are postulated which determine the masses of CH<sub>2</sub> and beryllium in the fissile sphere for a given H/Pu ratio. The volume of the sphere is dependent upon the sum of the Pu<sup>239</sup>, beryllium, polyethylene and void volumes. The various NCT fissile sphere compositions, densities and associated radii are presented in Table 6.2.

The remaining CH<sub>2</sub> (at 25% density) and beryllium not used in the fissile sphere are assumed to comprise a reflector completely surrounding the fissile sphere. The beryllium is uniformly distributed throughout the reflector volume in the amount of 1% by mass of the CH<sub>2</sub> mass. For the fissile sphere positioned in the centroid of the cask cavity, the reflector is a sphere. For the fissile sphere on the center floor or corner floor, the reflector occupies the same volume as the sphere but cylindrical in shape filling the lower portion of the cask. The reflector compositions are presented in Table 6.2 and representative views of the various NCT configurations are shown in Figures 6-3 through 6-5.

For the HAC cases, the total amount of CH<sub>2</sub> is based upon a maximum of 25% by volume of 10 drums. The total amount of beryllium is based upon a maximum of 1% by weight of the total mass of the CH<sub>2</sub> and the Pu<sup>239</sup> in the 10 drums. The HAC configurations are assumed to contain water as required by 10 CFR 71.55(b). Therefore, any remaining volume not filled with

polyethylene, Pu<sup>239</sup> and beryllium is considered to be filled with water. Densities are based upon smearing the materials with the water in the fissile sphere and the reflector.

For the HAC cases, the fissile sphere is comprised of 325 g Pu<sup>239</sup> uniformly distributed with the appropriate amounts of CH<sub>2</sub> and beryllium (as a special reflector/moderator) for the particular configuration. The remaining volume in the fissile sphere is filled with water. H/Pu ratios are postulated which determine the masses of CH<sub>2</sub> and beryllium in the fissile sphere for a given H/Pu ratio. The volume of the sphere is dependent upon the sum of the Pu<sup>239</sup>, beryllium, polyethylene and water volumes. The various HAC fissile sphere compositions and associated radii are presented in Table 6.3. Modifications of certain compositions were made to examine the effect of less beryllium (0% and 0.5% by mass of total CH<sub>2</sub> and Pu<sup>239</sup> mass) and by less polyethylene (20% by volume of the 10 drums). Representative views of the various HAC configurations are shown in Figures 6-6 through 6-9.

The HAC reflector contains the remaining CH<sub>2</sub> homogenized with sufficient H<sub>2</sub>O to fill the remaining cask cavity volume. Beryllium is added to the reflector as a special reflector and is uniformly distributed throughout the volume in the amount of 1% by mass of the CH<sub>2</sub> mass. The fissile sphere is located in the cask centroid, on the center floor, corner floor or corner ceiling. The reflector compositions are presented in Table 6.3. Modifications of certain compositions were made to examine the effect of less beryllium (0% and 0.5% by mass of total CH<sub>2</sub> mass) and by less polyethylene (20% by volume of the 10 drums).

### 6.3 GENERAL CONSIDERATIONS

#### 6.3.1 Model Configuration

Section 6.2 describes the fissile and reflector materials used in the criticality models.

Figures 6-1 and 6-2 present representative views of the normal condition 10-160B Cask with 10 drums. The radial and axial zone dimensions are shown in Table 6-4. The criticality model was developed using these dimensions and is essentially the same as the actual cask except that some details such as drain ports, lifting holes, and leak test ports are not included. The thermal barrier and impact limiter are also not included. These modeling simplifications will have a negligible impact on the criticality calculations and do not change the conclusions of the evaluation. A 12 inch water reflector region surrounds the cask.

The following additional assumptions are made in this evaluation.

1. The 10-160B is assumed to maintain its integrity under accident conditions; therefore, the cask model is based on nominal design dimensions and the payload is assumed to remain in the cask cavity under normal and accident conditions.
2. The fissile material is conservatively modeled as Pu<sup>239</sup> with no credit taken for any neutron poisons that may be present such as Pu<sup>240</sup> or Pu<sup>242</sup>, the drums, or internal support structures.
3. The moderating material is assumed to be bounded with polyethylene at a volume fraction of 25% of the total volume of waste (i.e., 25% of 550 gallons).

4. The maximum special reflecting material (beryllium) is 1% by weight in 550 gallons total volume of waste, i.e., 1% by weight of total mass of polyethelene and mass of plutonium.
5. Worse case NCT geometry is a sphere of fissile material. All plutonium is uniformly distributed within the sphere, as well as the polyethelene at a volume fraction of 25%. The beryllium is uniformly distributed within the sphere at 1% by weight of the total plutonium and polyethelene mass.
6. Worse case NCT reflector geometry contains the remaining polyethelene and beryllium. The reflector geometry is either a sphere surrounding the fissile material or a cylinder filling the bottom of the cask. In all cases, the polyethelene is at a packing fraction of 25% and the beryllium is uniformly distributed.
7. Worse case HAC geometry is a sphere of fissile material. All plutonium is uniformly distributed within the sphere, as well as the polyethelene (25%). The beryllium is uniformly distributed within the sphere at 1% by weight of the total plutonium and polyethelene mass. Water fills the remaining voids not filled by other materials.

Table2. NCT Fissile Sphere and Reflector Compositions.

NCT Fissile Plus Moderator - 25% CH <sub>2</sub> Volume Fraction <sup>b</sup> - 1% Be Weight Fraction <sup>c</sup>										
Material Identifier	H/Pu	Sphere Radius (cm)	Sphere Density (g/cm <sup>3</sup> )	Mass Fractions <sup>a</sup>						
				Hydrogen		Beryllium	Carbon	Oxygen		Plutonium
				H <sup>1</sup>	H <sup>2</sup>	Be <sup>9</sup>	C	O <sup>16</sup>	O <sup>17</sup>	Pu <sup>239</sup>
m130	700	19.04676	0.244252	0.13564500	0.00004067	0.00990099	0.80844128	N/A	N/A	0.04597206
m131	800	19.913170	0.242853	0.13643688	0.00004091	0.00990099	0.81316084	N/A	N/A	0.04046038
m132	850	20.31945	0.242277	0.13676564	0.00004100	0.00990099	0.81512025	N/A	N/A	0.03817212
m133	900	20.71011	0.241765	0.13705920	0.00004109	0.00990099	0.81686988	N/A	N/A	0.03612883
m134	950	21.08656	0.241307	0.13732294	0.00004117	0.00990099	0.81844173	N/A	N/A	0.03429317
m135	1000	21.45002	0.240895	0.13756117	0.00004124	0.00990099	0.81986157	N/A	N/A	0.03263503
m136	1100	22.14214	0.240183	0.13797461	0.00004137	0.00990099	0.82232566	N/A	N/A	0.02975738
m137	1200	22.79349	0.239589	0.13832104	0.00004147	0.00990099	0.82439041	N/A	N/A	0.02734609
m138	1300	23.40961	0.239087	0.13861554	0.00004156	0.00990099	0.82614562	N/A	N/A	0.02529629
m139	1400	23.99489	0.238656	0.13886897	0.00004163	0.00990099	0.82765605	N/A	N/A	0.02353235
m140	1500	24.55294	0.238283	0.13908936	0.00004170	0.00990099	0.82896956	N/A	N/A	0.02199839
m141	1600	25.08671	0.237957	0.13928277	0.00004176	0.00990099	0.83012231	N/A	N/A	0.02065217
m142	1700	25.59869	0.237669	0.13945388	0.00004181	0.00990099	0.83114211	N/A	N/A	0.01946121
m143	1800	26.09097	0.237412	0.13960633	0.00004186	0.00990099	0.83205070	N/A	N/A	0.01840013

NCT Reflector - 25% CH <sub>2</sub> Volume Fraction <sup>b</sup> - 1% Be Weight Fraction <sup>c</sup>										
Material Identifier	H/Pu	Sphere Radius (cm)	Reflector Density (g/cm <sup>3</sup> )	Mass Fractions <sup>a</sup>						
				Hydrogen		Beryllium	Carbon	Oxygen		Plutonium
				H <sup>1</sup>	H <sup>2</sup>	Be <sup>9</sup>	C	O <sup>16</sup>	O <sup>17</sup>	Pu <sup>239</sup>
m160	N/A	79.21023	0.233058	0.142249921	4.26486E-05	0.00990099	0.847806441	N/A	N/A	N/A
m161	N/A	79.21023	0.233058	0.142249921	4.26486E-05	0.00990099	0.847806441	N/A	N/A	N/A
m162	N/A	79.21023	0.233058	0.142249921	4.26486E-05	0.00990099	0.847806441	N/A	N/A	N/A
m163	N/A	79.21023	0.233058	0.142249921	4.26486E-05	0.00990099	0.847806441	N/A	N/A	N/A
m164	N/A	79.21023	0.233058	0.142249921	4.26486E-05	0.00990099	0.847806441	N/A	N/A	N/A
m165	N/A	79.21023	0.233058	0.142249921	4.26486E-05	0.00990099	0.847806441	N/A	N/A	N/A
m166	N/A	79.21023	0.233058	0.142249921	4.26486E-05	0.00990099	0.847806441	N/A	N/A	N/A
m167	N/A	79.21023	0.233058	0.142249921	4.26486E-05	0.00990099	0.847806441	N/A	N/A	N/A
m168	N/A	79.21023	0.233058	0.142249921	4.26486E-05	0.00990099	0.847806441	N/A	N/A	N/A
m169	N/A	79.21023	0.233058	0.142249921	4.26486E-05	0.00990099	0.847806441	N/A	N/A	N/A
m170	N/A	79.21023	0.233058	0.142249921	4.26486E-05	0.00990099	0.847806441	N/A	N/A	N/A
m171	N/A	79.21023	0.233058	0.142249921	4.26486E-05	0.00990099	0.847806441	N/A	N/A	N/A
m172	N/A	79.21023	0.233058	0.142249921	4.26486E-05	0.00990099	0.847806441	N/A	N/A	N/A
m173	N/A	79.21023	0.233058	0.142249921	4.26486E-05	0.00990099	0.847806441	N/A	N/A	N/A

<sup>a</sup> Values derived assuming 19.7 g/cm<sup>3</sup> for Pu, 1.85 g/cm<sup>3</sup> for Be, 0.923 g/cm<sup>3</sup> for CH<sub>2</sub>, and 1.0 g/cm<sup>3</sup> for H<sub>2</sub>O.

<sup>b</sup> CH<sub>2</sub> volume fractions based on ten 55 gallon drums

<sup>c</sup> Be weight fraction based upon mass of CH<sub>2</sub> and Pu (fissile region only)

Table 3. HAC Fissile Sphere and Reflector Compositions.

HAC Fissile Plus Moderator												
Material Identifier	H/Pu	CH <sub>2</sub> <sup>b</sup> Volume Fraction	Be <sup>c</sup> Weight Fraction	Sphere Radius (cm)	Sphere Density (g/cm <sup>3</sup> )	Mass Fractions <sup>a</sup>						
						Hydrogen		Beryllium	Carbon	Oxygen		Plutonium
						H <sup>1</sup>	H <sup>2</sup>	Be <sup>9</sup>	C	O <sup>16</sup>	O <sup>17</sup>	Pu <sup>239</sup>
m100	700	25%	1.0%	12.519999	1.019560	0.11441390	0.00003430	0.00264597	0.19336657	0.65049999	0.00026274	0.03877653
m101	800	25%	1.0%	13.088647	1.014851	0.11497677	0.00003447	0.00261028	0.19431786	0.65370021	0.00026404	0.03409638
m102	850	25%	1.0%	13.355327	1.012911	0.11521015	0.00003454	0.00259548	0.19471229	0.65502711	0.00026457	0.03215585
		25%	0.5%	13.352284	1.012326	0.11535548	0.00003459	0.00129870	0.19484164	0.65600821	0.00026497	0.03219641
		25%	0.0%	13.349243	1.011742	0.11550103	0.00003463	0.00000000	0.19497120	0.65699073	0.00026537	0.03223704
		20%	1.0%	13.393913	1.016274	0.11383931	0.00003413	0.00213088	0.15525677	0.69668428	0.00028140	0.03177324
m103	900	25%	1.0%	13.611761	1.011186	0.11541840	0.00003460	0.00258227	0.19506425	0.65621111	0.00026505	0.03042431
		25%	0.5%	13.608682	1.010604	0.11556323	0.00003465	0.00129208	0.19519253	0.65718959	0.00026545	0.03046248
		25%	0.0%	13.605605	1.010023	0.11570826	0.00003469	0.00000000	0.19532101	0.65816948	0.00026584	0.03050072
		20%	1.0%	13.651092	1.014565	0.11404263	0.00003419	0.00211700	0.15553406	0.69792857	0.00028190	0.03006165
m104	950	25%	1.0%	13.858882	1.009642	0.11560537	0.00003466	0.00257042	0.19538023	0.65727412	0.00026548	0.02886972
		25%	0.5%	13.855767	1.009063	0.11574973	0.00003470	0.00128613	0.19550755	0.65825023	0.00026587	0.02890577
		25%	0.0%	13.852654	1.008484	0.11589430	0.00003475	0.00000000	0.19563507	0.65922774	0.00026627	0.02894188
		20%	1.0%	13.898930	1.013035	0.11422516	0.00003425	0.00210454	0.15578300	0.69904565	0.00028235	0.02852505
m105	1000	25%	1.0%	14.097490	1.008253	0.11577416	0.00003471	0.00255972	0.19566550	0.65823377	0.00026587	0.02746628
		25%	0.5%	14.094340	1.007676	0.11591811	0.00003475	0.00128077	0.19579194	0.65920774	0.00026626	0.02750043
		25%	0.0%	14.091191	1.007100	0.11606226	0.00003480	0.00000000	0.19591858	0.66018308	0.00026665	0.02753463
		20%	1.0%	14.138232	1.011657	0.11438994	0.00003430	0.00209329	0.15600773	0.70005409	0.00028276	0.02713789
m106	1100	25%	1.0%	14.551873	1.005852	0.11606687	0.00003480	0.00254115	0.19616020	0.65989797	0.00026654	0.02503247

HAC Reflector												
Material Identifier	H/Pu	CH <sub>2</sub> <sup>b</sup> Volume Fraction	Be <sup>c</sup> Weight Fraction	Sphere Radius (cm)	Reflector Density (g/cm <sup>3</sup> )	Mass Fractions <sup>a</sup>						
						Hydrogen		Beryllium	Carbon	Oxygen		Plutonium
						H <sup>1</sup>	H <sup>2</sup>	Be <sup>9</sup>	C	O <sup>16</sup>	O <sup>17</sup>	Pu <sup>239</sup>
m150	N/A	25%	1.0%	N/A	0.991734	0.11510979	0.00003451	0.00105738	0.09054180	0.79293624	0.00032027	N/A
m151	N/A	25%	1.0%	N/A	0.991737	0.11510879	0.00003451	0.00105705	0.09051365	0.79296572	0.00032029	N/A
m152	N/A	25%	1.0%	N/A	0.991738	0.11510828	0.00003451	0.00105689	0.09049956	0.79298046	0.00032029	N/A
		25%	0.5%	N/A	0.991497	0.11516820	0.00003453	0.00052857	0.09052169	0.79342654	0.00032047	N/A
		25%	0.0%	N/A	0.991256	0.11522815	0.00003455	0.00000000	0.09054382	0.79387283	0.00032065	N/A
		20%	1.0%	N/A	0.993391	0.11445521	0.00003432	0.00084408	0.07227755	0.81206084	0.00032800	N/A
m153	N/A	25%	1.0%	N/A	0.991739	0.11510778	0.00003451	0.00105672	0.09048548	0.79299521	0.00032030	N/A
		25%	0.5%	N/A	0.991498	0.11516769	0.00003453	0.00052849	0.09050760	0.79344121	0.00032048	N/A
		25%	0.0%	N/A	0.991257	0.11522763	0.00003455	0.00000000	0.09052974	0.79388743	0.00032066	N/A
		20%	1.0%	N/A	0.993392	0.11445480	0.00003432	0.00084395	0.07226622	0.81207270	0.00032800	N/A
m154	N/A	25%	1.0%	N/A	0.991740	0.11510727	0.00003451	0.00105656	0.09047139	0.79300997	0.00032030	N/A
		25%	0.5%	N/A	0.991500	0.11516717	0.00003453	0.00052841	0.09049351	0.79345589	0.00032048	N/A
		25%	0.0%	N/A	0.991259	0.11522711	0.00003455	0.00000000	0.09051565	0.79392023	0.00032066	N/A
		20%	1.0%	N/A	0.993393	0.11445440	0.00003432	0.00084382	0.07225489	0.81208457	0.00032801	N/A
m155	N/A	25%	1.0%	N/A	0.991742	0.11510677	0.00003451	0.00105639	0.09045730	0.79302472	0.00032031	N/A
		25%	0.5%	N/A	0.991501	0.11516666	0.00003453	0.00052833	0.09047942	0.79347057	0.00032049	N/A
		25%	0.0%	N/A	0.991260	0.11522658	0.00003455	0.00000000	0.09050156	0.79391664	0.00032067	N/A
		20%	1.0%	N/A	0.993394	0.11445399	0.00003431	0.00084369	0.07224356	0.81209644	0.00032801	N/A
m156	N/A	25%	1.0%	N/A	0.991744	0.11510576	0.00003451	0.00105606	0.09042910	0.79305425	0.00032032	N/A

<sup>a</sup> Values derived assuming 19.7 g/cm<sup>3</sup> for Pu, 1.85 g/cm<sup>3</sup> for Be, 0.923 g/cm<sup>3</sup> for CH<sub>2</sub>, and 1.0 g/cm<sup>3</sup> for H<sub>2</sub>O.

<sup>b</sup> CH<sub>2</sub> volume fractions based on ten 55 gallon drums

<sup>c</sup> Be weight fraction based upon mass of CH<sub>2</sub> and Pu (fissile region only)

8. Worse case HAC reflector geometry contains the remaining polyethelene and beryllium (1% by weight of the polyethelene) surrounding the fissile sphere. In addition, water is used to fill the space not filled by the polyethelene and beryllium. All three components (i.e., water, polyethylene and beryllium) are homogenously mixed and uniformly distributed throughout the remaining cask volume.
9. The criticality analyses were performed for fully reflected external conditions. Therefore, a 30.48 cm (12-in.) water reflector completely surrounding the cask is used in all single cask calculations for normal and accident conditions. This configuration is consistent with the requirements of 10 CFR 71.55(b)(3), which require full reflection, and a U.S. Nuclear Regulatory Commission recommendation that the thickness of the water reflector be at least 30 cm.

The previous paragraphs describe the assumptions used to analyze the 10-160B Cask. These assumptions provide the following conservative attributes, as required by 10 CFR 71.55.

1. Spherical fissile geometry for maximum reactivity
2. Optimum moderation, including special reflecting material (i.e., beryllium)
3. Full reflection
4. No credit for drums and internal drum support structure
5. Flooded for HAC

Figure 6-1. Representative Elevation View of a Single 10-160B Cask  
With Ten 55-gal Drums in the Cask Cavity (Normal (As-Loaded) Configuration).

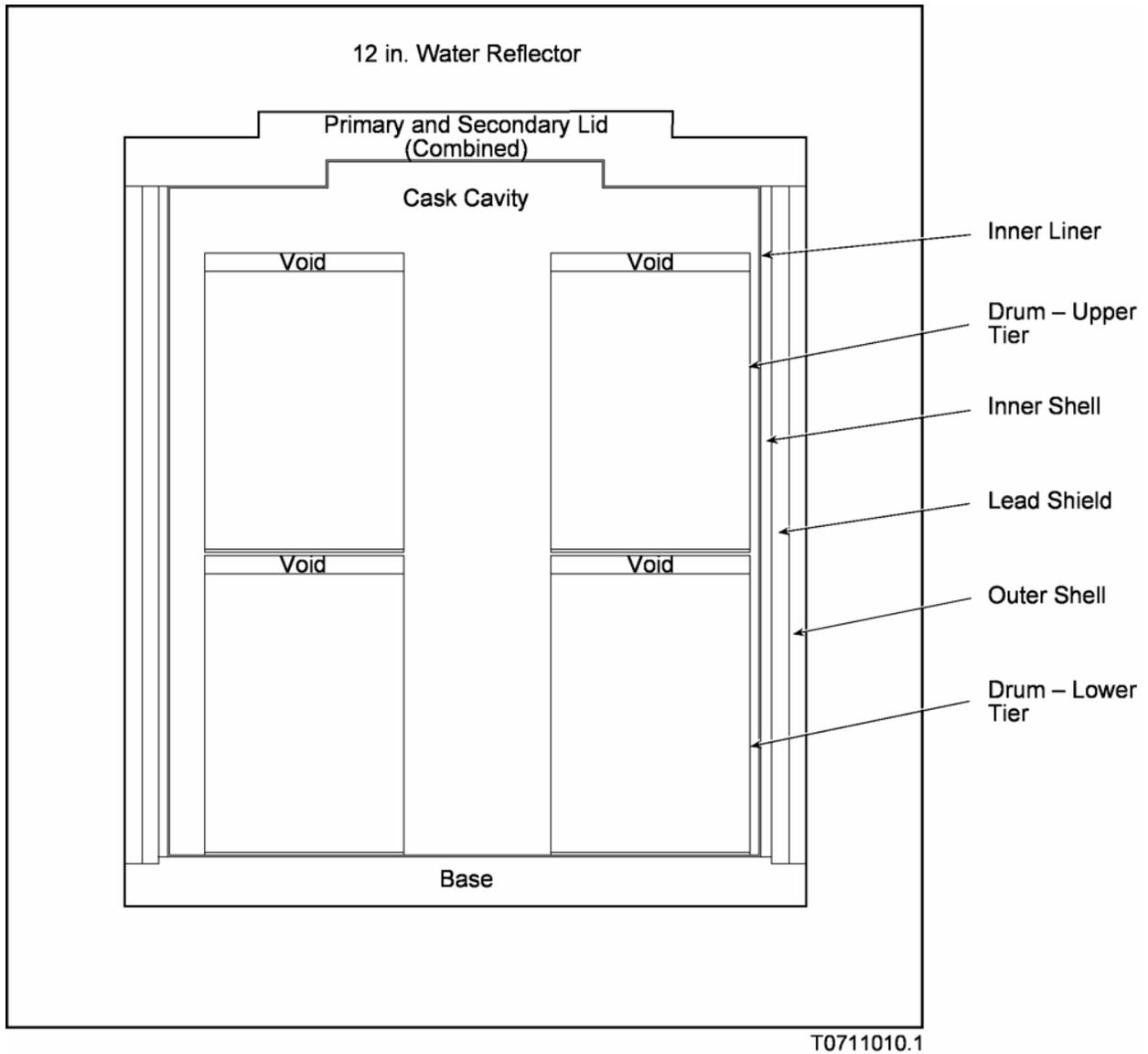


Figure 6-2. Representative Plan View of a Single 10-160B Cask  
With Ten 55-gal Drums in the Cask Cavity (Normal (As-Loaded) Configuration).

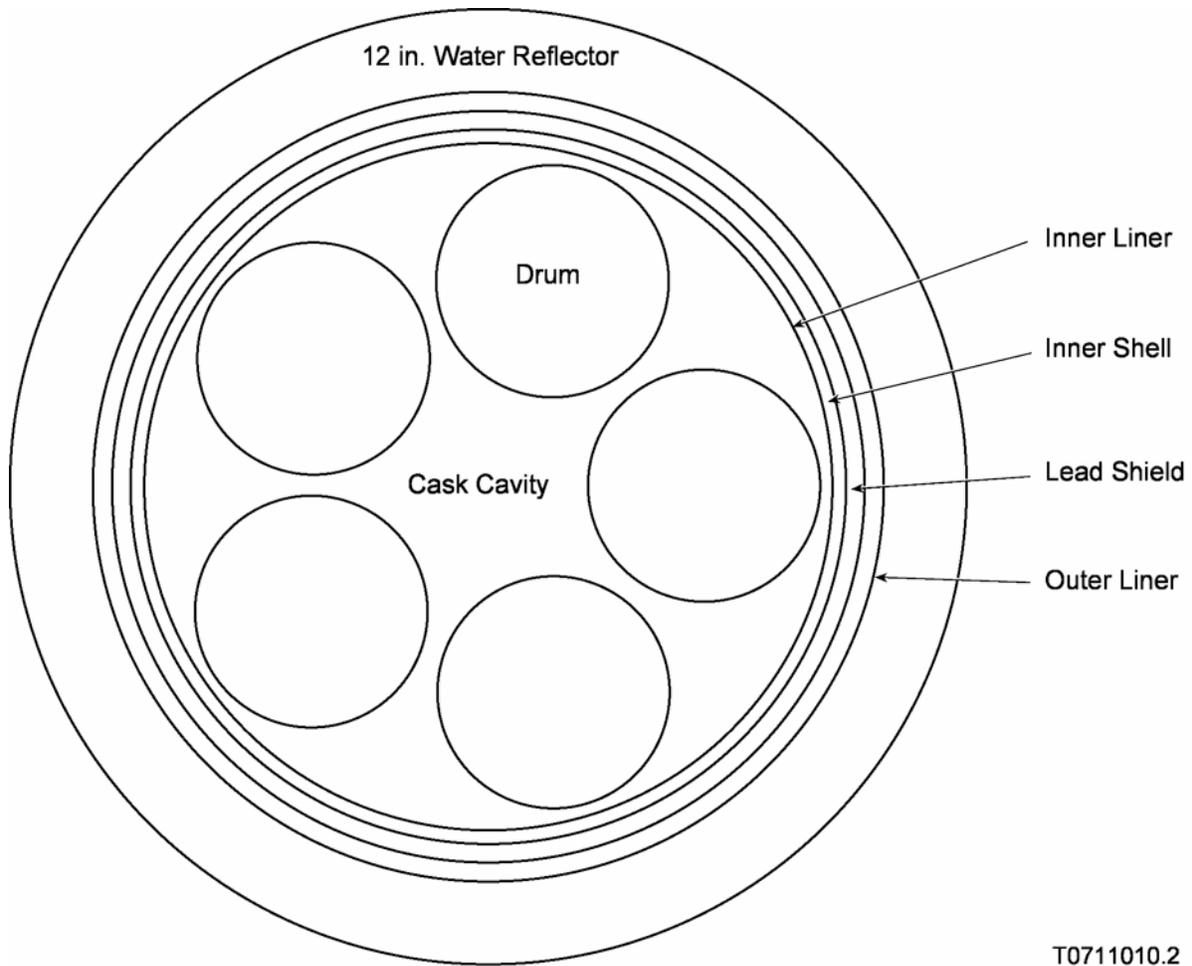


Figure 6-3. Elevation View of a Single 10-160B Cask with the Fissile and Reflector Regions for the NCT Centroid Case (Case f309).

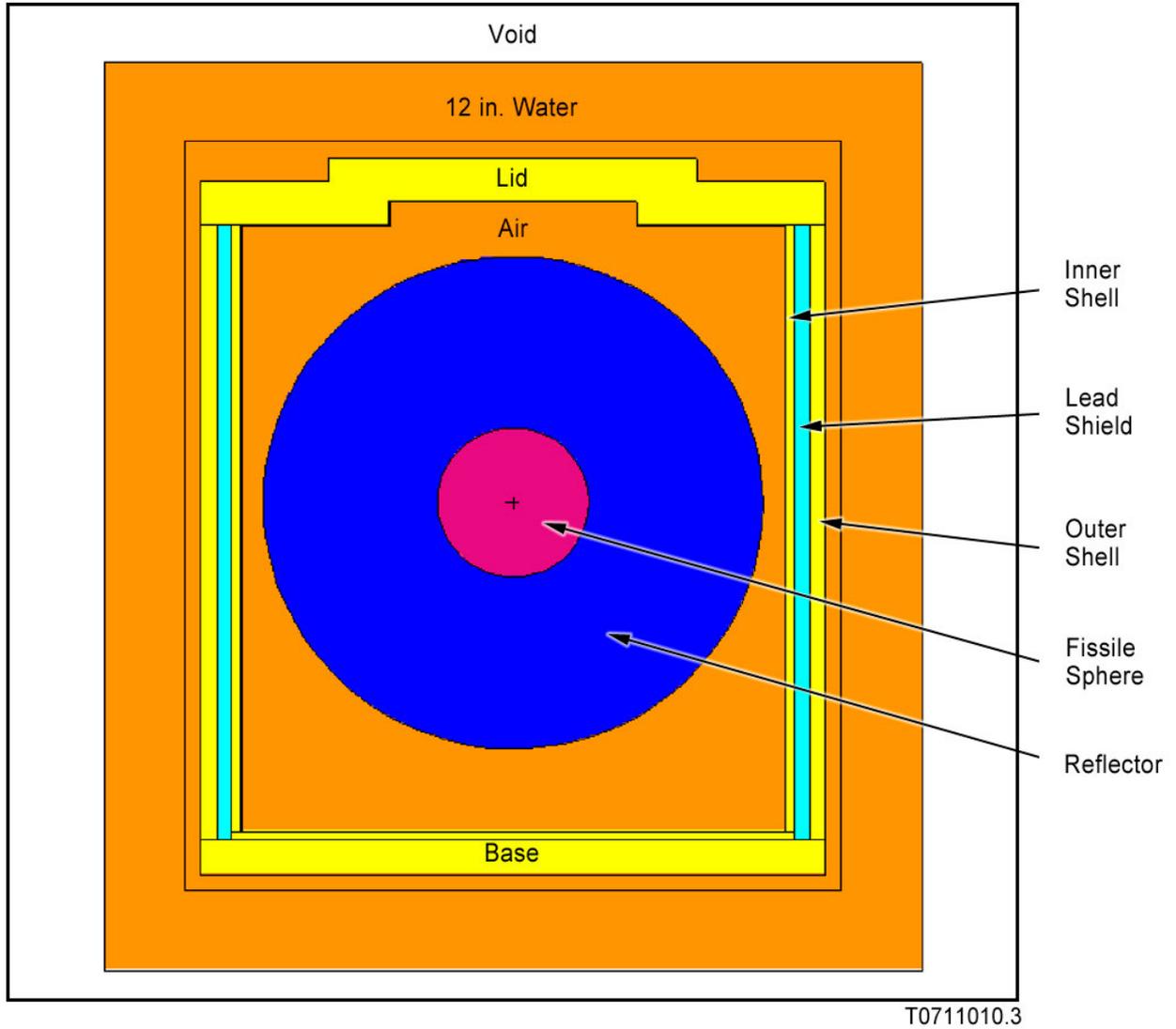


Figure 6-4. Elevation View of a Single 10-160B Cask with the Fissile and Reflector Regions for the NCT Base Center Case (Case f329).

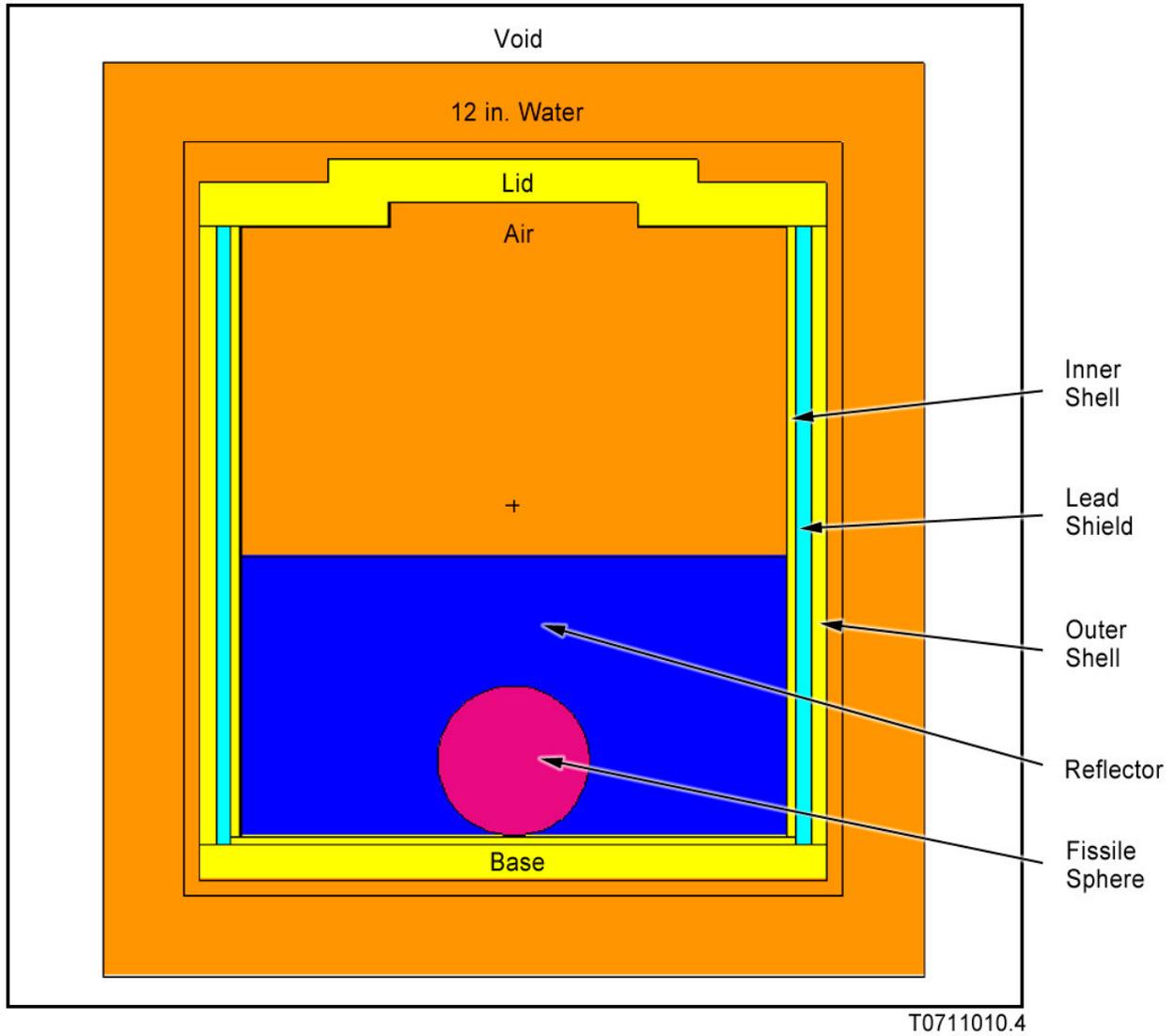


Figure 6-5. Elevation View of a Single 10-160B Cask with the Fissile and Reflector Regions for the NCT Base Corner Case (Case f349).

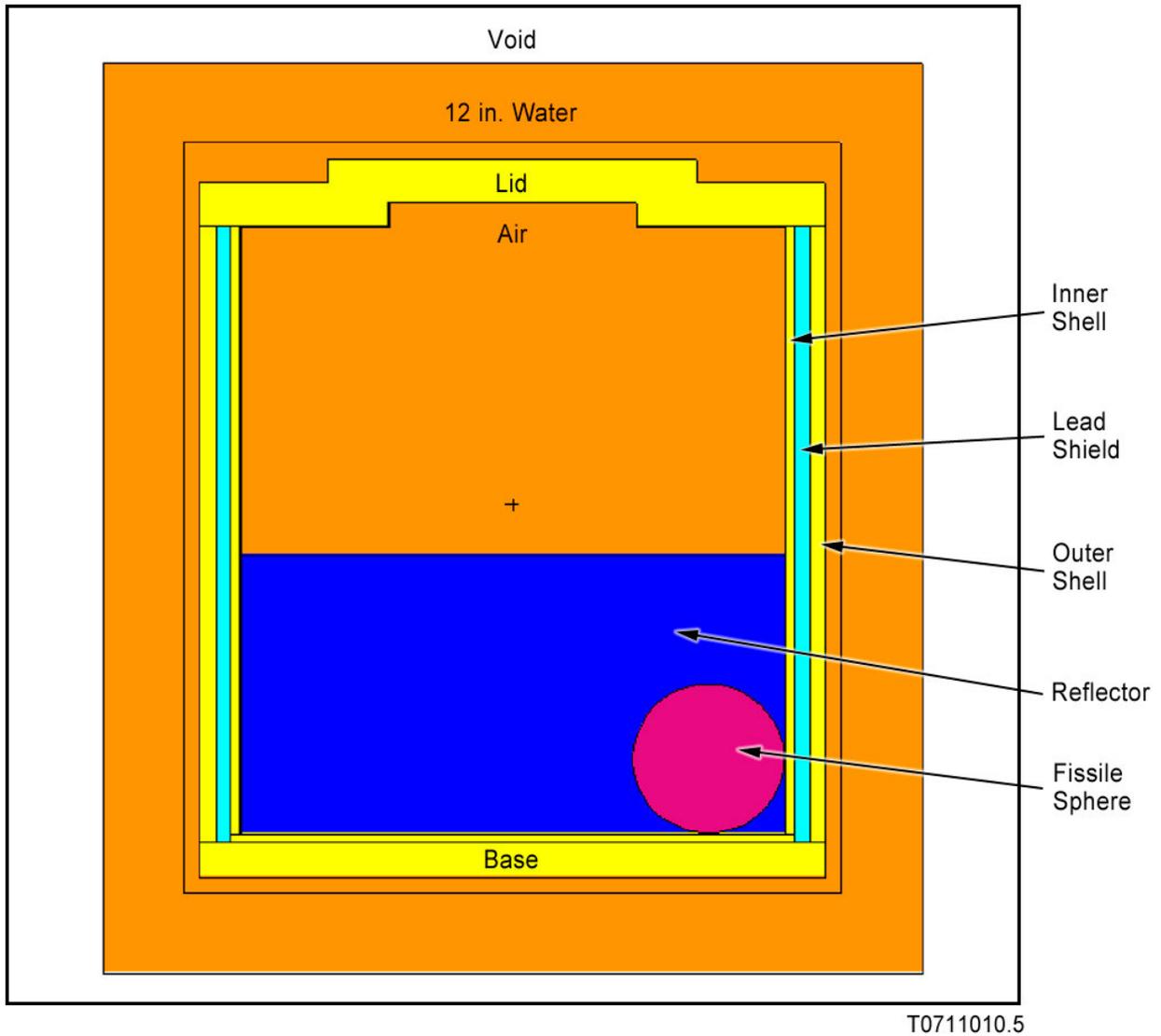


Figure 6-6. Elevation View of a Single 10-160B Cask with the Fissile and Reflector Regions for the HAC Centroid Case (Case f003).

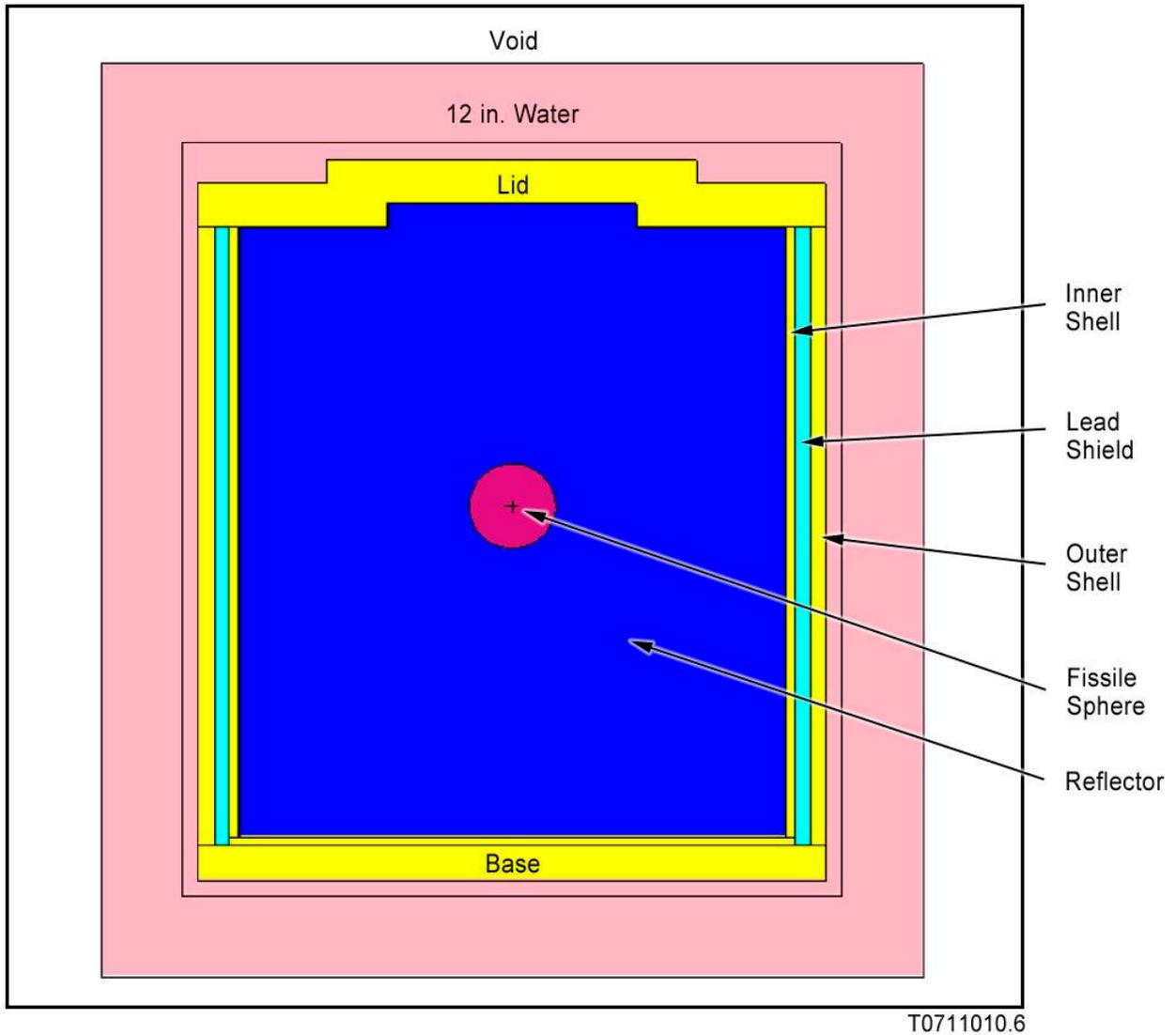


Figure 6-7. Elevation View of a Single 10-160B Cask with the Fissile and Reflector Regions for the HAC Base Center Case (Case f013).

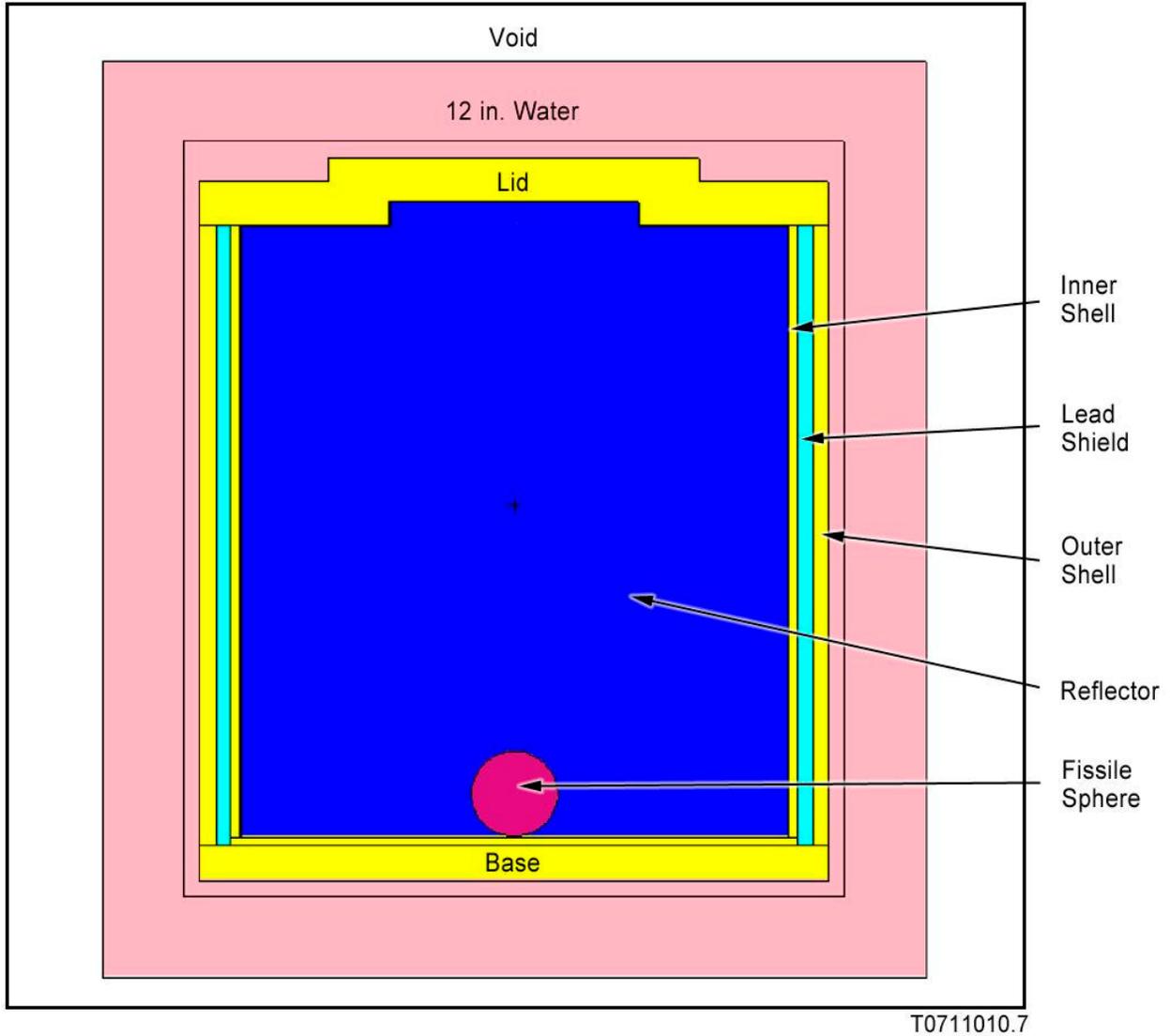


Figure 6-8. Elevation View of a Single 10-160B Cask with the Fissile and Reflector Regions for the HAC Base Corner Case (Case f023).

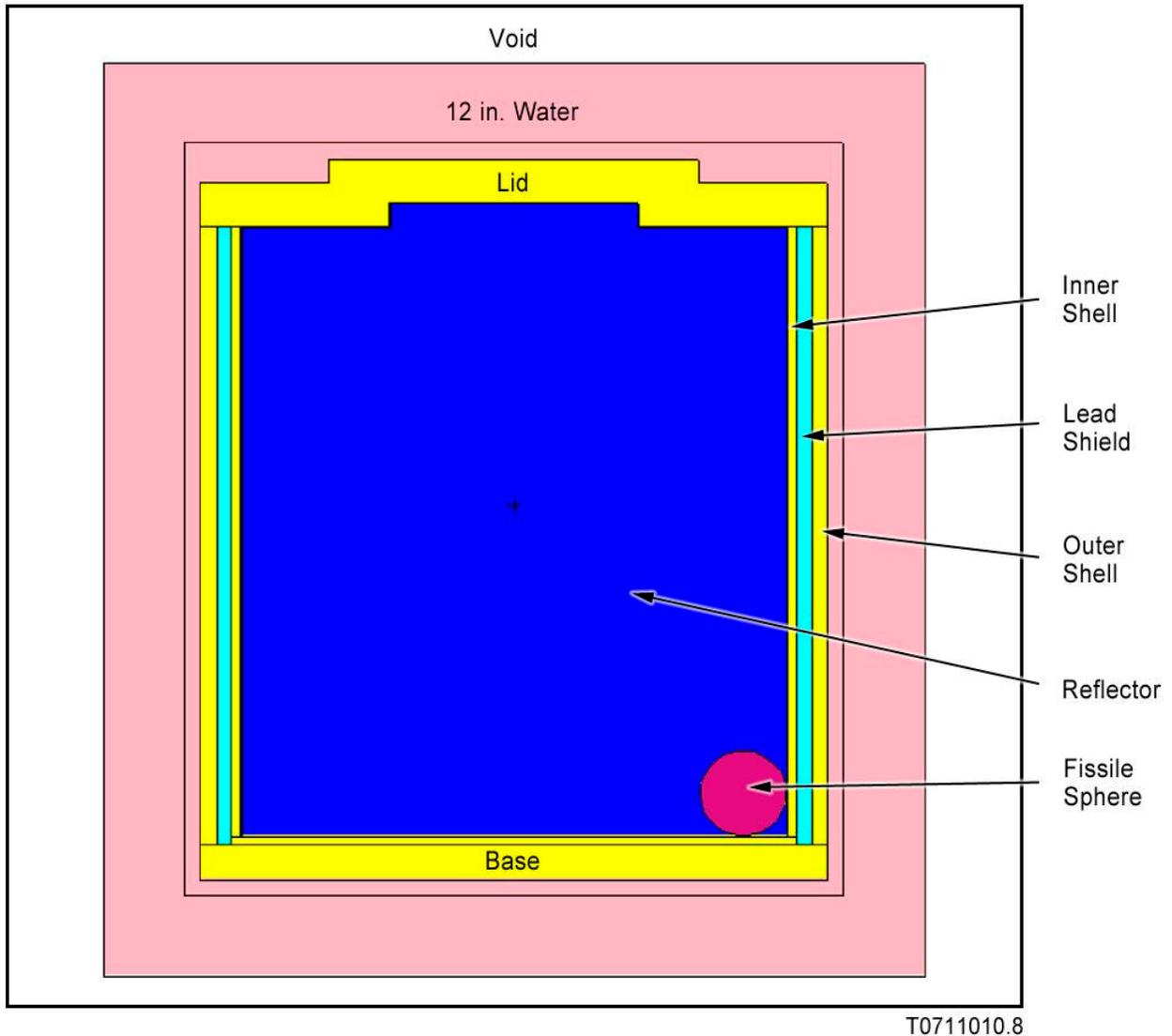


Figure 6-9. Elevation View of a Single 10-160B Cask with the Fissile and Reflector Regions for the HAC Lid Corner Case (Case f033).

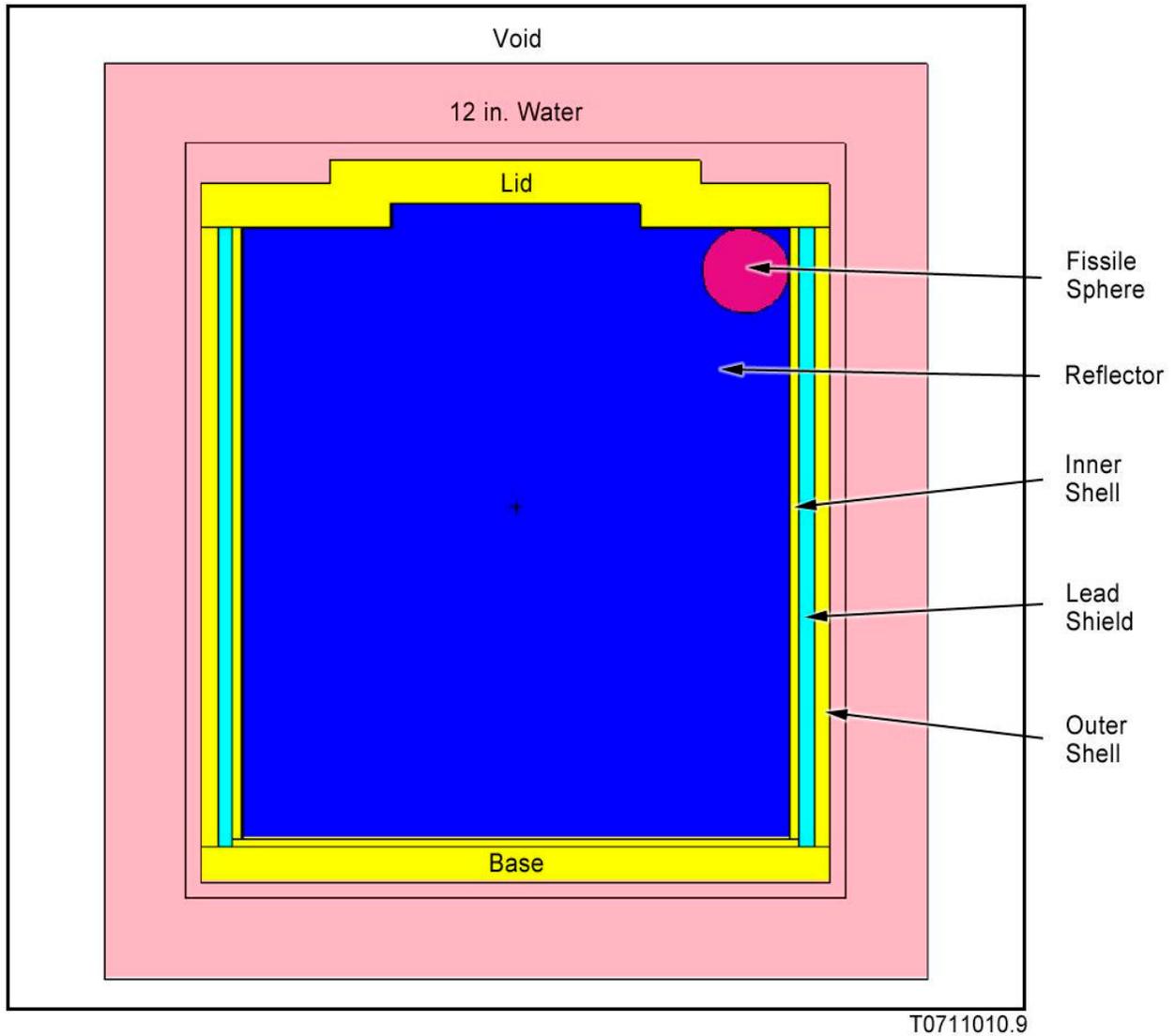


Table 6.4. Assumed Nominal Dimensions of the 10-160B Cask MCNP Criticality Model.

Zone (material)	Axial zone length		Zone outer radius		Zone radial thickness	
	in	cm	in	cm	in	cm
Cask Dimensions <sup>a</sup>						
Secondary Lid <sup>b</sup> (Carbon Steel)	5.5	13.970	23	58.420	23	58.420
Primary Lid <sup>b</sup> (Carbon Steel)	5.5	13.970	39	99.060	23.5	59.690
Cask cavity (void)	76.75	194.945	33.875	86.043	33.875	86.043
Inner liner <sup>c</sup> (SS 304)	77	195.580	34	86.360	0.125	0.318
Inner shell (Carbon Steel)	77	195.580	35.125	89.218	1.125	2.858
Lead shield (Lead)	78	198.120	37	93.980	1.875	4.763
Outer Shell (Carbon Steel)	78	198.120	39	99.060	2	5.080
Base (Carbon Steel)	5.5	13.970	39	99.060	39	99.060

<sup>a</sup> The bottom tapered edge of the cask is not modeled. Also, the impact limiter and thermal barrier are not included in the model. These modeling simplifications have negligible impact on the results.

<sup>b</sup> The primary and secondary lids are stepped. The dimensions listed in the table are the inner/outer-most dimensions.

<sup>c</sup> The inner lining is irregular in shape but essentially consists of 11 gage steel covering the entire cask inner cavity.

### 6.3.2 Material Properties

Table 6.5 shows the material compositions used in the MCNP models including the density of the material and the MCNP cross-sectional set name. Any changes in material properties under tests in 10 CFR 71.71 and 71.73, *Hypothetical Accident Conditions*, are minor and have a minimal impact on the results of this evaluation due to the conservative assumptions used to model the payload.

The S(□, □) cross-sections for hydrogen in the HAC regions were selected as light water (lwtr.60t) since the light water cross-sections provide a slightly higher reactivity than do the corresponding cross-sections for polyethylene.

Dry air was used for the NCT cases where the cask is dry. Air was assumed to only contain N<sub>2</sub> and O<sub>2</sub>, thereby ignoring the trace amounts of Ar and other gases.

Table 5. Materials and Elemental Compositions Used to Perform the Criticality Analyses for the 10-160B Cask.

Item	Isotope Element	MCNP ZAID	Mass Fraction	Density (g/cm <sup>3</sup> )
NCT Fissile	H <sup>1</sup>	1001.66c	Table 6.2	Table 6.2
	H <sup>2</sup>	1002.66c	Table 6.2	Table 6.2
	Be <sup>9</sup>	4009.66c	Table 6.2	Table 6.2
	C	6000.66c	Table 6.2	Table 6.2
	Pu <sup>239</sup>	94239.66c	Table 6.2	Table 6.2
	S(α,β)	poly.60t		
	S(α,β)	be.60t		
	Totals		1.00	Table 6.2
HAC Fissile	H <sup>1</sup>	1001.66c	Table 6.3	Table 6.3
	H <sup>2</sup>	1002.66c	Table 6.3	Table 6.3
	Be <sup>9</sup>	4009.66c	Table 6.3	Table 6.3
	C	6000.66c	Table 6.3	Table 6.3
	O <sup>16</sup>	8016.66c	Table 6.3	Table 6.3
	O <sup>17</sup>	8017.66c	Table 6.3	Table 6.3
	Pu <sup>239</sup>	94239.66c	Table 6.3	Table 6.3
	S(α,β)	lwtr.60t		
S(α,β)	be.60t			
Totals		1.00	Table 6.3	
NCT Reflector	H <sup>1</sup>	1001.66c	Table 6.2	Table 6.2
	H <sup>2</sup>	1002.66c	Table 6.2	Table 6.2
	Be <sup>9</sup>	4009.66c	Table 6.2	Table 6.2
	C	6000.66c	Table 6.2	Table 6.2
	Pu <sup>239</sup>	94239.66c	Table 6.2	Table 6.2
	S(α,β)	poly.60t		
	S(α,β)	be.60t		
	Totals		1.00	Table 6.2
HAC Reflector	H <sup>1</sup>	1001.66c	Table 6.3	Table 6.3
	H <sup>2</sup>	1002.66c	Table 6.3	Table 6.3
	Be <sup>9</sup>	4009.66c	Table 6.3	Table 6.3
	C	6000.66c	Table 6.3	Table 6.3
	O <sup>16</sup>	8016.66c	Table 6.3	Table 6.3
	O <sup>17</sup>	8017.66c	Table 6.3	Table 6.3
	Pu <sup>239</sup>	94239.66c	Table 6.3	Table 6.3
	S(α,β)	lwtr.60t		
S(α,β)	be.60t			
Totals		1.00	Table 6.3	
Air	N <sup>14</sup>	7014.66c	0.761985	9.30E-04
	N <sup>15</sup>	7015.66c	0.003015	3.68E-06
	O <sup>16</sup>	8016.66c	0.234905	2.87E-04
	O <sup>17</sup>	8017.66c	0.000095	1.16E-07
	Totals		1.00	0.00122

Item	Isotope Element	MCNP ZAID	Mass Fraction	Density (g/cm <sup>3</sup> )
Carbon Steel	C	6000.66c	0.003000	0.023550
	Si <sup>28</sup>	14028.66c	0.002572	0.020190
	Si <sup>29</sup>	14029.66c	0.000135	0.001060
	Si <sup>30</sup>	14030.66c	0.000092	0.000722
	P <sup>31</sup>	15031.66c	0.000400	0.003140
	S	16000.66c	0.000500	0.003925
	Mn <sup>55</sup>	25055.66c	0.010300	0.080855
	Fe <sup>54</sup>	26054.66c	0.055383	0.434757
	Fe <sup>56</sup>	26056.66c	0.901554	7.077199
	Fe <sup>57</sup>	26057.66c	0.021193	0.166365
	Fe <sup>58</sup>	26058.66c	0.002870	0.022530
	Cu <sup>63</sup>	29063.66c	0.001370	0.010755
	Cu <sup>65</sup>	29065.66c	0.000630	0.004946
	Totals		1.00	7.85
	SS-304	C	6000.66c	0.000300
Cr <sup>50</sup>		24050.66c	0.008345	0.067010
Cr <sup>52</sup>		24052.66c	0.167349	1.343812
Cr <sup>53</sup>		24053.66c	0.019341	0.155308
Cr <sup>54</sup>		24054.66c	0.004905	0.039387
Mn <sup>55</sup>		25055.66c	0.019994	0.160552
Fe <sup>54</sup>		26054.66c	0.038378	0.308175
Fe <sup>56</sup>		26056.66c	0.624743	5.016686
Fe <sup>57</sup>		26057.66c	0.014686	0.117929
Fe <sup>58</sup>		26058.66c	0.001989	0.015972
Ni <sup>58</sup>		28058.66c	0.067178	0.539439
Ni <sup>60</sup>		28060.66c	0.026768	0.214947
Ni <sup>61</sup>		28061.66c	0.001183	0.009499
Ni <sup>62</sup>		28062.66c	0.003834	0.030787
Ni <sup>64</sup>		28064.66c	0.001008	0.008094
Totals		1.00	8.03	
Lead	Pb	82000.50c	1.000000	11.34
	Totals		1.00	11.34
Water	H <sup>1</sup>	1001.66c	0.111865	0.111865
	H <sup>2</sup>	1002.66c	0.000034	3.35E-05
	O <sup>16</sup>	8016.66c	0.887743	0.887743
	O <sup>17</sup>	8017.66c	0.000359	0.000359
	S(α,β)	lwtr.60t		
Totals		1.00	1.00	

### 6.3.3 Computer Codes and Cross-Sectional Libraries

The  $k_{\text{eff}}$  values are calculated using the computer program MCNP Version 5, Release 1.40<sup>[3]</sup>. The MCNP computer program has been approved for use with quality affecting analyses and is under configuration control in accordance with FSWO-QAP-001, *Quality Assurance Procedures*, QP 3-10, *Software Management*<sup>[2]</sup>.

MCNP calculates  $k_{\text{eff}}$  using the Monte Carlo method from an arbitrary three-dimensional configuration using point wise continuous-energy cross-sectional data. Because of the statistical basis of this method, the results show an average  $k_{\text{eff}}$  value and a standard deviation, which represents the  $1\sigma$  (68%) confidence interval. The MCNP criticality runs used 4,000 neutrons per generation with 3950 active generations. This results in a standard deviation of approximately 0.00025 or less for all calculations performed in this evaluation.

Table 6.5 shows the material compositions used in the MCNP models including the density of the material and the MCNP cross-sectional set name. The input for MCNP does not include an entry explicitly for the nuclear properties of materials; rather, it obtains this information automatically based on the particular library specified by the user for each of the isotopes and/or elements of the materials used in the model. The libraries are distributed with the code, and many libraries have been developed over the years by different entities for specific purposes. Although multiple libraries are available for the materials of this package and payload, the library based on Evaluated Nuclear Data Files VI (ENDF-VI) is used exclusively with the exception of elemental lead (Pb) that is not adequately addressed in ENDF-VI. (ENDF-VI has three of the four naturally occurring isotopes of Pb.) This library, named "endf60," is used because it represents the most recent available data from the centralized U.S. organization coordinating the establishment of nuclear data (the National Nuclear Data Center at Brookhaven National Laboratory). The Evaluated Nuclear Data Files V (ENDF-V) is used for elemental lead.

### 6.3.4 Demonstration of Maximum Reactivity

As mentioned in Section 6.3.1, the fissile material is conservatively configured as a compact sphere of fuel with varying amounts of hydrogenous materials. The optimal H/Pu ratio was determined by selecting the configuration with the maximum reactivity. This is the most reactive configuration consistent with a possible damaged condition and the chemical and physical form of the material. This configuration is extremely conservative and would not be expected to occur under NCT or HAC. However, considering the fact that no credit is taken for geometry control provided by the waste drums, this configuration conservatively meets the requirements of 10 CFR 71.55(b) and 71.55(e)(1). The HAC criticality analyses were performed assuming that water leaked into the cask cavity, filling all voids not occupied by the polyethylene, plutonium or beryllium materials.

In addition, maximum reactivity is assured by other features of the simulation. The inclusion of beryllium as a special moderating/reflecting material was demonstrated to increase reactivity. Credit was not taken for the presence of neutron absorbers in the cask payload volume, such as the metal drums and internal drum support structure, which would lower the reactivity. The majority of the HAC cases had a 25% volume fraction of polyethylene and 1% by weight of beryllium as a special reflector. Four cases were run with the beryllium reduce to 0.5% and an additional four cases were run with beryllium eliminated. An additional four cases were run with the polyethylene reduced to 20% by volume. These cases establish that the 25% volume fraction of polyethylene and 1% by weight of beryllium were the most reactive configuration.

## 6.4 SINGLE PACKAGE EVALUATION

### 6.4.1 Configuration

The general requirements of 10 CFR 71.55(b) are that the package must be subcritical if water were to leak into the containment system so that, under the following conditions, maximum reactivity of the fissile material is attained:

1. Most reactive credible configuration consistent with the chemical and physical form of the material
2. Moderation by water to the most reactive credible extent
3. Close full reflection of the containment system by water on all sides or such greater reflection of the system as may additionally be provided by the surrounding material of the packaging.

The analysis assumes that water leaks into the cask cavity, and the waste drums are not present. The criticality requirements of 10 CFR 71.55(e) for fissile material packages in accident conditions impose three conditions on the analysis. These conditions must be applied to a package that has undergone the tests specified in 10 CFR 71.73, which means that credit may be taken for the cask remaining leaktight during HAC. The conditions are as follows.

1. The fissile material is in the most reactive credible configuration consistent with the damaged condition of the package and the chemical and physical form of the contents.
2. Water moderation occurs to the most reactive credible extent consistent with the damaged condition of the package and the chemical and physical form of the contents.
3. There is full reflection by water on all sides as close as is consistent with the damaged condition of the package.

### 6.4.2 Results

With the cask containment dry, the most reactive conditions occur when the quantity of fissile material is in a spherical form and most compact. Although the 10-160B Cask is designed to maintain the payload in the normal, as-loaded configuration shown in Figures 6-1 and 6-2, this evaluation does not take credit for the integrity of the waste drums. The most reactive configuration for this evaluation occurs when the plutonium, polyethylene, and beryllium form a sphere. Various H/Pu ratios are evaluated for the single cask. H/Pu ratio is associated with a given spherical diameter, assuming the material densities, as noted in Tables 6.2 (NCT) and 6.3 (HAC).

The results of the NCT analysis are shown in Figure 6-10 and summarized in Table 6.6. The most reactive NCT configuration was obtained with the fissile sphere in the base corner with water on the outside of the cask and an H/Pu ratio of 1400. The maximum  $K_{\text{eff}}$  is 0.42656. The results of the HAC analysis are presented in Figure 6-11 and summarized in Table 6.7. The most reactive HAC configuration was obtained with the fissile sphere in the lid corner with an H/Pu ratio of 900. The maximum  $K_{\text{eff}}$  is 0.93252 and is below the limit of 0.94. Table 6.7 shows that there is a subcritical margin even if the fissile material is in the worst case configuration. Tables 6.6 and 6.7 summarize these results and demonstrate that all payload configurations meet the NCT and HAC criticality requirements of 10 CFR 71.55(b), (d), and (e).

In addition, Table 6.7 summarizes the results of the analyses that were performed to examine the effect of less beryllium (0% and 0.5% by mass of total CH<sub>2</sub> and Pu<sup>239</sup>) and less polyethylene (20% by volume of the 10 drums). The results (Cases f042 through f065) clearly show, by comparison with Case f033, that the most reactive configuration is for 25% by volume CH<sub>2</sub> and 1% by mass for beryllium.

Figure 6-10. Single Unit  $K_{eff}$  vs. H/Pu Ratio for NCT for Various Configurations

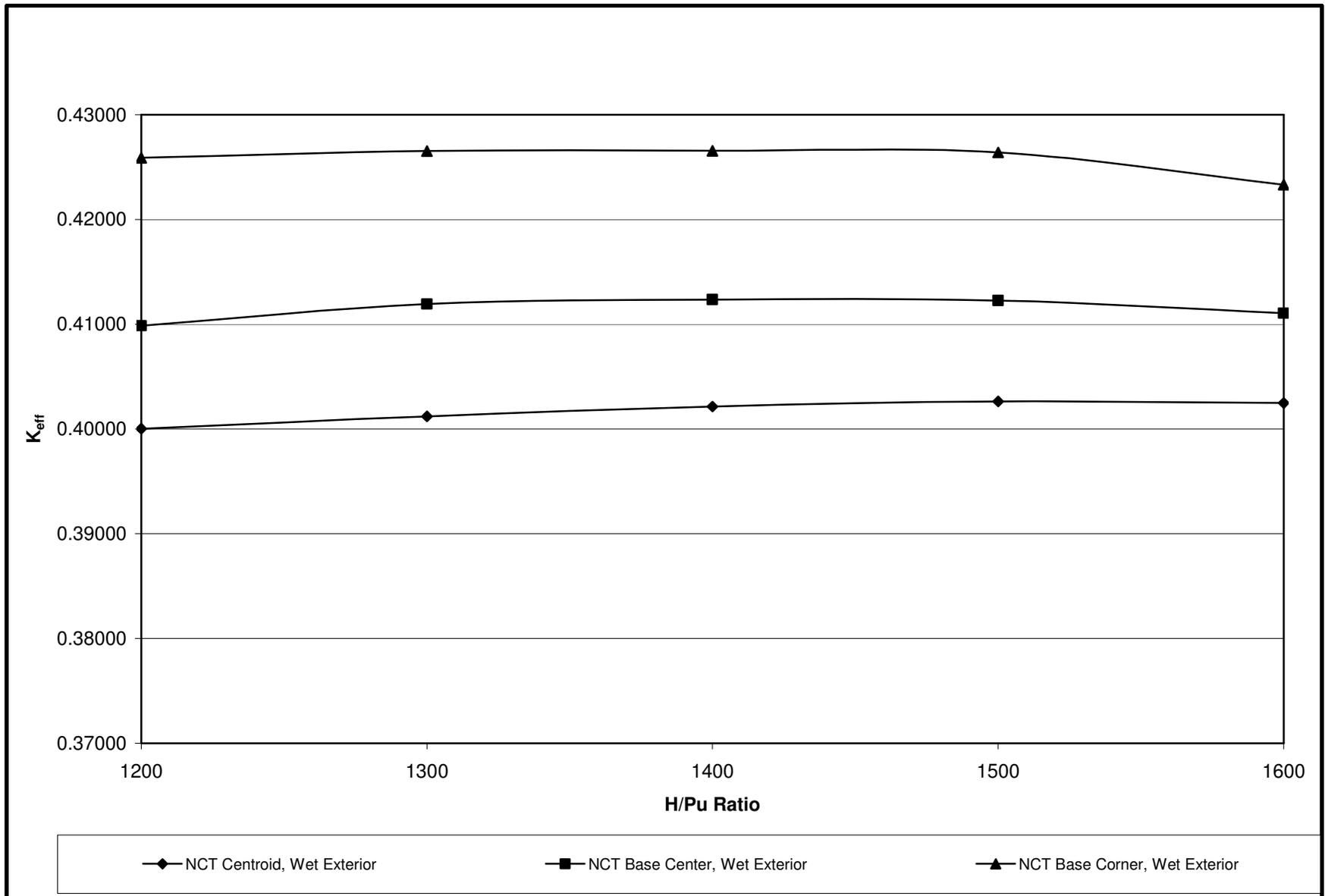


Table 6. Single Unit  $K_{\text{eff}}$  vs. H/Pu Ratio for NCT for Various Configurations

NCT 10-160B Single Cask					
Location	MCNP Case	H/Pu Ratio	$K_{\text{eff}}$	$\sigma_{\text{MCNP}}$	AEF <sup>a</sup> (eV)
NCT Centroid, Wet Exterior	f307	1200	0.40003	0.00015	0.0498
	f308	1300	0.40121	0.00015	0.0488
	f309	1400	0.40215	0.00014	0.0480
	f310	1500	0.40264	0.00014	0.0472
	f311	1600	0.40249	0.00015	0.0465
NCT Base Center, Wet Exterior	f327	1200	0.40987	0.00015	0.0508
	f328	1300	0.41195	0.00015	0.0497
	f329	1400	0.41236	0.00015	0.0488
	f330	1500	0.41228	0.00015	0.0480
	f331	1600	0.41108	0.00014	0.0473
NCT Base Corner, Wet Exterior	f367	1200	0.42589	0.00015	0.0519
	f368	1300	0.42655	0.00015	0.0507
	f369	1400	0.42656	0.00015	0.0497
	f370	1500	0.42641	0.00015	0.0489
	f371	1600	0.42334	0.00015	0.0481

<sup>a</sup> Energy corresponding to the average neutron lethargy causing fission (AEF)

Figure 6-11. Single Unit  $K_{eff}$  vs. H/Pu Ratio for HAC for Various Configurations

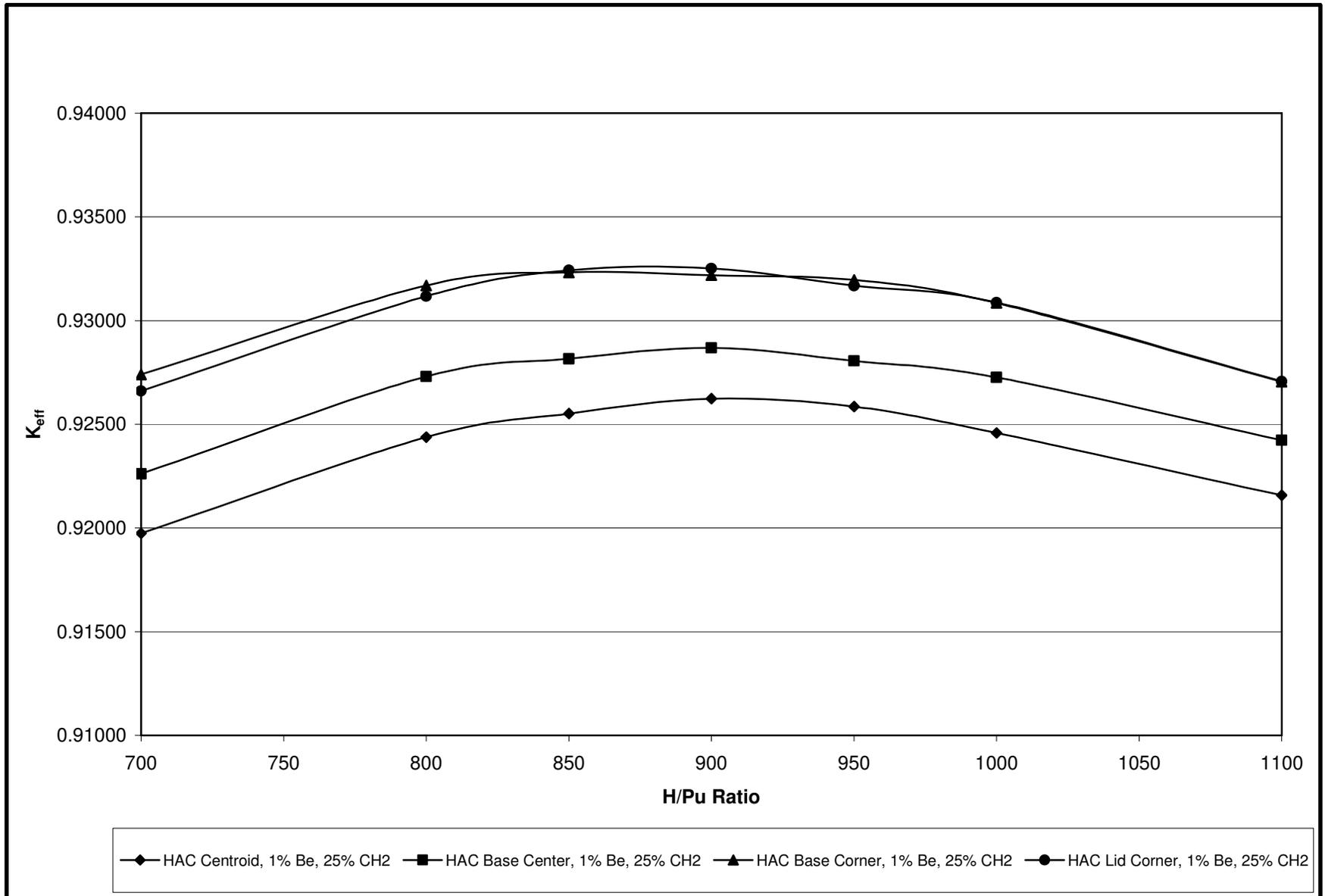


Table 7. Single Unit  $K_{\text{eff}}$  vs. H/Pu Ratio for HAC for Various Configurations

HAC 10-160B Single Cask					
Location	MCNP Case	H/Pu Ratio	$K_{\text{eff}}$	$\sigma_{\text{MCNP}}$	AEF <sup>a</sup> (eV)
HAC Centroid, 1% Be, 25% CH <sub>2</sub>	f000	700	0.91975	0.00022	0.0586
	f001	800	0.92438	0.00020	0.0556
	f002	850	0.92552	0.00021	0.0543
	f003	900	0.92624	0.00020	0.0532
	f004	950	0.92586	0.00021	0.0522
	f005	1000	0.92458	0.00020	0.0513
	f006	1100	0.92158	0.00019	0.0498
HAC Base Center, 1% Be, 25% CH <sub>2</sub>	f010	700	0.92261	0.00021	0.0590
	f011	800	0.92731	0.00020	0.0559
	f012	850	0.92816	0.00020	0.0546
	f013	900	0.92869	0.00021	0.0535
	f014	950	0.92806	0.00020	0.0525
	f015	1000	0.92726	0.00020	0.0515
	f016	1100	0.92424	0.00019	0.0499
HAC Base Corner, 1% Be, 25% CH <sub>2</sub>	f020	700	0.92741	0.00021	0.0594
	f021	800	0.93169	0.00021	0.0562
	f022	850	0.93232	0.00020	0.0548
	f023	900	0.93219	0.00021	0.0537
	f024	950	0.93197	0.00020	0.0527
	f025	1000	0.93085	0.00020	0.0517
	f026	1100	0.92705	0.00020	0.0502
HAC Lid Corner, 1% Be, 25% CH <sub>2</sub>	f030	700	0.92661	0.00021	0.0594
	f031	800	0.93118	0.00021	0.0562
	f032	850	0.93243	0.00020	0.0549
	f033	900	0.93252	0.00020	0.0537
	f034	950	0.93168	0.00020	0.0527
	f035	1000	0.93087	0.00020	0.0518
	f036	1100	0.92707	0.00019	0.0502
HAC Lid Corner, 0.5% Be, 25% CH <sub>2</sub>	f042	850	0.93202	0.00020	0.0549
	f043	900	0.93213	0.00020	0.0537
	f044	950	0.93219	0.00020	0.0526
	f045	1000	0.93076	0.00020	0.0518
HAC Lid Corner, 0.0% Be, 25% CH <sub>2</sub>	f052	850	0.93188	0.00021	0.0549
	f053	900	0.93199	0.00020	0.0536
	f054	950	0.93127	0.00020	0.0527
	f055	1000	0.93077	0.00020	0.0518
HAC Lid Corner, 1% Be, 20% CH <sub>2</sub>	f062	850	0.92786	0.00020	0.0549
	f063	900	0.92859	0.00020	0.0538
	f064	950	0.92790	0.00020	0.0526
	f065	1000	0.92661	0.00019	0.0518

<sup>a</sup> Energy corresponding to the average neutron lethargy causing fission (AEF)

## 6.5 EVALUATION OF PACKAGE ARRAYS UNDER NCT

### 6.5.1 Configuration

The criticality requirements in 10 CFR 71.59(a) for arrays of fissile material packages in NCT require that 5 times N undamaged packages with nothing between the packages be subcritical, assuming packages are stacked together in any arrangement and with close full reflection on all sides of the array by water.

Normally, the array calculations begin with an infinite array model because, if the infinite array is adequately subcritical, no additional array calculations are necessary. If the infinite array is not shown to be safely subcritical, a finite array of packages is analyzed until an array size is found that is adequately subcritical. An infinite array of 10-160B Casks with the payloads described in Section 6.2 is adequately subcritical during NCT. Therefore, finite array cases are not necessary. The MCNP model for the infinite array calculations is identical to the single-cask model except that the 30.5 cm (12-in.) water reflector is removed. Six reflective surfaces are added to form a tight-fitting hexagon around the cask and two reflective surfaces are placed at the top and bottom of the cask, as shown in Figure 6-12. The use of reflective surfaces around the side, top, and bottom simulates an infinite array of casks in the radial and axial directions. Two additional infinite array cases are run where the cask spacing is varied from 5 cm to 10 cm.

### 6.5.2 Results

Table 6.8 summarizes the results of the NCT infinite array calculations. Because the  $k_{\text{eff}}$  values decrease slightly with increasing cask spacing (0.45328 for close-packed versus 0.44635 for 10 cm cask spacing), these cases indicate that there is some neutronic communication between the casks in the array when the containment is dry and there is no interspersed moderation. The results for the NCT array calculations indicate that an infinite array of 10-160B Casks loaded with any fissile configurations is safely subcritical with a maximum  $k_{\text{eff}}$  value of 0.45328 (case f369a).

Figure 12. Plan View of an Infinite Array of NCT 10-160B Casks (MCNP case f369a).

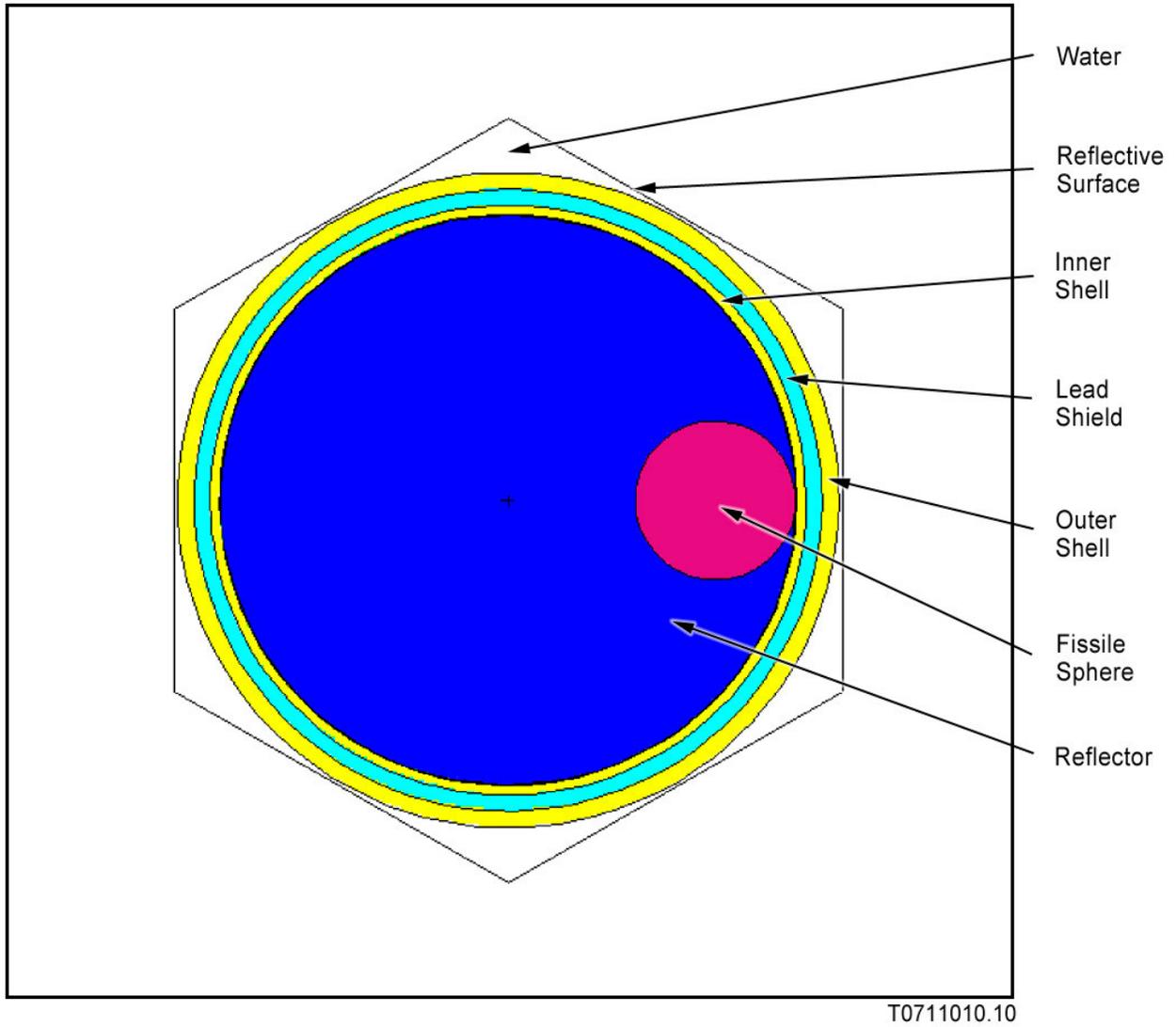


Table 8. Values of  $K_{\text{eff}}$  vs. Array Spacing for an Infinite Array of 10-160B Casks Under NCT.

NCT 10-160B Infinite Array					
Location	MCNP Case	Array Spacing	$K_{\text{eff}}$	$\sigma_{\text{MCNP}}$	AEF <sup>a</sup> (eV)
Base Corner	f369a	0.00	0.45328	0.00015	0.0495
	f369b	5.00	0.44946	0.00015	0.0496
	f369c	10.00	0.44635	0.00015	0.0496

<sup>a</sup> Energy corresponding to the average neutron lethargy causing fission (AEF)

## 6.6 EVALUATION OF PACKAGE ARRAYS UNDER HAC

### 6.6.1 Configuration

The criticality requirements of 10 CFR 71.59(a)(2), for arrays of fissile material packages under accident conditions require that 2 times N ( $N \geq 0.5$ ) damaged packages be subcritical, assuming the packages are stacked together in any arrangement, with close full reflection on all sides of the array by water, and with optimum interspersed hydrogenous moderation. These conditions are applied to a package that has undergone the tests specified in 10 CFR 71.73, which means that credit may be taken for the cask remaining leaktight during accident conditions. However, although the 10-160B Cask remains leaktight under the accident-condition tests specified in 10 CFR 71.73, the criticality analysis for arrays during accident conditions conservatively assumes in-flooding of the cask containment.

As discussed in Section 6.5, the array calculations normally begin with an infinite array model. If the infinite array is adequately subcritical, no additional array calculations are necessary. The infinite array model developed for NCT in Section 6.5 is used as the baseline model for the HAC array calculations. The only differences being the addition of interspersed moderation (see Figure 6.4) between the casks in the array per 10 CFR 71.59(a) (2) and the worst case single Cask model evaluated under HAC. The NCT array cases assumed nothing in between the casks per 10 CFR 71.59(a) (1).

With a hexagonal infinite array of casks, there are two basic orientations of the fissile sphere in a hexagonal cell, either at the flat (Figure 6-13) or at the apex (Figure 6-14). If the fissile sphere is at the flat, two spheres in adjacent cells are very close (four spheres if at the base or lid of the cask). If the fissile sphere is at the apex, three spheres in adjacent cell are farther apart (six spheres if at the base or lid of the case).

Figure 13. Plan View of an Infinite Array of HAC 10-160B Casks (MCNP case f022flat00).

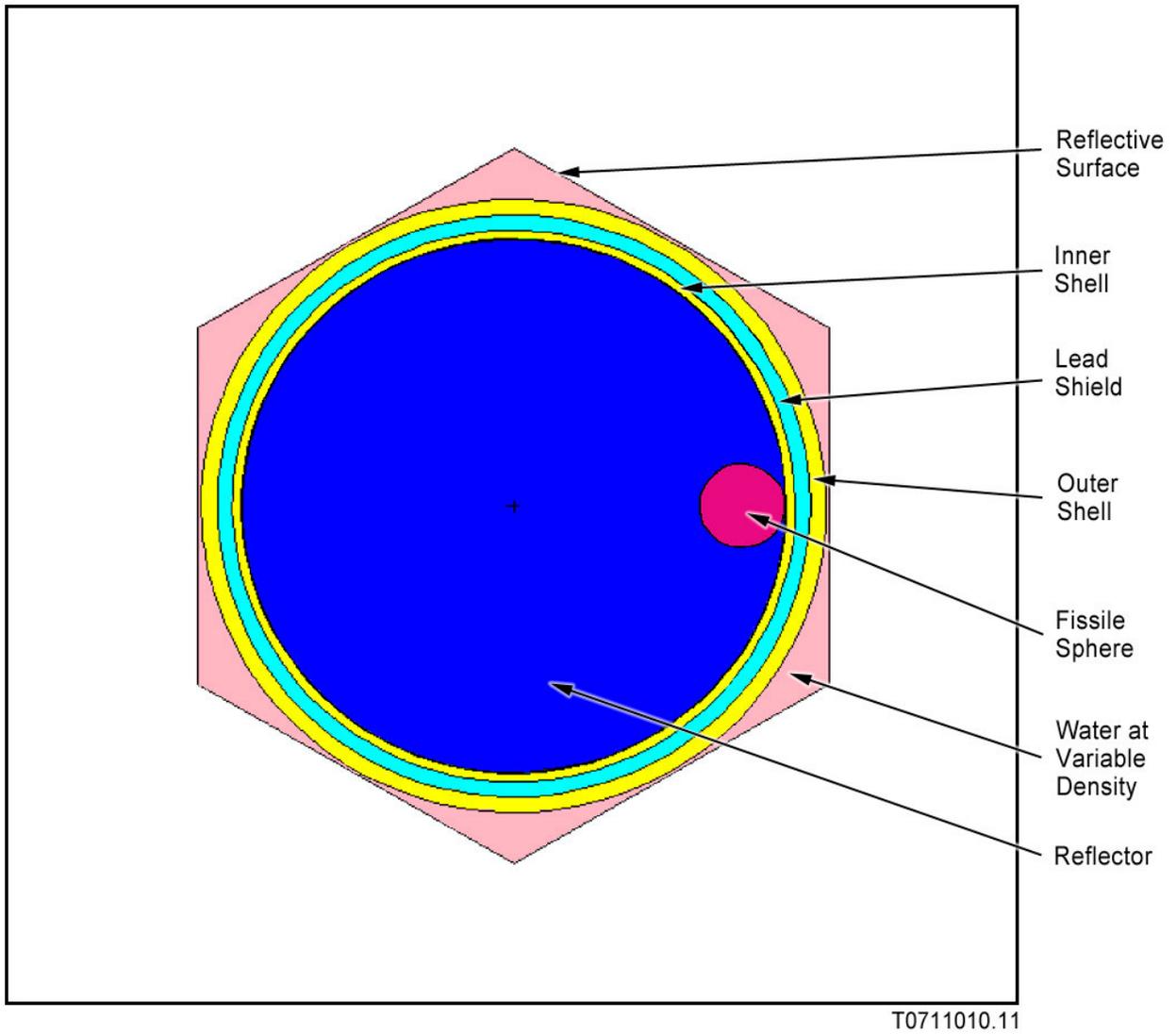
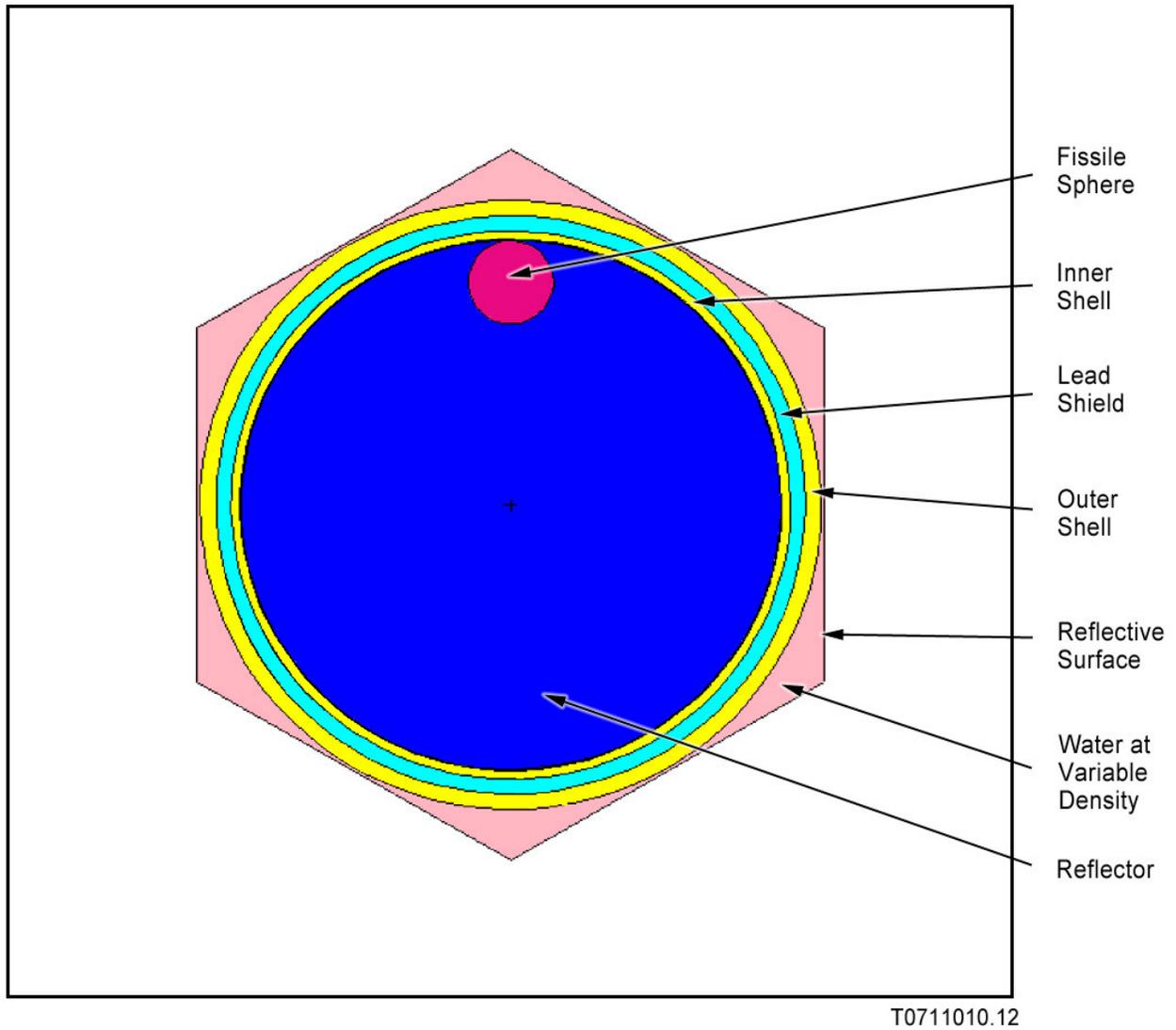


Figure 14. Plan View of an Infinite Array of HAC 10-160B Casks (MCNP case f022apex00).



### 6.6.2 Results

The individual HAC cases, as summarized in Table 6.7, show that case f033 was the most reactive. Case f033 was a lid corner case. Since the effective axial distance between adjacent casks in an infinite array is greater with a lid corner case, the most reactive base corner case (f022) was selected for infinite array evaluation as well.

The HAC array cases have a baseline external configuration identical to the NCT array cases except that the interspersed region is filled with water at various densities and the fissile sphere is evaluated at the apex and flat (see Figures 6.13 and 6.14). Table 6.9 summarizes the values of  $K_{\text{eff}}$  for an infinite array of 10-160B casks under HAC for various interspersed water densities ranging from 0.00 to 1.00 g/cm<sup>3</sup>. As noted before, single unit cases designated as f033 and f022 were selected for infinite array evaluation in the apex and flat orientations. Table 6.9 presents the evaluation of these four general cases for water densities ranging from 0.00 to 0.10 g/cm<sup>3</sup>. The f022 flat cases were extended to a maximum water density of 1.00 g/cm<sup>3</sup> since that composition and orientation was the most reactive from 0.00 to 0.10 g/cm<sup>3</sup>.

The differences between the  $k_{\text{eff}}$  values for very low interspersed water densities (i.e., 0 to 0.001 g/cm<sup>3</sup>) are statistically insignificant. However, water densities greater than 0.01 g/cm<sup>3</sup> indicate that the  $k_{\text{eff}}$  values decrease with increasing density. This is most likely due to the increased absorption of neutrons in the water. Therefore, optimum interspersed moderation corresponds to dry, or very low, moderation between the casks in the array.

The results for the HAC array calculations indicate that an infinite array of 10-160B Casks loaded with any of the fissile configurations is safely subcritical with a maximum  $k_{\text{eff}}$  value of 0.93873 (case f022flat02). Because an infinite array of 10-160B Casks, with the contents described in Section 6.2, are safely subcritical during HAC no finite array cases are necessary. Appendix 6.9.2 contains representative MCNP input files used in this evaluation.

Table 9. Values of  $K_{\text{eff}}$  vs Interspersed Water Densities for an Infinite Array of 10-160B Casks Under HAC.

HAC 10-160 B Infinite Array					
Location	MCNP Case	Water Fraction	$K_{\text{eff}}$	$\sigma_{\text{MCNP}}$	AEF <sup>a</sup> (eV)
HAC Base Corner	f022apex00	0.00000	0.93764	0.00021	0.0548
	f022apex01	0.00010	0.93749	0.00020	0.0548
	f022apex02	0.00100	0.93770	0.00020	0.0548
	f022apex03	0.01000	0.93754	0.00020	0.0548
	f022apex04	0.10000	0.93594	0.00020	0.0549
	f022flat00	0.00000	0.93871	0.00020	0.0548
	f022flat01	0.00010	0.93870	0.00020	0.0548
	f022flat02	0.00100	0.93873	0.00020	0.0548
	f022flat03	0.01000	0.93829	0.00021	0.0548
	f022flat04	0.10000	0.93745	0.00021	0.0548
	f022flat05	0.20000	0.93708	0.00021	0.0549
	f022flat06	0.30000	0.93674	0.00020	0.0548
	f022flat07	0.40000	0.93611	0.00020	0.0548
	f022flat08	0.50000	0.93551	0.00021	0.0549
	f022flat09	0.60000	0.93535	0.00020	0.0549
	f022flat10	0.70000	0.93529	0.00021	0.0549
	f022flat11	0.80000	0.93518	0.00020	0.0548
	f022flat12	0.90000	0.93461	0.00020	0.0548
f022flat13	1.00000	0.93468	0.00020	0.0549	
HAC Lid Corner	f033apex00	0.00000	0.93610	0.00020	0.0537
	f033apex01	0.00010	0.93613	0.00020	0.0537
	f033apex02	0.00100	0.93609	0.00020	0.0537
	f033apex03	0.01000	0.93603	0.00020	0.0537
	f033apex04	0.10000	0.93391	0.00020	0.0537
	f033flat00	0.00000	0.93692	0.00020	0.0536
	f033flat01	0.00010	0.93700	0.00020	0.0537
	f033flat02	0.00100	0.93713	0.00020	0.0537
	f033flat03	0.01000	0.93666	0.00020	0.0537
	f033flat04	0.10000	0.93568	0.00021	0.0537

<sup>a</sup> Energy corresponding to the average neutron lethargy causing fission (AEF)

## 6.7 FISSILE MATERIAL PACKAGES FOR AIR TRANSPORT

This section is not applicable. The Applicant did not design the 10-160B Cask for air transport nor does the Applicant seek authorization for air transport.

## 6.8 BENCHMARK EVALUATIONS

This section summarizes calculations for experimental criticality benchmarks used to validate the computer code MCNP 5 (LANL 2003) with pointwise ENDF/B-VI cross sections processed as described in Appendix G of the MCNP manual. The bias factor obtained from these calculations of the critical experiments is applied to the MCNP-calculated  $k_{\text{eff}}$  values in Sections 6.4 and 6.5 to ensure that adequate subcriticality margin exists for shipment of the 10-160B Cask.

The MCNP 5 executable was verified initially by executing the 42 standard test problems provided by the code developer, Los Alamos National Laboratory, and confirming that the results agree with the standard output (OUTP and MCTAL) files provided by Los Alamos National Laboratory. This section focuses on validation of MCNP's pointwise ENDF/B-VI cross-sectional library using 40 experimental criticality benchmarks involving plutonium.

### 6.8.1 Applicability of Benchmark Experiments

The experimental benchmarks are taken from NEA/NSC/DOC (95)03, *International Handbook of Evaluated Criticality Safety Benchmark Experiments*,<sup>[4]</sup> which discusses each experiment in detail. It includes estimates of the uncertainty in the measurements, detailed information regarding dimensions and material compositions, comparisons between the multiplication factor calculated by various computer codes, and a list of input files that are used in their calculations. The cases of interest to establish a bias for this criticality evaluation involve critical experiments for thermal plutonium solution forms. The plutonium measurements are designated in NEA/NSC/DOC (95)03 as PU-SOL-THERM-001, -002, -003, -004, -006, and -009. These are judged to be the most applicable to the 10-160B Cask criticality evaluation, which contains plutonium in solution form.

The MCNP input files for these critical experiments are taken directly from NEA/NSC/DOC (95)03 with one modification. The material definitions for several elements were modified because some elements in the MCNP ENDF/B-V cross-sectional library no longer have corresponding cross sections in the ENDF/B-VI library. This results in the need to convert material compositions for an element into the corresponding material compositions for the naturally occurring isotopes of that element. For example, if the original input file has a material composition consisting entirely of iron (cross-section ID = 26000.50c), the revised input file for the ENDF/B-VI cross sections contains a material composition as follows:

26054.66c	0.0584	( <sup>54</sup> Fe)
26056.66c	0.9175	( <sup>56</sup> Fe)
26057.66c	0.0212	( <sup>57</sup> Fe)
26058.66c	0.0028	( <sup>58</sup> Fe)

This procedure is done to reflect the naturally occurring isotopic abundances of iron of 0.058, 0.9172, 0.022, and 0.0028 for <sup>54</sup>Fe, <sup>56</sup>Fe, <sup>57</sup>Fe, and <sup>58</sup>Fe, respectively. Similar changes are made for the following elements: silicon (z=14), chromium (z=24), nickel (z=28), copper (z=29), and lead (z=82).

Additionally, three elements were simulated with the single isotope present in the EDF/B-V cross-sectional library. The material compositions were modified to allow for the additional

naturally-occurring isotope available in the ENDF/B-VI library. Therefore, hydrogen was expanded from 1001.50c to 1001.66c and 1002.66c. Nitrogen was expanded from 7014.50c to 7014.66c and 7015.66c. Oxygen was expanded from 8016.50c to 8016.66c and 8017.66c. Cross-sections were not available for 8018.66c so that naturally occurring percentage was lumped into the 8016.66c. These are minor changes that reflect the cross-section philosophy used in the criticality evaluations.

### **6.8.2 Bias Determination**

The results of the plutonium benchmark calculations are shown in Table 6.10. The first three columns of this table show a unique case number and case identifier. The fourth column shows the ratio of elemental hydrogen to fissile ( $\text{Pu}^{239}$  plus  $\text{Pu}^{241}$ ). The fifth column shows the  $\text{Pu}^{240}$  content as a percentage of the total Pu. The sixth column shows the MCNP calculated  $k_{\text{eff}}$  value, and the seventh column is the one-standard-deviation statistical uncertainty in the MCNP calculation. The eighth column is an estimate of the one-standard-deviation experimental uncertainty. The ninth column of Table 6.10 shows the average neutron energy causing fission (AEF) for these experiments that is calculated by MCNP. This parameter is useful for characterizing the neutron spectrum of the system.

These benchmark cases were chosen to bracket the criticality simulations of the 10-160B Cask. As presented at the bottom of Table 6.10, the H/X ratio of the benchmark cases ranged from a low of 91 to a high of 2807, with eighteen between 700 and 1100.

The  $\text{Pu}^{240}$  content of the 10-160B criticality simulations was assumed to be zero since  $\text{Pu}^{240}$  acts as a neutron poison. However,  $\text{Pu}^{239}$  without  $\text{Pu}^{240}$  would be unusual so benchmark cases with low  $\text{Pu}^{240}$  content were chosen when possible. All forty benchmark cases had  $\text{Pu}^{240}$  contents less than 4.65%. Thirty-three benchmark cases had  $\text{Pu}^{240}$  contents less than 3.1% and four cases less than 0.54%  $\text{Pu}^{240}$ .

The AEF values for the criticality cases for the 10-160B Cask (see Tables 6.6, 6.7, 6.8, and 6.9) range from 0.0495 to 0.0594, and are well bracketed by the AEF values for the benchmark cases.

Table 10. Results of Monte Carlo N-Particle Calculations  
of the Forty Plutonium Benchmark Experiments.

	Case Identifier <sup>a</sup>		H/X	Pu240/Pu	$K_{eff}$	$\sigma_{MCNP}$	$\sigma_{experiment}$	AEF (eV) <sup>b</sup>
1	pust.001	Case 1.T8A	370	0.04650	1.00441	0.00045	0.005	0.0877
2	pust.001	Case 2.T8A	271	0.04650	1.00505	0.00045	0.005	0.1106
3	pust.001	Case 3.T8A	215	0.04650	1.00735	0.00046	0.005	0.1344
4	pust.001	Case 4.T8A	190	0.04650	1.00338	0.00046	0.005	0.1507
5	pust.001	Case 5.T8A	180	0.04650	1.00682	0.00047	0.005	0.1591
6	pust.001	Case 6.T8A	91	0.04650	1.00752	0.00046	0.005	0.3477
7	pust.002	Case 1	524	0.03107	1.00393	0.00044	0.0047	0.0707
8	pust.002	Case 2	505	0.03107	1.00401	0.00044	0.0047	0.0724
9	pust.002	Case 3	451	0.03107	1.00264	0.00043	0.0047	0.0775
10	pust.002	Case 4	421	0.03107	1.00527	0.00045	0.0047	0.0808
11	pust.002	Case 5	393	0.03107	1.00835	0.00044	0.0047	0.0844
12	pust.002	Case 6	344	0.03107	1.00344	0.00044	0.0047	0.0924
13	pust.002	Case 7	309	0.03107	1.00599	0.00044	0.0047	0.0998
14	pust.003	Case 1	788	0.01753	1.00347	0.00041	0.0047	0.0579
15	pust.003	Case 2	756	0.01753	1.00198	0.00041	0.0047	0.0590
16	pust.003	Case 3	699	0.03107	1.00564	0.00042	0.0047	0.0615
17	pust.003	Case 4	682	0.03107	1.00431	0.00042	0.0047	0.0623
18	pust.003	Case 5	627	0.03107	1.00564	0.00042	0.0047	0.0651
19	pust.003	Case 6	563	0.03107	1.00524	0.00043	0.0047	0.0690
20	pust.003	Case 7	738	0.03107	1.00698	0.00042	0.0047	0.0588
21	pust.003	Case 8	714	0.03107	1.00567	0.00042	0.0047	0.0598
22	pust.004	Case 1	987	0.00538	1.00454	0.00039	0.0047	0.0530
23	pust.004	Case 2	977	0.00538	0.99927	0.00039	0.0047	0.0532
24	pust.004	Case 3	935	0.00538	1.00143	0.00039	0.0047	0.0543
25	pust.004	Case 4	889	0.00538	0.99917	0.00039	0.0047	0.0555
26	pust.004	Case 5	942	0.01753	1.00023	0.00040	0.0047	0.0542
27	pust.004	Case 6	927	0.03107	1.00216	0.00040	0.0047	0.0544
28	pust.004	Case 7	892	0.03107	1.00588	0.00040	0.0047	0.0555
29	pust.004	Case 8	869	0.03107	1.00186	0.00040	0.0047	0.0562
30	pust.004	Case 9	805	0.03107	1.00147	0.00041	0.0047	0.0583
31	pust.004	Case 10	689	0.03107	1.00171	0.00040	0.0047	0.0629
32	pust.004	Case 11	592	0.03107	1.00023	0.00041	0.0047	0.0679
33	pust.004	Case 12	893	0.03107	1.00326	0.00039	0.0047	0.0554
34	pust.004	Case 13	903	0.03416	1.00041	0.00040	0.0047	0.0553
35	pust.006	Case 1	1061	0.03107	1.00133	0.00037	0.0035	0.0521
36	pust.006	Case 2	1018	0.03107	1.00273	0.00038	0.0035	0.0531
37	pust.006	Case 3	940	0.03107	1.00220	0.00038	0.0035	0.0548
38	pust.009	Case 1A	2652	0.02511	1.01585	0.00043	0.0033	0.0413
39	pust.009	Case 2A	2783	0.02511	1.02009	0.00041	0.0033	0.0408
40	pust.009	Case 3A	2807	0.02511	1.01875	0.00040	0.0033	0.0408
Average of All Experiments					1.00474	0.00042	0.00455	
Range	Minimum		91	0.00538	0.99917	0.00037		0.0408
	Maximum		2807	0.04650	1.02009	0.00047		0.3477

<sup>a</sup> All cases from NEA/NSC/DOC(95)03.<sup>b</sup> Energy corresponding to the average neutron lethargy causing fission (AEF), in units of electronvolts.NEA/NSC/DOC(95)03, *International Handbook of Evaluated Criticality Safety Benchmark Experiments* [4]

NUREG/CR-5661, *Recommendations for Preparing the Criticality Safety Evaluation of Transportation Packaging for Radioactive Material*,<sup>[5]</sup> recommends the following general relationship for establishing acceptance criteria for criticality calculations:

$$k_c - \Delta k_u \geq k_{\text{eff}} + 2\sigma + \Delta k_m,$$

where:

$k_c$  =  $k_{\text{eff}}$  resulting from the calculation of benchmark critical experiments using a specific calculational method and data

$\Delta k_u$  = An allowance for the calculational uncertainty

$\Delta k_m$  = A required margin of subcriticality (0.05)

$k_{\text{eff}}$  = The calculated value obtained from the Monte Carlo analysis for the package or array of packages

$\sigma$  = The standard deviation of the  $k_{\text{eff}}$  value obtained from the Monte Carlo analysis.

If the calculational bias  $\beta$  is defined as  $\beta = 1 - k_c$ , then the bias is positive if  $k_c < 1$  and negative if  $k_c > 1$ . The acceptance relationship may be rewritten as:

$$1.00 - \beta - \Delta k_u \geq k_{\text{eff}} + 2\sigma + 0.05, \text{ or}$$

$$k_{\text{eff}} + \beta + 2\sigma + \Delta k_u \leq 0.95.$$

To account for the calculational and experimental uncertainty for the benchmark criticals, the mean value of  $\sigma_{\text{MCNP}}$  from MCNP for the critical experiments and the experimental uncertainty  $\sigma_{\text{experiment}}$  ( $=\Delta k_u$ ) are combined in quadrature with the standard deviation ( $\sigma$ ) of the  $k_{\text{eff}}$  value obtained from the MCNP NCT or HAC analysis. This results in the following acceptance relationship:

$$k_{\text{eff}} + \beta + 2(\sigma^2 + \sigma_{\text{MCNP}}^2 + \sigma_{\text{experiment}}^2)^{0.5} \leq 0.95$$

The statistical summary at the bottom of Table 6-10 is used to obtain the calculational and experimental uncertainties for the benchmark criticals. The bias,  $\beta$ , is conservatively taken to be the maximum for the plutonium experiments, which is 0.00 since all the benchmark experiments are calculated by MCNP to exceed 1.0. Therefore, with the bias and uncertainties, the acceptance criteria is:

$$k_{\text{eff}} + 0.00 + 2(\sigma^2 + 0.00092^2 + 0.00479^2)^{0.5} \leq 0.95$$

In a typical MCNP calculation for the 10-160B Cask, the standard deviation ( $\sigma_{\text{MCNP}}$ ) is less than 0.00025. Therefore, solving for  $k_{\text{eff}}$  yields:

$$k_{\text{eff}} \leq 0.95 - [0.00 + 2(\sigma^2 + 0.00092^2 + 0.00479^2)^{0.5}]$$

The  $k_{\text{eff}}$  from the above equation is 0.94002 for  $\sigma = \sigma_{\text{MCNP}} = 0.00025$ .

The effective criticality limit for this evaluation is set to 0.9400, which assumes that the MCNP calculation is run long enough to obtain a  $\sigma_{\text{MCNP}} \leq 0.00025$ . This means that the MCNP-

calculated  $k_{\text{eff}}$  values must be less than 0.9400 to demonstrate adequate subcriticality margin after accounting for bias and uncertainties as long as  $\sigma_{\text{MCNP}} \leq 0.00025$ .

## 6.9 APPENDIX

The appendices to Chapter 6 include a list of references and representative MCNP input listings.

### 6.9.1 References

1. *Packaging and Transportation of Radioactive Material*, Code of Federal Regulations, Title 10, Part 71, Washington, DC (January 2006)
2. FSWO-QAP-001, *Quality Assurance Procedures*, Procedure QP 3-10, *Software Management*, EnergySolutions Federal Services, Inc., Western Operations, Richland, Washington
3. *MCNP—A General Monte Carlo N-Particle Transport Code, Version 5*, LA-UR-03-1987, Release 1.4, Los Alamos National Laboratory, Los Alamos, New Mexico (2003)
4. *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, NEA/NSC/DOC(95)03, September 2002 Edition, *Organization for Economic Co-operation and Development*, Nuclear Energy Agency, Paris, France (2002)
5. *Recommendations for Preparing the Criticality Safety Evaluation of Transportation Packaging for Radioactive Material*, NUREG/CR-5661, U.S. Nuclear Regulatory Commission, Washington, DC (1997)
6. U.S. Department of Energy (DOE), *Remote-Handled Transuranic Waste Authorized Methods for Payload Control (RH-TRAMPAC)*, U.S. Department of Energy, Carlsbad Field Office, Carlsbad, New Mexico.
7. Neeley, G. W., D. L. Newell, S. L. Larson, and R. J. Green, *Reactivity Effects of Moderator and Reflector Materials on a Finite Plutonium System*, SAIC-1322-001, Revision 1, Science Applications International Corporation, Oak Ridge, Tennessee, May 2004.
8. WP-8-PT.09, *Test Plan to Determine the TRU Waste Polyethylene Packing Fraction*, Washington TRU Solutions, LLC., Revision 0, June 2003.

**6.9.2 Representative MCNP Input Files****NCT Single Cask – f369**

10-160B

c

3000 139 -0.238656 -2000

imp:n=1

3001 169 -0.233058 +2000 +120 -2100 -30

imp:n=1

4000 500 -0.00122 +120 -149 -30 +2100

c 4000 901 -0.983047 +120 -149 -30

c 4000 902 -0.985333 +120 -149 -30

c 4000 903 -0.987607 +120 -149 -30

#(+130 +10 )

imp:n=1

c

c Cask Regions

5 300 -8.03 ((30:-120)(-40 110 -130)):(130 -140 10 -40):

(10 -20 140 -149):(149 -150 -20) imp:n=1 \$ Liner 11 ga - SS304

10 200 -7.85 (100 -109 -70) imp:n=1 \$ Base-Carbon Steel

15 200 -7.85 (109 -110 -50) imp:n=1 \$ Base-Carbon Steel

20 200 -7.85 (110 -140 40 -50) imp:n=1 \$ Inner Shell-Carbon Steel

25 400 -11.34 (109 -140 50 -60) imp:n=1 \$ Lead wall

30 200 -7.85 (109 -140 60 -70) imp:n=1 \$ steel

40 200 -7.85 (140 -150 20 -70):(150 -160 -70):(160 -170 -25)

imp:n=1 \$ Prim/2ndary lid-Carbon Steel

c

c Water reflector

5000 600 -1.0 (-500 510 -520) (((70:-100) -160):(160 25):170)

imp:n=1 \$ 1st 5 cm

5001 600 -1.0 (-501 511 -521) (500:-510:520) imp:n=0.25 \$ Out to 12 inches

5002 0 (501:-511:521) imp:n=0 \$ Outside universe

c

9000 0 -2001 imp:n=1

c

c Cask Radial Zones

10 cz 39.0525 \$ Lid recess liner

20 cz 39.37 \$ Lid recess

25 cz 58.42 \$ 2ndary lid

30 cz 86.0425 \$ Inner cavity

40 cz 86.36 \$ OD Liner (11 ga)

50 cz 89.2175 \$ OD Inner shell

60 cz 93.98 \$ OD Lead

70 cz 99.06 \$ OD Outer shell

80 cz 99.695 \$ OD Thermal barrier-not included in model

c Cask Axial Zones

100 pz 0.0001 \$ Bottom cask  
 109 pz 11.43 \$ Bottom lead in side wall  
 110 pz 13.97 \$ Base plate  
 120 pz 14.2875 \$ Bottom liner  
 125 pz 174.32655 \$ Top of mixture for H/D=0.93  
 130 pz 209.2325 \$ Cavity hgt  
 140 pz 209.55 \$ Top liner  
 149 pz 216.8525 \$ Lid recess liner  
 150 pz 217.17 \$ Top of lid recess  
 160 pz 223.52 \$ Primary lid  
 170 pz 231.14 \$ Top of 2nd lid

c

c Planes for water reflector - 1st 5 cm and out to 12 inches

c

500 cz 104.06  
 501 cz 129.54  
 510 pz -5  
 511 pz -30.48  
 520 pz 236.14  
 521 pz 261.62

c

1000 so 1000 \$ beyond problem

c

2000 s 61.948 0.000 38.382 23.994894  
 2001 s 61.948 0.000 38.382 19.0  
 2002 s 61.948 0.000 38.382 79.210227

c

2100 pz 103.79361

c

c

mode n

kcode 4000 0.9 50 4000

sdef x=d1 y=d2 z=d3 ccc=9000 eff=0.00001

c ksrc 0 0 120

c

si1 -19.0 86.1

sp1 0 1

c

si2 -19.0 19.0

sp2 0 1

c

si3 14.0 210.0

sp3 0 1

c

## c Material Definitions

c

c

c H/Pu 1400

c H2O/CH2 0.0000000

c Be w% 1.000000% of CH2 + Pu

c Radius 23.994894 cm

c Pu-239 Mass 325.000000 g

c Density 0.238656 g/cc

c 0.000 0.000 120.000 23.99489 Center

c 0.000 0.000 38.382 23.99489 Bottom

c 61.948 0.000 38.382 23.99489 Lower Corner

c 61.948 0.000 185.138 23.99489 Upper Corner

c

m139 1001.66c -0.13886897 \$ H-1

1002.66c -0.00004163 \$ H-2

4009.66c -0.00990099 \$ Be-nat

6000.66c -0.82765605 \$ C-nat

c 8016.66c 0.00000000 \$ O-16 &amp; O-18

c 8017.66c 0.00000000 \$ O-17

94239.66c -0.02353235 \$ Pu-239

mt139 poly.60t be.60t

c

c

c H2O/CH2 0.000

c Be w% 1.00% of CH2

c Density 0.104514 g/cc Full Vessel

c Density 0.233058 Sphere Reflector

c Radius 79.210227 Sphere Reflector

c Height 0.000000

c

m169 1001.66c -0.14224992 \$ H-1

1002.66c -0.00004265 \$ H-2

4009.66c -0.00990099 \$ Be-nat

6000.66c -0.84780644 \$ C-nat

c 8016.66c 0.00000000 \$ O-16 &amp; O-18

c 8017.66c 0.00000000 \$ O-17

mt169 poly.60t be.60t

c

c

c

c Carbon Steel

c Density 7.85 g/cc

c

m200 6000.66c -0.003000 \$ C-nat

14028.66c	-0.002572	\$ Si-28
14029.66c	-0.000135	\$ Si-29
14030.66c	-0.000092	\$ Si-30
15031.66c	-0.000400	\$ P-31
16000.66c	-0.000500	\$ S-nat
25055.66c	-0.010300	\$ Mn-55
26054.66c	-0.055383	\$ Fe-54
26056.66c	-0.901554	\$ Fe-56
26057.66c	-0.021193	\$ Fe-57
26058.66c	-0.002870	\$ Fe-58
29063.66c	-0.001370	\$ Cu-63
29065.66c	-0.000630	\$ Cu-65

c

c SS-304 - from STDNEUT.dos file

c Density 8.03 g/cc

c

m300 6000.66c -0.000300 \$ C-nat

24050.66c	-0.008345	\$ Cr-50
24052.66c	-0.167349	\$ Cr-52
24053.66c	-0.019341	\$ Cr-53
24054.66c	-0.004905	\$ Cr-54
25055.66c	-0.019994	\$ Mn-55
26054.66c	-0.038378	\$ Fe-54
26056.66c	-0.624743	\$ Fe-56
26057.66c	-0.014686	\$ Fe-57
26058.66c	-0.001989	\$ Fe-58
28058.66c	-0.067178	\$ Ni-58
28060.66c	-0.026768	\$ Ni-60
28061.66c	-0.001183	\$ Ni-61
28062.66c	-0.003834	\$ Ni-62
28064.66c	-0.001008	\$ Ni-64

c

c Lead

c Density 11.34 g/cc

c

m400 82000.50c -1.0 \$ Lead

c

c Air

m500 7014.66c -0.761985 \$ N-14

7015.66c	-0.003015	\$ N-15
8016.66c	-0.234905	\$ O-16 & O-18
8017.66c	-0.000095	\$ O-17

c

c Water

c Density 1.00 g/cc

c

m600 1001.66c -0.11186481 \$ H-1  
1002.66c -0.00003354 \$ H-2  
8016.66c -0.88774309 \$ O-16 & O-18  
8017.66c -0.00035857 \$ O-17

mt600 lwtr.60t

c

c

c Be 1.85 g/cc

c

m800 4009.66c -0.00497513 \$ Be-nat

mt800 be.60t

c

print

**HAC Single Cask – f033**

10-160B

c

3000 103 -1.011186 -2000  
   imp:n=1  
 4000 153 -0.991739 +120 -149 -30  
   +2000  
   #(+130 +10 )  
   imp:n=1

c

c Cask Regions

5 300 -8.03 ((30:-120)(-40 110 -130)):(130 -140 10 -40):  
   (10 -20 140 -149):(149 -150 -20) imp:n=1 \$ Liner 11 ga - SS304  
 10 200 -7.85 (100 -109 -70) imp:n=1 \$ Base-Carbon Steel  
 15 200 -7.85 (109 -110 -50) imp:n=1 \$ Base-Carbon Steel  
 20 200 -7.85 (110 -140 40 -50) imp:n=1 \$ Inner Shell-Carbon Steel  
 25 400 -11.34 (109 -140 50 -60) imp:n=1 \$ Lead wall  
 30 200 -7.85 (109 -140 60 -70) imp:n=1 \$ steel  
 40 200 -7.85 (140 -150 20 -70):(150 -160 -70):(160 -170 -25)  
   imp:n=1 \$ Prim/2ndary lid-Carbon Steel

c

c Water reflector

5000 600 -1.0 (-500 510 -520) (((70:-100) -160):(160 25):170)  
   imp:n=1 \$ 1st 5 cm  
 5001 600 -1.0 (-501 511 -521) (500:-510:520) imp:n=0.25 \$ Out to 12 inches  
 5002 0 (501:-511:521) imp:n=0 \$ Outside universe

c

9000 0 -2001 imp:n=1

c

c Cask Radial Zones

10 cz 39.0525 \$ Lid recess liner  
 20 cz 39.37 \$ Lid recess  
 25 cz 58.42 \$ 2ndary lid  
 30 cz 86.0425 \$ Inner cavity  
 40 cz 86.36 \$ OD Liner (11 ga)  
 50 cz 89.2175 \$ OD Inner shell  
 60 cz 93.98 \$ OD Lead  
 70 cz 99.06 \$ OD Outer shell  
 80 cz 99.695 \$ OD Thermal barrier-not included in model

c Cask Axial Zones

100 pz 0.0001 \$ Bottom cask  
 109 pz 11.43 \$ Bottom lead in side wall  
 110 pz 13.97 \$ Base plate  
 120 pz 14.2875 \$ Bottom liner

```

125 pz 174.32655 $ Top of mixture for H/D=0.93
130 pz 209.2325 $ Cavity hgt
140 pz 209.55 $ Top liner
149 pz 216.8525 $ Lid recess liner
150 pz 217.17 $ Top of lid recess
160 pz 223.52 $ Primary lid
170 pz 231.14 $ Top of 2nd lid
c
c Planes for water reflector - 1st 5 cm and out to 12 inches
c
500 cz 104.06
501 cz 129.54
510 pz -5
511 pz -30.48
520 pz 236.14
521 pz 261.62
c
1000 so 1000 $ beyond problem
c
2000 s 72.331 0.000 195.521 13.611761
2001 s 72.331 0.000 195.521 12.5
c
c
mode n
kcode 4000 0.9 50 4000
sdef x=d1 y=d2 z=d3 ccc=9000 eff=0.00001
c ksrc 0 0 120
c
si1 -12.5 86.1
sp1 0 1
c
si2 -12.5 12.5
sp2 0 1
c
si3 14.0 210.0
sp3 0 1
c
c Material Definitions
c
c
c H/Pu 900
c H2O/CH2 3.245
c Be w% 1.00000% of CH2 + Pu
c Radius 13.611761 cm
c Pu-239 Mass 325.0000 g

```

c Density 1.011186 g/cc  
 c 0.000 0.000 120.000 13.611761 Center  
 c 0.000 0.000 27.999 13.611761 Bottom  
 c 72.331 0.000 27.999 13.611761 Lower Corner  
 c 72.331 0.000 195.521 13.611761 Upper Corner

c  
 m103 1001.66c -0.11541840 \$ H-1  
 1002.66c -0.00003460 \$ H-2  
 4009.66c -0.00258227 \$ Be-nat  
 6000.66c -0.19506425 \$ C-nat  
 8016.66c -0.65621111 \$ O-16 & O-18  
 8017.66c -0.00026505 \$ O-17  
 94239.66c -0.03042431 \$ Pu-239

mt103 lwtr.60t be.60t

c  
 c  
 c H2O/CH2 8.453226  
 c Be w% 1.00000% of CH2  
 c Density 0.991739 g/cc

c  
 m153 1001.66c -0.11510778 \$ H-1  
 1002.66c -0.00003451 \$ H-2  
 4009.66c -0.00105672 \$ Be-nat  
 6000.66c -0.09048548 \$ C-nat  
 8016.66c -0.79299521 \$ O-16 & O-18  
 8017.66c -0.00032030 \$ O-17

mt153 lwtr.60t be.60t

c  
 c  
 c  
 c Carbon Steel  
 c Density 7.85 g/cc

c  
 m200 6000.66c -0.003000 \$ C-nat  
 14028.66c -0.002572 \$ Si-28  
 14029.66c -0.000135 \$ Si-29  
 14030.66c -0.000092 \$ Si-30  
 15031.66c -0.000400 \$ P-31  
 16000.66c -0.000500 \$ S-nat  
 25055.66c -0.010300 \$ Mn-55  
 26054.66c -0.055383 \$ Fe-54  
 26056.66c -0.901554 \$ Fe-56  
 26057.66c -0.021193 \$ Fe-57  
 26058.66c -0.002870 \$ Fe-58  
 29063.66c -0.001370 \$ Cu-63  
 29065.66c -0.000630 \$ Cu-65

c

c SS-304 - from STDNEUT.dos file

c Density 8.03 g/cc

c

m300	6000.66c	-0.000300	\$ C-nat
	24050.66c	-0.008345	\$ Cr-50
	24052.66c	-0.167349	\$ Cr-52
	24053.66c	-0.019341	\$ Cr-53
	24054.66c	-0.004905	\$ Cr-54
	25055.66c	-0.019994	\$ Mn-55
	26054.66c	-0.038378	\$ Fe-54
	26056.66c	-0.624743	\$ Fe-56
	26057.66c	-0.014686	\$ Fe-57
	26058.66c	-0.001989	\$ Fe-58
	28058.66c	-0.067178	\$ Ni-58
	28060.66c	-0.026768	\$ Ni-60
	28061.66c	-0.001183	\$ Ni-61
	28062.66c	-0.003834	\$ Ni-62
	28064.66c	-0.001008	\$ Ni-64

c

c Lead

c Density 11.34 g/cc

c

m400 82000.50c -1.0 \$ Lead

c

c Air

m500	7014.66c	-0.761985	\$ N-14
	7015.66c	-0.003015	\$ N-15
	8016.66c	-0.234905	\$ O-16 & O-18
	8017.66c	-0.000095	\$ O-17

c

c Water

c Density 1.00 g/cc

c

m600	1001.66c	-0.11186481	\$ H-1
	1002.66c	-0.00003354	\$ H-2
	8016.66c	-0.88774309	\$ O-16 & O-18
	8017.66c	-0.00035857	\$ O-17

mt600 lwtr.60t

c

c

c Be 1.85 g/cc

c

m800 4009.66c -0.00497513 \$ Be-nat

mt800 be.60t

c

print



**NCT Infinite Array – f369a**

10-160B

c

3000 139 -0.238656 -2000

imp:n=1

3001 169 -0.233058 +2000 +120 -2100 -30

imp:n=1

4000 500 -0.00122 +120 -149 -30 +2100

c 4000 901 -0.983047 +120 -149 -30

c 4000 902 -0.985333 +120 -149 -30

c 4000 903 -0.987607 +120 -149 -30

#(+130 +10 )

imp:n=1

c

c Cask Regions

5 300 -8.03 ((30:-120)(-40 110 -130)):(130 -140 10 -40):

(10 -20 140 -149):(149 -150 -20) imp:n=1 \$ Liner 11 ga - SS304

10 200 -7.85 (100 -109 -70) imp:n=1 \$ Base-Carbon Steel

15 200 -7.85 (109 -110 -50) imp:n=1 \$ Base-Carbon Steel

20 200 -7.85 (110 -140 40 -50) imp:n=1 \$ Inner Shell-Carbon Steel

25 400 -11.34 (109 -140 50 -60) imp:n=1 \$ Lead wall

30 200 -7.85 (109 -140 60 -70) imp:n=1 \$ steel

40 200 -7.85 (140 -150 20 -70):(150 -160 -70):(160 -170 -25)

imp:n=1 \$ Prim/2ndary lid-Carbon Steel

c

c Around cask, interspersed

201 0 (-503 504 -508 507 -505 506 501 -502)

(((70:-100) -160):(160 25):170) imp:n=1

c Outside World

200 0 (503:-504:508:-507:505:-506:-501:502) imp:n=0

c

c

9000 0 -2001 imp:n=1

c

c Cask Radial Zones

10 cz 39.0525 \$ Lid recess liner

20 cz 39.37 \$ Lid recess

25 cz 58.42 \$ 2ndary lid

30 cz 86.0425 \$ Inner cavity

40 cz 86.36 \$ OD Liner (11 ga)

50 cz 89.2175 \$ OD Inner shell

60 cz 93.98 \$ OD Lead

70 cz 99.06 \$ OD Outer shell

80 cz 99.695 \$ OD Thermal barrier-not included in model

## c Cask Axial Zones

100 pz 0.0001 \$ Bottom cask  
 109 pz 11.43 \$ Bottom lead in side wall  
 110 pz 13.97 \$ Base plate  
 120 pz 14.2875 \$ Bottom liner  
 125 pz 174.32655 \$ Top of mixture for H/D=0.93  
 130 pz 209.2325 \$ Cavity hgt  
 140 pz 209.55 \$ Top liner  
 149 pz 216.8525 \$ Lid recess liner  
 150 pz 217.17 \$ Top of lid recess  
 160 pz 223.52 \$ Primary lid  
 170 pz 231.14 \$ Top of 2nd lid

c

c Hexagonal Cell Surrounding Cask for Infinite array

c

c inner hex surfaces bounding lattice,  $(n-0.5)*p*\cos30$ 

c surfaces for outer hexagonal duct

\*501 pz -1.000 \$  
 \*502 pz 232.140 \$  
 \*503 px 100.0000  
 \*504 px -100.0000  
 \*505 p -1.0000000 1.7320508 0.0000000 200.0000  
 \*506 p -1.0000000 1.7320508 0.0000000 -200.0000  
 \*507 p 1.0000000 1.7320508 0.0000000 -200.0000  
 \*508 p 1.0000000 1.7320508 0.0000000 200.0000

c

1000 so 1000 \$ beyond problem

c

2000 s 61.948 0.000 38.382 23.994894  
 2001 s 61.948 0.000 38.382 19.0  
 2002 s 61.948 0.000 38.382 79.210227

c

2100 pz 103.79361

c

c

mode n

kcode 4000 0.9 50 4000

sdef x=d1 y=d2 z=d3 ccc=9000 eff=0.00001

c ksrc 0 0 120

c

si1 -19.0 86.1

sp1 0 1

c

si2 -19.0 19.0

sp2 0 1

```

c
si3  14.0  210.0
sp3  0    1
c
c Material Definitions
c
c
c H/Pu  1400
c H2O/CH2  0.0000000
c Be w%  1.000000%  of CH2 + Pu
c Radius  23.994894  cm
c Pu-239 Mass  325.000000  g
c Density  0.238656  g/cc
c 0.000  0.000  120.000  23.99489  Center
c 0.000  0.000  38.382  23.99489  Bottom
c 61.948  0.000  38.382  23.99489  Lower Corner
c 61.948  0.000  185.138  23.99489  Upper Corner
c
m139  1001.66c  -0.13886897  $  H-1
      1002.66c  -0.00004163  $  H-2
      4009.66c  -0.00990099  $  Be-nat
      6000.66c  -0.82765605  $  C-nat
c     8016.66c  0.00000000  $  O-16 & O-18
c     8017.66c  0.00000000  $  O-17
      94239.66c  -0.02353235  $  Pu-239
mt139  poly.60t  be.60t
c
c
c H2O/CH2  0.000
c Be w%  1.00%  of CH2
c Density  0.104514  g/cc  Full Vessel
c Density  0.233058  Sphere Reflector
c Radius  79.210227  Sphere Reflector
c Height  0.000000
c
m169  1001.66c  -0.14224992  $  H-1
      1002.66c  -0.00004265  $  H-2
      4009.66c  -0.00990099  $  Be-nat
      6000.66c  -0.84780644  $  C-nat
c     8016.66c  0.00000000  $  O-16 & O-18
c     8017.66c  0.00000000  $  O-17
mt169  poly.60t  be.60t
c
c
c
c Carbon Steel

```

c Density 7.85 g/cc

c

m200	6000.66c	-0.003000	\$ C-nat
	14028.66c	-0.002572	\$ Si-28
	14029.66c	-0.000135	\$ Si-29
	14030.66c	-0.000092	\$ Si-30
	15031.66c	-0.000400	\$ P-31
	16000.66c	-0.000500	\$ S-nat
	25055.66c	-0.010300	\$ Mn-55
	26054.66c	-0.055383	\$ Fe-54
	26056.66c	-0.901554	\$ Fe-56
	26057.66c	-0.021193	\$ Fe-57
	26058.66c	-0.002870	\$ Fe-58
	29063.66c	-0.001370	\$ Cu-63
	29065.66c	-0.000630	\$ Cu-65

c

c SS-304 - from STDNEUT.dos file

c Density 8.03 g/cc

c

m300	6000.66c	-0.000300	\$ C-nat
	24050.66c	-0.008345	\$ Cr-50
	24052.66c	-0.167349	\$ Cr-52
	24053.66c	-0.019341	\$ Cr-53
	24054.66c	-0.004905	\$ Cr-54
	25055.66c	-0.019994	\$ Mn-55
	26054.66c	-0.038378	\$ Fe-54
	26056.66c	-0.624743	\$ Fe-56
	26057.66c	-0.014686	\$ Fe-57
	26058.66c	-0.001989	\$ Fe-58
	28058.66c	-0.067178	\$ Ni-58
	28060.66c	-0.026768	\$ Ni-60
	28061.66c	-0.001183	\$ Ni-61
	28062.66c	-0.003834	\$ Ni-62
	28064.66c	-0.001008	\$ Ni-64

c

c Lead

c Density 11.34 g/cc

c

m400 82000.50c -1.0 \$ Lead

c

c Air

m500	7014.66c	-0.761985	\$ N-14
	7015.66c	-0.003015	\$ N-15
	8016.66c	-0.234905	\$ O-16 & O-18
	8017.66c	-0.000095	\$ O-17

c

c Water  
c Density 1.00 g/cc  
c  
m600 1001.66c -0.11186481 \$ H-1  
1002.66c -0.00003354 \$ H-2  
8016.66c -0.88774309 \$ O-16 & O-18  
8017.66c -0.00035857 \$ O-17  
mt600 lwtr.60t  
c  
c  
c Be 1.85 g/cc  
c  
m800 4009.66c -0.00497513 \$ Be-nat  
mt800 be.60t  
c  
print

**HAC Infinite Array – f022flat02**

10-160B

c

3000 102 -1.012911 -2000  
                                   imp:n=1  
 4000 152 -0.991738 +120 -149 -30  
                                   +2000  
                                   #(+130 +10 )  
                                   imp:n=1

c

c Cask Regions

5 300 -8.03 ((30:-120)(-40 110 -130)): (130 -140 10 -40):  
                                   (10 -20 140 -149):(149 -150 -20) imp:n=1 \$ Liner 11 ga - SS304  
 10 200 -7.85 (100 -109 -70) imp:n=1 \$ Base-Carbon Steel  
 15 200 -7.85 (109 -110 -50) imp:n=1 \$ Base-Carbon Steel  
 20 200 -7.85 (110 -140 40 -50) imp:n=1 \$ Inner Shell-Carbon Steel  
 25 400 -11.34 (109 -140 50 -60) imp:n=1 \$ Lead wall  
 30 200 -7.85 (109 -140 60 -70) imp:n=1 \$ steel  
 40 200 -7.85 (140 -150 20 -70):(150 -160 -70):(160 -170 -25)  
                                   imp:n=1 \$ Prim/2ndary lid-Carbon Steel

c

c

c Around cask, interspersed

201 600 -0.0010 (-503 504 -508 507 -505 506 501 -502)  
                                   (((70:-100) -160):(160 25):170) imp:n=1

c Outside World

200 0 (503:-504:508:-507:505:-506:-501:502) imp:n=0

c

9000 0 -2001 imp:n=1

c

c Cask Radial Zones

10 cz 39.0525 \$ Lid recess liner  
 20 cz 39.37 \$ Lid recess  
 25 cz 58.42 \$ 2ndary lid  
 30 cz 86.0425 \$ Inner cavity  
 40 cz 86.36 \$ OD Liner (11 ga)  
 50 cz 89.2175 \$ OD Inner shell  
 60 cz 93.98 \$ OD Lead  
 70 cz 99.06 \$ OD Outer shell  
 80 cz 99.695 \$ OD Thermal barrier-not included in model

c Cask Axial Zones

100 pz 0.0001 \$ Bottom cask  
 109 pz 11.43 \$ Bottom lead in side wall

```

110 pz 13.97 $ Base plate
120 pz 14.2875 $ Bottom liner
125 pz 174.32655 $ Top of mixture for H/D=0.93
130 pz 209.2325 $ Cavity hgt
140 pz 209.55 $ Top liner
149 pz 216.8525 $ Lid recess liner
150 pz 217.17 $ Top of lid recess
160 pz 223.52 $ Primary lid
170 pz 231.14 $ Top of 2nd lid
c
c Hexagonal Cell Surrounding Cask for Infinite array
c
c inner hex surfaces bounding lattice, (n-0.5)*p*cos30
c surfaces for outer hexagonal duct
*501 pz -1.000 $
*502 pz 232.140 $
*503 px 100.0000
*504 px -100.0000
*505 p -1.0000000 1.7320508 0.0000000 200.0000
*506 p -1.0000000 1.7320508 0.0000000 -200.0000
*507 p 1.0000000 1.7320508 0.0000000 -200.0000
*508 p 1.0000000 1.7320508 0.0000000 200.0000
c
1000 so 1000 $ beyond problem
c
2000 s 72.587 0.000 27.743 13.355327
2001 s 72.587 0.000 27.743 12.5
c
c
mode n
kcode 4000 0.9 50 4000
sdef x=d1 y=d2 z=d3 ccc=9000 eff=0.00001
c ksrc 0 0 120
c
si1 -12.5 86.1
sp1 0 1
c
si2 -12.5 12.5
sp2 0 1
c
si3 14.0 210.0
sp3 0 1
c
c Material Definitions

```

c  
 c  
 c H/Pu 850  
 c H2O/CH2 3.245  
 c Be w% 1.00000% of CH2 + Pu  
 c Radius 13.355327 cm  
 c Pu-239 Mass 325.0000 g  
 c Density 1.012911 g/cc  
 c 0.000 0.000 120.000 13.355327  
 c 0.000 0.000 27.743 13.355327  
 c 72.587 0.000 27.743 13.355327  
 c 72.587 0.000 195.778 13.355327  
 c  
 m102 1001.66c -0.11521015 \$ H-1  
     1002.66c -0.00003454 \$ H-2  
     4009.66c -0.00259548 \$ Be-nat  
     6000.66c -0.19471229 \$ C-nat  
     8016.66c -0.65502711 \$ O-16 & O-18  
     8017.66c -0.00026457 \$ O-17  
     94239.66c -0.03215585 \$ Pu-239  
 mt102 lwtr.60t be.60t  
 c  
 c  
 c H2O/CH2 8.451753  
 c Be w% 1.00000% of CH2  
 c Density 0.991738 g/cc  
 c  
 m152 1001.66c -0.11510828 \$ H-1  
     1002.66c -0.00003451 \$ H-2  
     4009.66c -0.00105689 \$ Be-nat  
     6000.66c -0.09049956 \$ C-nat  
     8016.66c -0.79298046 \$ O-16 & O-18  
     8017.66c -0.00032029 \$ O-17  
 mt152 lwtr.60t be.60t  
 c  
 c  
 c  
 c Carbon Steel  
 c Density 7.85 g/cc  
 c  
 m200 6000.66c -0.003000 \$ C-nat  
     14028.66c -0.002572 \$ Si-28  
     14029.66c -0.000135 \$ Si-29  
     14030.66c -0.000092 \$ Si-30  
     15031.66c -0.000400 \$ P-31

16000.66c	-0.000500	\$ S-nat
25055.66c	-0.010300	\$ Mn-55
26054.66c	-0.055383	\$ Fe-54
26056.66c	-0.901554	\$ Fe-56
26057.66c	-0.021193	\$ Fe-57
26058.66c	-0.002870	\$ Fe-58
29063.66c	-0.001370	\$ Cu-63
29065.66c	-0.000630	\$ Cu-65

c

c SS-304 - from STDNEUT.dos file

c Density 8.03 g/cc

c

m300	6000.66c	-0.000300	\$ C-nat
24050.66c	-0.008345	\$ Cr-50	
24052.66c	-0.167349	\$ Cr-52	
24053.66c	-0.019341	\$ Cr-53	
24054.66c	-0.004905	\$ Cr-54	
25055.66c	-0.019994	\$ Mn-55	
26054.66c	-0.038378	\$ Fe-54	
26056.66c	-0.624743	\$ Fe-56	
26057.66c	-0.014686	\$ Fe-57	
26058.66c	-0.001989	\$ Fe-58	
28058.66c	-0.067178	\$ Ni-58	
28060.66c	-0.026768	\$ Ni-60	
28061.66c	-0.001183	\$ Ni-61	
28062.66c	-0.003834	\$ Ni-62	
28064.66c	-0.001008	\$ Ni-64	

c

c Lead

c Density 11.34 g/cc

c

m400 82000.50c -1.0 \$ Lead

c

c Air

m500	7014.66c	-0.761985	\$ N-14
7015.66c	-0.003015	\$ N-15	
8016.66c	-0.234905	\$ O-16 & O-18	
8017.66c	-0.000095	\$ O-17	

c

c Water

c Density 1.00 g/cc

c

m600	1001.66c	-0.11186481	\$ H-1
1002.66c	-0.00003354	\$ H-2	
8016.66c	-0.88774309	\$ O-16 & O-18	

8017.66c -0.00035857 \$ O-17  
mt600 lwtr.60t  
c  
c  
c Be 1.85 g/cc  
c  
m800 4009.66c -0.00497513 \$ Be-nat  
mt800 be.60t  
c  
print

————— 6.0 CRITICALITY EVALUATION

~~Not applicable to the CNS 10-160B package.~~

## 7.0 OPERATING PROCEDURE

This chapter describes the general procedure for loading and unloading of the CNS 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  $\pm$  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, 1<sup>3</sup>/<sub>4</sub>" – 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 1<sup>3</sup>/<sub>4</sub>" – 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  $20 \pm 2$  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  $300 \pm 30$  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  $300 \pm 30$  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 CFR 172).

(c) That all radiation and surface contamination levels are within the limits of the applicable federal regulations.

(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) 1 $\frac{3}{4}$ " – 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.

**NOTE: 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.

**NOTE: 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 ~~CNS-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  $15 \pm 1$  psig. for fifteen minutes.
- Depressurize to  $\sim 0$  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.

## 8.0 ACCEPTANCE TESTS AND MAINTENANCE

### 8.1 Acceptance Test

Prior to the first use of the CNS 10-160B package, the following tests and evaluations will be performed:

#### 8.1.1 Visual Examination

The package will be examined visually for any adverse conditions in materials or fabrication.

#### 8.1.2 Structural Tests

Containment welds identified on Dwg. C-110-D-29003-010 are inspected per ASME Code, Section III, Div. I, Subsection ND, Article ND-5000.

All ferromagnetic material welds are inspected per ASME Code, Section III, Div. I, Subsection NF, NF-5230 for Class 3 support attachments, and Section V Article 7 for magnetic particle (MT) examinations, and Section V Article 6 for liquid penetrant (PT) examinations. Acceptance standards are per ASME Section III, Div. I, Subsection NF, NF-5340 and NF-5350, as appropriate.

All non-ferromagnetic material welds are liquid penetrant (PT) inspected per ASME Code, Section V, Article 6 with acceptance criteria per ASME Code, Section III, Div. I, Subsection NF, NF-5350.

Welds on lifting and tiedown lugs are inspected before and after 150% load test in accordance with the ASME Code requirements for MT examination as specified above.

### 8.1.3 Leak Tests

This test shall be performed, prior to acceptance and operation of a newly fabricated package, in accordance with ASTM E-427 using a halogen leak detector or ASTM E-499 using a helium leak detector depending on the test gas used. The detector shall be capable of meeting the applicable sensitivity requirements specified in Figures 4.4, 4.8, or 4.12 in Chapter 4. Calibration of the leak detector shall be performed using a leak rate standard traceable to NIST. The leak standard's setting shall correspond to the approved leak test rate (see Chapter 4). The annulus between the o-ring seals of the 10-160B primary and secondary lids will be evacuated to a minimum vacuum of 20<sup>7</sup>Hg, and then be pressurized to a minimum pressure of 25 psig with pure dichlorodifluoromethane (R-12) or 1,1,1,2 – tetrafluoroethane (R-134a). Helium testing does not require evacuation of the annulus prior to pressurization. The detector probe shall be moved along the interior surface of the inner seal according to the specifications of ASTM E-427 or E-499.

If installed, the vent and drain lines will be tested as above by evacuating and pressurizing the inlet (cavity) side of the lines and checking for leaks at the outlet side of the cap screw.

The maximum allowable leak rate (which is temperature dependent) is specified in Section 4.5, 4.6, or 4.7 (depending on the test gas used). Any condition, which results in leakage in excess of this value, shall be corrected.

### 8.1.4 Component Tests

Gasket and seals will be procured and examined in accordance with the Duratek Quality Assurance Program.

### 8.1.5 Test for Shielding Integrity

Shielding integrity of the package will be verified by gamma scan or gamma probe methods to assure package is free of significant voids in the poured shield annulus. All gamma scanning will be performed on a 4-inch square or less grid system. The

acceptance criteria will be that voids resulting in shield loss in excess of 10% of the normal lead thickness in the direction measured shall not be acceptable.

#### 8.1.6 Thermal Acceptance Tests

No thermal acceptance testing will be performed on the ~~CNS~~ 10-160B package. Refer to the Thermal Evaluation, Section 3.0 of this report.

#### 8.1.7 Impact Limiter Foam

Acceptance testing of the impact limiter foam will be performed as required by ES-M-172, which is included in Appendix 8.3.1.

#### 8.1.8 Pressure Test

A pressure test of the containment system will be performed as required by 10CFR71.85. As determined in Section 3.4.4, the maximum normal operating pressure for the cask cavity is 8.4 psig, therefore the minimum test pressure will be  $1.5 \times 8.4 = 12.6$  psig.

### 8.2 Maintenance Program

Duratek is committed to an ongoing preventative maintenance program for all shipping packages. The 10-160B package will be subjected to routine and periodic inspection and tests as outlined in this section and Duratek approved procedure.

#### 8.2.1 Routine Maintenance

Unless noted otherwise, for loaded packages containing large quantity LSA materials or greater than Type A quantities of non-LSA materials, each of the following safety related items and functional features shall be visually examined for defects or replacement. Corrective action for defects shall be as noted.

### 8.2.1.1 Fasteners

The primary and secondary lid bolts shall be visually inspected for defects whenever it is necessary to remove the corresponding lid. Obtain replacement parts as specified on Drawing C-110-D-29003-010 (current revision) for any components that show cracking or other visual signs of distress.

The cap screws for the vent port, test ports and drain shall be visually inspected for defects whenever it is necessary to remove them. Obtain replacement cap screws as specified on Drawing C-110-D-29003-010 (current revision) for any cap screws that show cracking or other visual signs of distress.

### 8.2.1.2 Gaskets and Seals

#### a. Primary Lid Seals

The primary lid O-ring seals shall be visually inspected for serviceability, ensuring that they are in the proper position and free of cracks, tears, cuts or discontinuities that may prevent them from sealing properly. The seal seating surfaces shall be visually inspected to ensure that they are free of damage, dirt, gravel or any foreign matter, which might damage the seals. If any defects are detected, the seals shall be replaced and/or the seal seating surfaces shall be reworked as necessary to ensure that the lid will seal properly.

New O-rings shall be lightly coated with a lightweight lubricant such as Parker Super O-Lube or equivalent prior to installation. The lubricant will minimize deterioration or cracking of the elastomer during usage and tearing if removal from the dovetail groove is necessary for inspection. If new O-rings have not been installed, coat the exposed surfaces of the O-rings with the lightweight lubricant immediately prior to closing the lid. Excess lubricant shall be wiped off before closing the lid.

b. Secondary Lid Seals

The secondary lid O-ring seals and seating surfaces shall be inspected as specified in Section 8.2.1.2 (a) at any time it is necessary to remove the secondary lid. Seal replacement and/or seating surface repair shall be as specified in Section 8.2.1.2 (a).

c. Test/Vent Ports and Drain Seals

The above seals and seating surfaces shall be inspected as specified in Section 8.2.1.2 (a) at any time it is necessary to remove them. Seal replacement and/or seating surface repair shall be as specified in Section 8.2.1.2 (a).

8.2.1.3 Painted Surfaces Identification Markings and Match Marks Used for Closure Orientation

The above items shall be visually inspected to ensure that painted surfaces are in good condition, identification markings are legible and that match marks used for closure orientation remain legible and are easy to identify.

8.2.2 Periodic Maintenance

The following inspections and/or tests shall be performed as specified.

8.2.2.1 Periodic Leak Tests

The package shall be leak tested as described in Section 8.1.3 after its third use. In addition, the containment system, before actual use for shipment, shall have been leak tested according to Section 8.1.3, or to the Leaktight Test specified below, within the preceding 12-month period.

The Leaktight Test shall be performed in accordance with ANSI N14.5 using a mass spectrometer leak detector capable of meeting the sensitivity requirements specified in Chapter 4, Section 4.9. Calibration of the leak detector shall be performed using a leak rate standard traceable to NIST. The leak standard's setting shall correspond to the leaktight leak test rate (see Chapter 4, Section 4.9). The test is conducted by evacuating the cask cavity to a 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 monitored leak rate must satisfy the leak criterion specified in Section 4.9. If installed, the vent and drain lines will be tested as above by evacuating and pressurizing the inlet (cavity) side of the lines and monitoring the helium concentration at the outlet side of the cap screw. Any condition, which results in leakage in excess of the leak criterion, shall be corrected before use of the cask.

Also, before actual use for shipment, all seals shall have been replaced within the preceding 12-month period.

#### 8.2.2.2 Assembly Verification Leak Test

This test is required before each shipment of Type B material quantities. The test will verify that the containment system has been assembled properly.

The test will be performed by pressurizing the annulus between the O-ring seals of either the primary or the secondary lid or the inlet to the vent and drain lines (if applicable) with dry air or nitrogen.

NOTE: PRESHIPMENT LEAKAGE RATE TESTING IS REQUIRED ONLY FOR THE CONTAINMENT BOUNDARY AREAS THAT HAVE BEEN OPENED DURING THE UNLOAD-LOADING CYCLE.

NOTE: IF AIR IS USED FOR THE TEST, THE AIR SUPPLY SHOULD BE CLEAN AND DRY. IF IT IS NOT, OR IF THE QUALITY OF THE AIR SUPPLY IS UNCERTAIN, THE TEST SHOULD BE PERFORMED WITH NITROGEN TO ENSURE RELIABLE RESULTS.

The test shall be performed using a pressure gauge, accurate within 1%, or less, of full scale.

The test pressure shall be applied for at least 15 minutes (10 minutes for vent or drain ports). A drop in pressure of greater than the minimum detectable amount shall be cause for test failure. The maximum sensitivity of the gauge shall be 0.1 psig.

Sensitivity at the test conditions is equivalent to the prescribed procedure sensitivity of  $10^{-3}$  ref-cm<sup>3</sup>/sec based on dry air at standard conditions as defined in ANSI N14.5-1997 (See Section 4.4 for the determination of the test conditions).

#### 8.2.2.3 Ratchet Binders

Ratchet binders are designed for long use with minimal maintenance. Inspection for operation is conducted prior to each use of the cask. The ratchet binder mechanism as well as the threads on the joining bolt are checked for dryness and ease of operation. If required, these parts are lubricated with standard chassis lubricant.

Ratchet binders which show excessive wear or have received impact or suspected overloading in an accident must be completely disassembled and inspected or replaced. Cause for rejection during an inspection shall include:

- a. Cracks in the jaws or joining bolt.
- b. Deformation of the jaws or joining bolt.
- c. Excessive rust or corrosion pitting in the threads of the jaw or joining bolts.

#### 8.2.3 Subsystem Maintenance

The CNS 10-160B package contains no subsystem assemblies.

#### 8.2.4 Valves Rupture Discs and Gaskets on Containment Vessel

As a minimum, all gasket seals will be replaced prior to the annual leak test specified in 8.2.2.1.

#### 8.2.5 Shielding

No shielding tests will be performed after acceptance testing unless there has been a repair to a damaged area, which will affect shield integrity. Any shield testing which might be required would be in accordance with the original criteria specified in Section 8.1.5.

**Appendix 8.3.1**  
**Polyurethane Foam Specification**  
**ES-M-172**