Los Alamos
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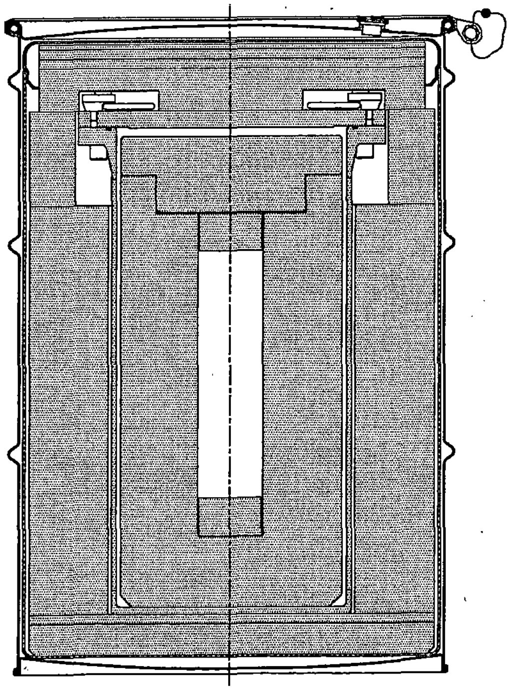
S300

Fissile Material Transport Package



Safety Analysis Report

Revision 5
June 2010

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1. GENERAL INFORMATION

This chapter of the Safety Analysis Report (SAR) presents a general introduction and description of the model **S300** packaging. The S300 packaging is identical to the S300 pipe overpack currently used as a payload container within the TRUPACT-II[1], and is qualified as a DOT 7A Type A transportation packaging. This application seeks validation of the S300 packaging as a Type AF-96 fissile materials shipping container per the definitions in 10 CFR §71.4[2].

The major components comprising the S300 packaging are discussed in Section 1.2.1, *Packaging*, and a detailed drawing of the package design is presented in Section 1.3.1, *Packaging General Arrangement Drawings*.

1.1 Introduction

The S300 packaging has been developed as a safe means for transporting a single Los Alamos Special Form Capsule (SFC). Radioactive contents consist of neutron sources, alpha reference standards, foils (e.g., threshold detectors), and other similar source configurations containing plutonium. As determined in Section 1.2.2, *Contents*, the S300 package carries a Type A quantity of fissile material. The S300 package is designed for transport via highway, rail, vessel, or air. The S300 is designed, fabricated, and used according to the Quality Assurance program requirements discussed in Chapter 9, *Quality Assurance*.

As shown in Section 6.7, *Fissile Material Packages for Air Transport*, the S300 meets the requirements of 10 CFR §71.55(f) and TS-R-1[3] §680 for the transport of fissile material by air. Since the authorized contents of the S300 include plutonium, and since it is not demonstrated that the S300 meets the requirements of 10 CFR §71.64, the S300 will not be transported by air in any airspace which is subject to the laws and regulations of the United States.

1.2 Package Description

1.2.1 Packaging

1.2.1.1 Packaging Description

As illustrated in Figure 1-1, the S300 packaging is functionally divided into three parts: 1) the impact-absorbing protection provided by the 55-gallon drum and dunnage, 2) the confinement vessel consisting of the pipe component, and 3) the neutron shielding provided by the high-density polyethylene (HDPE) shielding insert. Containment and criticality control are afforded

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[1] U.S. Department of Energy (DOE), *Safety Analysis Report for the TRUPACT-II Shipping Package*, USNRC Certificate of Compliance 71-9218, U.S. Department of Energy, Carlsbad Field Office, Carlsbad, New Mexico.

[2] Title 10, Code of Federal Regulations, Part 71 (10 CFR 71), Packaging and Transportation of Radioactive Material, 01-01-06 Edition.

[3] IAEA, *Regulations for the Safe Transport of Radioactive Material*, TS-R-1, 2009.

by the SFC. The S300 packaging is identical to the S300 Pipe Overpack, described in Section 4.4 of the CH-TRU Payload Appendices.

Overpack Components. The S300 package design utilizes a standard 55-gallon drum as an outer container. A standard bolted clamping ring secures the drum lid to the drum body. The drum, clamping ring, and bolt may be plated or painted carbon steel, or bare stainless steel. A rigid polyethylene liner (body and lid) is located within the inside periphery of the drum. The liner lid is pierced and the drum lid is fitted with a filter vent to allow continuous venting of the volume within the drum. Cane fiberboard dunnage is used within the poly liner to hold the pipe component in an approximately central position and to absorb shock. The lower shock absorbing buffer includes a sheet of exterior plywood. Using shims of fiberboard or plywood, the clearance between the dunnage and the interior surface of the liner lid is maintained to less than 1/2 inch.

Pipe Component. As illustrated in Figure 1-2, the pipe component consists of a cylindrical pipe welded to a flat cap at the bottom end and a pipe bolting flange at the other end. The pipe component is closed with a flat lid which is attached by 12, 7/8-9 UNC stainless steel bolts having a minimum tensile strength of 75,000 psi. The weldment and lid are made from ASTM Type 304 or 304L stainless steel material. The lid features two lift rings located on the bolt circle, or optionally, a single, centrally located lift ring. A filter vent is installed in the lid. The lid/flange joint features a butyl or ethylene/propylene rubber O-ring dust seal of nominally 3/16 inch cross sectional diameter.

The maximum outer diameter of the pipe is 12.8 inches, the outer diameter of the flange is 16.3 inches, and the overall maximum length (including lifting rings and bolt heads) is 27.5 inches. The minimum thickness of the pipe wall is 0.219 inches, and the minimum thickness of the bottom cap is 0.25 inches. The nominal thickness of the lid is 0.9 inches.

Shielding Insert. The neutron shielding insert is a two-part assembly consisting of a cylindrical body and stepped lid which nominally fills the cavity within the pipe component. The shielding lid is held in place by the bolted lid of the pipe component. The insert is made from solid, high-density polyethylene (HDPE) plastic. The thickness of the sides and ends is nominally four inches. Supplemental shield plugs having a thickness of two inches are used at both ends of the payload cavity. The remaining payload cavity is nominally 13 inches long and 3.5 inches in diameter.

Two specific SFC types are used within the S300 package, as discussed in greater detail in Section 1.2.2, *Contents.*

1.2.1.2 Gross Weight

The gross shipping weight of the S300 package is a maximum of 480 pounds. A summary of component weights is provided in Table 2-1 of Section 2.1.3, *Weights and Centers of Gravity.*

1.2.1.3 Neutron Moderation and Absorption

The S300 package does not require specific design features to provide neutron moderation and absorption for criticality control. Fissile material in the payload is limited to an amount that ensures safely subcritical packages for both NCT and HAC. The fissile material limit is based on an optimally moderated and reflected configuration of fissile material. A finite array of bare SFCs is safely subcritical as discussed in Chapter 6, *Criticality Evaluation.*

1.2.1.4 Receptacles, Valves, Testing, and Sampling Ports

A filter vent through the S300 packaging drum lid and a second filter vent in the pipe component lid comprise the only penetrations to the payload cavity. The SFC is not vented. No other receptacles, valves, testing, or sampling ports are utilized on the S300 packaging.

1.2.1.5 Heat Dissipation

The S300 package is designed with a passive thermal system. The amount of decay heat generated by the maximum payload is insignificant, as discussed in Section 3.1.2, *Content's Decay Heat.*

1.2.1.6 Coolants

Due to the passive heat transfer design of the S300 package, no coolants are utilized.

1.2.1.7 Protrusions

The external configuration of the S300 packaging is that of a standard 55-gallon drum, and consequently has no significant protrusions.

1.2.1.8 Lifting and Tie-down Devices

The S300 packaging is lifted, handled, and tied down using separate hardware designed for these purposes. Consequently, there are no lifting or tiedown devices which are an integral or structural part of the packaging.

1.2.1.9 Pressure Relief System

Containment of radioactive materials is afforded by the payload SFC, which has no pressure relief devices. As discussed earlier, one filter vent is located in the drum lid and one in the pipe component lid.

1.2.1.10 Shielding

As discussed in Chapter 5, *Shielding Evaluation*, the payload sources emit alpha particles, neutrons, and minor gamma photons. The HDPE neutron shielding insert is used to demonstrate compliance with NCT dose limits. As will be demonstrated, no neutron shielding is required for compliance with HAC dose limits.

Of note, when transporting the maximum permitted contents for air transport of 206g of Pu (see Section 1.2.2, *Contents*), the surface radiation level does not exceed 200 mrem/hr (equivalent to 2 mSv/hr). Therefore a special arrangement is not required in accordance with TS-R-1, §575.

1.2.2 Contents

Contents are divided into two categories. Content no. 1 consists of plutonium-based neutron sources, and content no. 2 consists of general plutonium material, which includes alpha reference standards (e.g., check sources), foils (e.g., threshold detectors), and other source configurations containing plutonium. The plutonium used to manufacture the neutron sources is comprised of the following six isotopes: Pu-238, Pu-239, Pu-240, Pu-241, Pu-242, and Am-241. The radioisotope distribution representative of most sources is obtained from Section 5.5.1, *Radionuclide Distribution Document LA-UR-09-06701*, and is shown in Table 1-1. Neutron sources consist of plutonium mixed with target material such as beryllium. Other target materials such as boron, fluorine, or other light elements may be used; however, the beryllium target is bounding, as discussed in Section 5.2, *Source Specification*. Alpha reference standards are typically small disks of substrate material with a thin plutonium deposit on the surface, while foils are thin layers of plutonium sandwiched between cladding material.

Total contents are limited to less than an A_1 quantity using the sum of the fractions rule. Dose rate measurements are made on all packages to ensure compliance with DOT regulations as stated in Section 7.1.3, *Preparation for Transport*.

The S300 package transports a single Special Form Capsule (SFC) within the shielding insert. There are two different SFC models of similar design, carrying the designations Model II and Model III. Each is fabricated of Type 304 stainless steel, with a nominal wall thickness of 1/2 inch, and bottom and threaded top cap thicknesses of 3/4 inch. The top cap holds a tapered sealing plug in place, and is designed with a shearable stem to preclude removing the cap once installed. The Model II has an additional impact plug held loosely in place with a snap ring. The capsule dimensions are given in the following table.

Capsule	Outer Diameter, in	Outer length, in*
Model II	3.0	11.75
Model III	2.5	7.0

*After stem shear-off.

The Model II SFC is shown in Figure 1-3, and the Model III SFC is shown in Figure 1-4. Additional discussion of the special form capsules is provided in Section 2.10, *Special Form*. Table 1-2 gives the maximum contents for the S300 package for the Model II and Model III capsules under non-exclusive and exclusive use for surface (i.e., land or sea) transport. A different criticality safety index (CSI) applies to the two content types. The CSI for content no. 1 is 0.3, while the CSI for content no. 2 is 4.0. Table 1-3 gives the maximum contents limits for air transport, which is the same for both content types.

Table 1-1 - Representative Radionuclide Distribution for Plutonium Used in Sources

Isotope	Composition, Wt. %
Pu-238	0.015
Pu-239	92.6
Pu-240	6.75
Pu-241	0.62
Pu-242	0.033
Am-241*	0.025

*The americium is present at the time of manufacture, and is additive to the plutonium. Therefore, 1g of Pu will have 0.00025g Am-241 prior to decay, or a Pu+Am mass of 1.00025g.

Table 1-2 - S300 Package Contents Limits for Surface Transport

Maximum Contents, grams of Pu			
Non-Exclusive Use		Exclusive Use	
Model II SFC	Model III SFC	Model II SFC	Model III SFC
Content no. 1, Neutron Sources, CSI = 0.3			
206	160	350	160
Content no. 2, General Plutonium Material, CSI = 4.0			
300	160	300	160

Table 1-3 - S300 Package Contents Limits for Air Transport

Maximum Contents, grams of Pu, Content no. 1 or no. 2	
Model II SFC	Model III SFC
206	160

1.2.3 Special Requirements for Plutonium

The S300 package contains a maximum of 350 grams of Pu in solid form. Therefore, no special requirements apply.

1.2.4 Operational Features

The S300 package is not considered to be operationally complex. All operational features are readily apparent from an inspection of the drawing provided in Section 1.3.1, *Packaging General Arrangement Drawings*, and the previous discussions presented in Section 1.2.1, *Packaging*. Operational procedures and instructions for loading, unloading, and preparing an empty S300 package for transport are provided in Chapter 7, *Operating Procedures*.

Security-Related Information Figure Withheld Under 10 CFR 2.390.

Figure 1-1 – S300 Package Configuration

Security-Related Information Figure Withheld Under 10 CFR 2.390.

Figure 1-2 – Pipe Component (Confinement Vessel) Configuration

Security-Related Information Figure Withheld Under 10 CFR 2.390.

Figure 1-3 – Model II Special Form Capsule

Security-Related Information Figure Withheld Under 10 CFR 2.390.

Figure 1-4 – Model III Special Form Capsule

1.3 Appendix

1.3.1 Packaging General Arrangement Drawings

(60999-SAR, 3 sheets)

60999-SAR	1	1

Security-Related Information Figure Withheld Under 10 CFR 2.390.

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REVISION HISTORY

APPD			
APPD			
APPD	P. NOSS	Phil Noss	2/11/10
ENGR	P. NOSS	Phil Noss	2/11/10
QA	K. King		1/25/10
CHECK	DL STEVENSON		[illegible]
DRAWN	R. LE		01/13/10

AREVA
AREVA Federal Services LLC
Packaging Projects
Tacoma, WA 98402

S300 PACKAGING
SAR DRAWING

TOLERANCES, UNLESS OTHERWISE SPECIFIED:

ASSY:	1 PLACE DECIMAL:
A2	±0.1
A3	±0.1
A4	±.03

ANGULAR: ±2°

SCALE: N/A
WT. N/A
REV: 1
SHEET 1 OF 3
DWG SIZE D
DWG NO. 60999-SAR
CADFILE: [illegible]

Security-Related Information Figure Withheld Under 10 CFR 2.390.

REV: 1 SHEET 2 OF 3
DWG NO.
60999-SAR

Security-Related Information Figure Withheld Under 10 CFR 2.390.

REV: 1 SHEET 3 OF 3
DWG NO.
60999-SAR

2. STRUCTURAL EVALUATION

This chapter identifies and describes the principal structural design aspects of the S300 package, and demonstrates the structural safety of the packaging system and compliance with the structural requirements of 10 CFR 71. Demonstration of compliance is accomplished using a combination of performance tests, reference to previous demonstrations, and reasoned argument.

For normal conditions of transport (NCT), demonstration of compliance is by testing of a S300 package prototype (vibration, free drop, corner drop) and by reference to tests of similar packages (water spray, stacking, penetration). For hypothetical accident conditions (HAC), demonstration is by reference to tests of similar packages, showing that the environment provided for the SFC by the S300 package in the free drop, puncture, and fire tests is bounded by the tests used to qualify the capsules as special form.

2.1 Description of Structural Design

2.1.1 Discussion

The S300 package is designed to transport a single Special Form Capsule (SFC). Radioactive contents consist of neutron sources, alpha reference standards, foils (e.g., threshold detectors), and other source configurations containing plutonium.

The packaging is functionally divided into three parts: 1) the impact-absorbing protection provided by the 55-gallon drum and dunnage, 2) the confinement vessel consisting of the pipe component, and 3) the neutron shielding provided by the high-density polyethylene (HDPE) shielding insert. Containment of radioactive material is afforded by the SFC, per 10 CFR §71.4.

The S300 package employs cane fiberboard dunnage within the overpack to provide attenuation of shock loading during normal conditions of transport (NCT) and hypothetical accident conditions (HAC). The pipe component, made of austenitic stainless steel, provides a compact, robust confinement for the SFC during NCT and during most HAC events. While the pipe component may not remain fully intact following the entire series of HAC mechanical test events, it nonetheless provides an environment that is less severe than the mechanical testing performed on the special form capsule during its qualification. The shielding insert provides, besides biological shielding of neutrons, further attenuation of shock and vibration. Of note, the shielding analysis documented in Chapter 5, *Shielding Evaluation* and the criticality evaluation documented in Chapter 6, *Criticality Evaluation*, demonstrate that an adequate level of biological shielding and subcriticality under worst-case moderation, respectively, are maintained by a bare capsule under HAC.

2.1.2 Design Criteria

The S300 package, in conjunction with the SFC, has been designed to meet all the applicable structural requirements of 10 CFR 71. The design objectives for the S300 package are twofold:

1. Demonstrate that, under NCT, the S300 package maintains confinement of the SFC within the shield insert, and experiences an insignificant reduction in its effectiveness to withstand HAC; and
2. Demonstrate that the environment afforded to the SFC by the S300 under HAC is bounded by the environment to which the SFC was exposed during special form qualification testing.

Consequently, the design criteria for NCT are that the S300 package exhibit only minor damage subsequent to the NCT conditions and tests, including no damage that would materially affect the outcome of a subsequent HAC test.

For HAC, the design criteria are that the S300 package protect the SFC from conditions more severe than those experienced in the special form qualification 9-meter free drop, percussion, and heat tests specified in 10 CFR §71.75.

For air transport, no structural integrity is assumed for the hypothetical accident conditions defined in 10 CFR §71.55(f). Instead, the materials of the packaging and contents are assumed to reconfigure into a worst-case criticality geometry as discussed in Section 6.7, *Fissile Material Packages for Air Transport.*

Material properties are controlled by the acquisition of critical components to ASTM standards, as described in Section 2.2, *Materials.*

The materials utilized in the S300 package are not subject to brittle fracture. The steel drum, due to its thin section (approximately 0.055 inches) is not susceptible to brittle fracture at cold temperatures. The pipe component and lid bolts are made from austenitic stainless steel, and are thus not subject to brittle fracture.

The S300 package is normally used for one-time shipment and permanent storage, and is consequently not subject to cyclic usage fatigue. If used more than once, the only components of the S300 package which could be subject to cyclic usage stress are the fasteners. These items (the pipe component lid bolts and the drum closure ring bolt) are few and simple, and can be adequately inspected to ensure integrity prior to use. Fatigue associated with normal vibration over the road is discussed in Section 2.6.5, *Vibration.*

2.1.3 Weights and Centers of Gravity

Weights of the S300 packaging components are presented in Table 2-1. Due to the symmetric design, the center of gravity is located approximately at the geometric center of the package.

Table 2-1 – S300 Component Weights

Component	Weight (lb)
Overpack (drum, liner, dunnage)	180
Pipe Component (empty)	180
Shield Insert	90
Special Form Capsule (Loaded)	30
Total:	**480**

2.1.4 Identification of Codes and Standards for Package Design

The S300 package functions primarily as an overpack for the SFC. In lieu of reliance on the use of codes or standards in design, compliance with requirements is demonstrated via full scale testing of the S300 package for NCT, and via U.S. DOT special form certification of the SFC for both NCT and HAC.

2.2 Materials

2.2.1 Material Properties and Specifications

The S300 packaging is constructed of several common structural materials, such as carbon steel, stainless steel, cane fiberboard, and high density polyethylene (HDPE). The pipe component is made from ASTM Type 304/304L stainless steel, having a minimum yield strength of 25,000 psi and a minimum ultimate strength of 70,000 psi. The pipe component lid bolts are made from stainless steel having a minimum ultimate strength of 75,000 psi. The cane fiberboard dunnage is made from ASTM C208 material, having a minimum density of 14 lb/ft^3.

2.2.2 Chemical, Galvanic, or Other Reactions

The materials of construction are inherently resistant to chemical or galvanic corrosion. Deleterious corrosion or other reactions are not anticipated during normal use. In addition, all of these materials have been used in Type A packagings for many years without incident. However, if unusual corrosion of the carbon steel outer drum occurs, this can be readily detected during preparation of the packaging for use. Both the pipe component and the SFC are made from austenitic stainless steel. The other packaging components, such as HDPE and fiberboard, are not subject to chemical degradation or corrosion during normal use.

High density polyethylene (HDPE) is a thermoplastic material based on chains of CH_2 monomers. It does not contain any corrosive ions such as chlorides. As a thermoplastic, the material melts without significant chemical change. Thus the solid or molten material is not caustic to the stainless steel used for the SFC. If the material is exposed to the hypothetical fire, the combustion products will consist mainly of carbon dioxide and carbon monoxide. The smoke may also contain low levels of aldehydes, ketones, organic acids or hydrocarbons. These substances are generally not corrosive to stainless steel. Additionally, since the fire event is of limited duration, exposure to the combustion products of HDPE will have no significant effect on the SFC.

2.2.2.1 Effect of Contents on the SFC

The SFC is made of Type 304 stainless steel, which is approximately 18% Cr, 8% Ni, and the balance Fe. During the hypothetical fire, the temperature of the SFC may be elevated to 800 °C (1,475 °F) for a brief period as discussed in Section 3.4.3, *Maximum Temperatures and Pressures*. The quaternary phase system of stainless steel with Pu is complex, but Pu is known to form a eutectic with Fe at 410 °C having approximately 10 atomic percent Fe. A review of the metallurgical data obtained from diffusion couples and irradiated stainless steel clad Pu metallic fuels was performed by Tsai, et. al.[1] In that study, the following formula was given for the rate of wall thinning of a stainless steel can due to Pu alloying at temperatures above 600 °C, which includes the maximum SFC temperature:

$$R = e^{(6.75 - 9{,}850/T)}$$

where R is the rate of penetration (μm/s), and T is temperature (K). At 800 °C (1,073 K), the rate of penetration is 0.088 μm/s, or $3.465(10^{-6})$ in/s. The eutectic only begins to form above 410 °C (770 °F), but conservatively, the time duration for potential alloying will be taken as the entire fire duration of 30 minutes, plus one hour after the end of the fire (at which time the SFC temperature is back down to approximately 400 °F per Section 3.4.3), or a total of 5,400 seconds. The conservative overestimate of the penetration distance would therefore be 5,400s × $3.465(10^{-6})$ in/s = 0.019 inches. Since the thinnest SFC wall belongs to the Model II, having a thickness of ½ × (3 – 2.062) = 0.469 inches (see Figure 1-3), the maximum depth of penetration into the wall by the eutectic liquid (0.019 inches) equals only 4% of the wall thickness. The soak time at a temperature of 800 °C required to completely penetrate the SFC wall thickness is:

$$t_{soak} = \frac{0.469}{3.465\left(10^{-6}\right)} = 135{,}354\ \text{s} = 37.6\ \text{hours}$$

This time period is far longer than the SFC exposure to high temperature. Thus, compromise of the SFC containment boundary by the possible attack of Pu on the SFC material of construction is not of concern.

The SFC is closed with an air atmosphere. The ignition temperature of Pu metal in dry air can be as low as approximately 300 °C[2], which will be exceeded in the hypothetical fire accident condition. The combustion product would consist of PuO_2; plutonium nitride (from the nitrogen in the air) does not form under these conditions. The Model II SFC has the largest internal volume of the two capsules. Conservatively ignoring the volume taken by the impact plug (see

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[1] Hanchung Tsai, Yung Liu, Allen Smith, Nick Gupta, and Steve Bellamy, *Potential Eutectic Failure Mechanism for Stainless Steel Cans Containing Plutonium Metal*, Argonne National Laboratory, in *Proceedings of the 15th International Symposium on the Packaging and Transport of Radioactive Materials*, PATRAM 2007.

[2] O. J. Wick, Ed., *Plutonium Handbook: A Guide to Technology*, Gordon and Breach Science Publishers,New York, 1967.

Figure 1-3) and the internal payload materials, the length of the internal cavity of the Model II SFC is equal to:

$$11.75 - 1.0 - 0.75 - 0.78 = 9.22 \text{ inches.}$$

The volume is therefore:

$$V = \pi / 4(2.062)^2(9.22) = 30.79 \text{ in}^3 = 504.5 \text{ cm}^3$$

Since one mole of air occupies 22.4 liters at STP, or 22,400 cm^3, the Model II SFC contains 504.5/22,400 = 0.0225 moles of air, or, since oxygen comprises 21% of air, 0.0047 moles of O_2. Since the species formed by oxidation is PuO_2, then it takes only 0.0047 moles of Pu to completely consume all of the oxygen in the SFC. Since Pu weighs 239 g/mol, the weight of Pu consumed would be 0.0047 mole × 239 g/mol = 1.1g Pu. This represents a very small amount of chemical heat and reactant volume, thus, the possible combustion of the Pu with the available oxygen inside the SFC is not of concern.

2.2.3 Effects of Radiation on Materials

The radioactive contents of the SFC generate primarily neutrons via a α-n reaction. Most of the neutrons are captured by the shield insert before reaching any other components of the packaging. In any case, the payload represents a relatively weak source of neutrons, and no significant degradation of the materials of the packaging will occur. Thus, the requirements of 10 CFR §71.43(d) are satisfied.

2.3 Fabrication and Examination

2.3.1 Fabrication

The S300 packaging uses conventional processes for the fabrication of the packaging components. No special processes or techniques are used. All parts are fabricated or purchased in accordance with approved fabrication drawings. Pipe component flange and bottom end welds are made in accordance with the ASME B&PV Code, Section III, Division 1, Subsection NG, Article NG-4400, and are complete joint penetration welds.

2.3.2 Examination

Each component of the S300 packaging is examined per the approved fabrication drawings to ensure acceptable materials and workmanship. Pipe component flange and bottom end welds are examined in accordance with the ASME B&PV Code, Section III, Division 1, Subsection NG, Articles NG-5230 and NG-5260, and accepted in accordance with Articles NG-5350 and NG-5360.

2.4 General Requirements for All Packages

2.4.1 Minimum Package Size

The minimum dimension of the S300 packaging is the drum diameter of approximately 24 inches. Thus, the minimum four-inch requirement of 10 CFR §71.43(a) is satisfied.

2.4.2 Tamper-Indicating Feature

A tamper-indicating lock wire and seal is installed through a cross-drilled hole in the drum lid bolting-ring bolt. The drum lid cannot be removed without destroying the seal. Thus, the requirement of 10 CFR §71.43(b) is satisfied.

2.4.3 Positive Closure

The containment system of the S300 packaging is supplied by the SFC. Once closed, the SFC cannot be opened without destroying the capsule, thus meeting the requirement of 10 CFR §71.4. The SFC is carried within the shield insert, which is confined within the pipe component. The lid of the pipe component is attached by 12 bolts which are not accessible during transport. Thus, the SFC cannot be released from the shield unintentionally, meeting the requirement of 10 CFR §71.43(c).

2.5 Lifting and Tie-Down Standards for All Packages

2.5.1 Lifting Devices

No lifting devices are provided that are used to lift the entire packaging.

2.5.2 Tie-Down Devices

There are no tie-down devices which are a structural part of the S300 packaging. Either single or multiple packages in the same shipment may be palletized, with strapping, banding, shrink-wrapping, and/or netting used to secure and immobilize the packages. Failure of these restraint devices will not compromise the ability of the S300 package to protect the payload, satisfying the requirement of 10 CFR §71.45(b). For shipment as exclusive use, the S300 package shall be secured to a pallet or shipping skid at least four inches in height.

2.6 Normal Conditions of Transport

2.6.1 Heat

2.6.1.1 Summary of Pressures and Temperatures

As presented in Section 3.3.1, *Heat and Cold,* the maximum S300 package temperature is 165 °F. Since all cavities of the package are vented, the maximum normal operating pressure (MNOP) is equal to ambient.

2.6.1.2 Differential Thermal Expansion

The shield insert, made of HDPE, takes up most of the volume inside the pipe component. It has an outer diameter of 11.8 inches and an assembled length of 24.8 inches. The pipe component has a minimum internal diameter of 12.0 inches and an internal length equal to:

$$25.6 - 0.1 - 0.35 - 0.05 = 25.1 \text{ inches,}$$

where:

25.6 inches is the nominal length of the body
0.1 inches is the negative tolerance on body length
0.35 inches is the maximum bottom plate thickness
0.05 inches is the thickness of the lid step which protrudes into the cavity on the lid end.

The thermal expansion coefficient for HDPE is 0.0001 in/in/°F.[3] The differential temperature is between the NCT hot temperature of 165 °F and room temperature of 70 °F, or 95 °F. The diametral (D-CLR) and axial (A-CLR) clearances are:

$$\mathrm{D-CLR} = 12.0 - 11.8(1 + 0.0001 \times 95) = 0.088 \text{ inches}$$
$$\mathrm{A-CLR} = 25.1 - 24.8(1 + 0.0001 \times 95) = 0.064 \text{ inches}$$

Note that the thermal expansion of the steel pipe component is conservatively neglected. Therefore positive clearances under NCT hot temperatures are maintained.

2.6.1.3 Stress Calculations

Since there are no interferences of components and no internal pressures, this section does not apply.

2.6.1.4 Comparison with Allowable Stresses

Since there are no stresses in the S300 packaging due to heat conditions, this section does not apply.

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[3] CRC Press, *Handbook of Tables for Applied Engineering Science*, 2nd Edition, 1973, p. 152.

2.6.2 Cold

As presented in Section 3.3.1, *Heat and Cold*, with an internal decay heat load of zero, no insolation, and an ambient temperature of -40 °F, the average package temperature will be -40 °F. None of the materials of construction (i.e., thin carbon steel comprising the 55-gallon drum, austenitic stainless steel comprising the pipe component and special form capsules, high-density polyethylene shielding, and cane fiberboard and wood dunnage) undergo a ductile-to-brittle transition at temperatures of -40 °F or higher.

The inner diameter of the shielding insert is 3.5 inches, and the outer diameter of the largest SFC (the Model II) is 3.0 inches. At a temperature of -40 °F, the diameter of the shielding insert would be equal to $3.5(1 - 110 \times 0.0001) = 3.462$ inches, where the differential temperature from an ambient of 70 °F to -40 °F is 110 °F, and the thermal expansion coefficient for HDPE is 0.0001 in/in/°F as stated above. The remaining clearance between the shielding insert and the SFC is $3.462 - 3.0 = 0.462$ inches. Axial clearance of the SFC is greater than one inch.

Therefore, the NCT cold event is of negligible consequence.

2.6.3 Reduced External Pressure

Since containment of radioactive material is afforded by the SFC, and since both the pipe component and the overpack drum are vented, the effect of a reduced external pressure on the S300 package of 3.5 psia, per 10 CFR §71.71(c)(3), is negligible.

2.6.4 Increased External Pressure

Since containment of radioactive material is afforded by the SFC, and since both the pipe component and the overpack drum are vented, the effect of an increased external pressure on the S300 package of 20 psia, per 10 CFR §71.71(c)(4), is negligible.

2.6.5 Vibration

The effects of vibration normally incident to transport have been evaluated by test, both on generic 17C, 55-gallon drums and on three S300 package prototypes.

As documented in the U.S. Department of Energy *Test and Evaluation Document for DOT Specification 7A Type A Packaging*, Appendix D, Table D-24 (reproduced as Figure 2-1), the effects of the vibration test specified in 49 CFR 178.608[4] on three generic 17C drums loaded with sand and lead bricks and weighing between 900 and 1000 lb, were negligible.

Specific testing of three S300 prototype packages was also performed as documented in Appendix 2.12.1, *Type A Testing*. The prototypes were identical in design and manufacture to standard production units. Using a steel bar as a simulated payload, the pipe component and outer drum were closed and fasteners torqued as for shipment. Each package was subjected to testing on a vibrating platform, where the sinusoidal motion had a peak-to-peak displacement of one inch. The packages were not restrained except by passive horizontal barriers at the edges of

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[4] Title 49, Code of Federal Regulations, Part 178, Subpart K, *Specifications for Packagings for Class 7 (Radioactive) Materials*, and Subpart M, *Testing of Non-bulk Packagings and Packages*.

the platform. For a test duration of one hour, each package was vibrated such that a strip of steel having a thickness of 1/16 inch could be passed between the bottom of the package and the test platform. After the tests, the packages were opened and inspected. The test had no observable effect on the drum, the poly liner, shield insert, or pipe component. Only a small amount of dust was generated from sliding wear of the cane fiberboard components. Thus, the effect of vibration normally incident to transport, per 10 CFR §71.71(c)(5), is not of concern for the S300 package.

2.6.6 Water Spray

As documented in the U.S. Department of Energy *Test and Evaluation Document for DOT Specification 7A Type A Packaging*, Appendix D, Table D-24 (reproduced as Figure 2-2), the 17C and 17H 55-gallon steel drums passed the water spray test as specified in 10 CFR §71.71(c)(6) without damage or inleakage of water. The filter used in the drum lid is not capable of passing significant amounts of water. Furthermore, since the drum outer package is made of metal with a sealed and bolted lid, the water spray will have no effect on the materials of the package which could affect any of the subsequent tests. Thus, the effect of water spray is not of concern for the S300 package.

2.6.7 Free Drop

For a package mass less than 11,000 lb, 10 CFR §71.71(c)(7) requires a free drop of the specimen through a distance of four feet onto a flat, essentially unyielding surface. The package should fall in an orientation for which the maximum damage is expected. In determining the worst-case orientation, it is noted that the primary consideration must be the retention of the drum closure lid. The worst-case orientation for closure lid retention will be one for which the deformation at the drum lid closure ring is greatest. Other considerations, such as impact severity, are not governing for a package such as the S300 which has a relatively compliant response and for drops from the comparatively low height of only four feet. Since no significant damage occurs to the internal pipe component as a result of the much more challenging 30 ft HAC free drop, as discussed in Section 2.7.1, *Free Drop*, the pipe component cannot be damaged in the 4 ft NCT free drop.

The worst-case orientation for drum lid closure ring deformation is the center of gravity (CG) over corner, lid down case. This is because the deformation of the package is concentrated in one location at the impact point. Other orientations may be considered as follows. In the top-down orientation (axis vertical), the entire drum lid closure ring would strike the ground at one time, and the deformation would be well distributed. It would thus not be possible to dislodge the drum closure lid in the top-down orientation. In a side-slapdown orientation, some of the kinetic energy would be applied to the primary impact end, and the remainder to the secondary impact end. This division of energy means that the deformation at the drum lid closure ring would be less than in the CG over corner case, where all of the energy is applied in one location. Therefore, the CG over corner orientation is worst-case. The drum lid closure ring joint should be placed at the point of impact, since the ring is not continuous at that point and somewhat more deformation can therefore be expected.

As documented in Appendix 2.12.1, *Type A Testing*, one S300 package was dropped from four feet in two orientations: one center of gravity over corner, and one horizontal. In each case, the drum lid clamping ring bolt was at the point of impact. The test target had a weight well in excess of 10 times the test package. Since the water spray test had no effect as documented above, the free drop test unit was not subject to water spray prior to the free drop test.

From both tests, the damage was bounded by a crush distance of one inch (measured along a line from the theoretical corner of the drum towards the geometric center of the drum.) After testing, the lid remained securely fastened to the drum. There was no effect on the internal shielding or dunnage components, nor any effect on the pipe component. Thus, the effect of the free drop test is not of concern for the S300 package.

2.6.8 Corner Drop

This test does not apply, since the S300 package is a fissile material cylindrical package weighing more than 220 lb, as specified in 10 CFR 71.71(c)(8).

2.6.9 Compression

As documented in the U.S. Department of Energy *Test and Evaluation Document for DOT Specification 7A Type A Packaging*, Appendix D, Table D-24 (reproduced as Figure 2-3), a 17C, 55-gallon drum weighing 1,000 lb was loaded with a weight of 5,525 lb (a weight conservatively much greater than the required 5 times the weight of the actual S300 package which is 5 × 480 = 2,400 lb) for 24 hours. There were no effects on the package, which passed the test. Thus, the effect of the compression test, per 10 CFR §71.71(c)(9), is not of concern for the S300 package.

2.6.10 Penetration

As documented in the U.S. Department of Energy *Test and Evaluation Document for DOT Specification 7A Type A Packaging*, Appendix D, Table D-31 (reproduced as Figure 2-4), 17C and 17H 55-gallon drums, including bung filters, are capable of passing the penetration test specified in 10 CFR §71.71(c)(10) with negligible damage (small dents). Thus, the effect of the penetration test is not of concern for the S300 package.

2.7 Hypothetical Accident Conditions

10 CFR §71.55 requires that packages containing fissile material be evaluated for criticality with the inclusion of any damage resulting from the NCT tests specified in §71.71 plus the damage from the HAC tests specified in §71.73. As demonstrated in Section 2.6, *Normal Conditions of Transport*, the damage from the NCT tests was negligible, and consequently its effects are not included in the HAC considerations below. The following sections describe the response of the S300 package and of the SFC payload to the hypothetical accident conditions. As discussed in Section 2.1.2, *Design Criteria*, the design criteria for HAC are that the S300 package protect the SFC from conditions more severe than those experienced in the special form qualification 30-ft free drop, percussion, and heat tests of the SFC, specified in 10 CFR §71.75.

2.7.1 Free Drop

10 CFR §71.73(c)(1) requires a free drop of the specimen through a distance of 30 ft onto a flat, essentially unyielding surface. A comprehensive series of tests in the worst-case orientations was not performed on the S300 package; however, a conservative prediction of its response may be made as follows.

The effect of the free drop impact on the internal pipe component will be discussed first. The response of the pipe component to various impact orientations is documented in Ammerman, *et al*,[5] which describes drop testing performed during qualification of the pipe overpack container for use in the TRUPACT-II package. The S300 is structurally identical to the pipe overpack container which is the subject of the report. The container was dropped 30 ft in both horizontal and vertical orientations. In the horizontal orientation, the pipe component lid was vertical, and the closure bolts were consequently loaded in shear by the weight of the pipe lid. In the vertical orientation, the pipe component lid was horizontal, and the closure bolts were consequently loaded in tension by the weight of the contents of the pipe and by the pipe lid. These two orientations bound the loading on the pipe component lid. In both cases, the pipe component was leaktight after testing. In the case of the S300, there is no requirement for the pipe component to be leaktight, since special form capsules are transported. Therefore, the pipe component will easily emerge intact from the HAC free drop test.

Next, the response of the S300 drum overpack will be considered. Smith and Gelder[6] report on 30-ft free drop tests of the 6M Specification Package at various impact orientations. The 6M package is a drum package of similar size, weight, and construction to the S300. The weight of the package was 640 lb. The results showed that for the standard clamping ring, total loss of the drum lid could not be ruled out, particularly in the center of gravity over corner and shallow angle orientations. Blanton[7] reports similar results from testing similar drum closures. Consequently, it would be conservative to assume that the S300 drum lid could be lost in the free drop test. In that case, the ejection of the drum contents, including the steel pipe component, might be possible. However, since the drum lid could not be lost until impact, which occurs at essentially zero elevation, the pipe component itself, which is located within a surrounding layer of shock-absorbing cane fiberboard, would not experience any significant damage from the free drop test.

From these considerations, it is concluded that, subsequent to the free drop test, the pipe component may be separated from the S300 outer components, but will remain intact without significant damage. This is a conservative assumption which bounds all other post-drop assumptions in which the package exhibits a greater degree of integrity.

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[5] Ammerman, D. J., Bobbe, J.G., Arviso, M, and Bronowski, D.R., *Testing in Support of Transportation of Residues in the Pipe Overpack Container*, SAND97-0716, Sandia National Laboratories, April 1997.

[6] Smith, Allen C., and Gelder, Lawrence F., *Drop Tests for the 6M Specification Package Closure Investigation*, WSRC-MS-2004-00221, April 30, 2004.

[7] Blanton, P. S., *Responses of Conventional Ring Closures of Drum Type Packages to Regulatory Drop Tests with Application to the 9974/9975 Package*, WSRC-MS-2002-00452, August, 2002.

2.7.2 Crush

10 CFR §71.73(c)(2) requires that the crush test be performed on fissile material packages which have a mass not greater than 1,100 lb and a density not greater than 62.4 lb/ft^3. Because the S300 package has a maximum weight of 480 lb and a volume of 8.13 ft^3 (based on a diameter of 22.6 inches and a height of 35 inches), leading to a maximum density of 480/8.13 = 59 lb/ft^3, the crush test is applicable. The crush test is specified as an impact of a 1,100 lb mass falling from 30 ft, striking a specimen oriented so as to suffer the maximum damage. Since a conservative evaluation of the free drop test concludes that the pipe component may become separated from the S300 package during the free drop test, the crush test must be considered to occur on the pipe component, resting on an unyielding surface. The crush test on the S300 pipe component is evaluated analytically using a dynamic finite element model. The analysis is discussed in detail in Appendix 2.12.2, *HAC Crush Test Evaluation*. The crush plate impacts the pipe component lying on its side, resting on an unyielding surface. Although the pipe bottom end and the adjacent part of the shielding insert are heavily deformed by the impact, the results show that the cavity of the shield does not deform significantly. In fact, the minimum deformed diameter of the shielding insert cavity is 3.38 inches (a reduction of 0.12 inches), which occurs at a location corresponding to the bottom end of the SFC. Since the largest SFC (the Model II) is only 3 inches in diameter, it is clear that the crush test does not cause squeezing or pressure forces to occur on the SFC. Since the SFC was successfully qualified to 10 CFR §71.75(b)(1), which consisted of a bare, 30 ft free drop onto an unyielding surface, it follows that the crush test, in which no impact forces are imparted to the SFC, will not compromise the ability of the SFC to perform its containment function.

Due to the impact of the crush plate with the pipe component, a shear load could be developed in the pipe component lid bolts. While Appendix 2.12.2, *HAC Crush Test Evaluation*, shows that closure bolt failure is unlikely, it may be conservatively assumed that all of the lid bolts shear off, removing the lid, and allowing the SFC to be separated from the pipe component. Of note, this separation occurs only as a consequence of the potential shear of the pipe component lid bolts. Since the potential separation of the SFC from the pipe component could only occur after impact, when the crush plate had essentially come to rest, no significant interactions between the SFC and the crush plate could occur.

2.7.3 Puncture

10 CFR §71.73(c)(3) requires the drop of the package onto a six-inch diameter steel bar from a height of 40 inches. Although the analytical evaluation discussed in Section 2.7.2, *Crush*, showed that the pipe component lid remained intact as a result of the crush plate impact, it is more conservative to assume that the SFC becomes separated from all other parts of the S300 packaging and interacts directly with the puncture bar.

Because the SFC is smaller than the puncture bar, the flat top of the puncture bar presents essentially the same target as the free drop target (i.e., flat and essentially unyielding). However, as required by 10 CFR §71.75, the SFC was dropped onto an essentially unyielding flat surface from a height of 30 ft during special form qualification testing, or nine times as far as in the 40-

inch puncture drop test. Therefore the most conservative puncture bar test scenario is bounded, to a very significant degree, by the special form qualification testing performed on the SFC.

Other, less severe outcomes could result from the free drop, crush, and puncture drop tests. While it is unlikely that the drum could survive all of these tests with its lid fully intact, the SFC could still be retained within the pipe component. The criticality consequences of this scenario, as well as the most conservative case of the release of the SFC from the pipe component, are considered in Chapter 6, *Criticality Evaluation*.

2.7.4 Thermal

10 CFR §71.73(c)(4) requires the exposure of the S300 packaging to a hypothetical fire. The most conservative assumption regarding the initial conditions of the S300 packaging before the fire, as discussed above, is that due to the mechanical tests (free drop, crush, and puncture), the SFC has been separated entirely from the package and is exposed to the fire without any package components to shield it. The thermal evaluation is presented in Section 3.4, *Thermal Evaluation under Hypothetical Accident Conditions*.

2.7.4.1 Summary of Pressures and Temperatures

As shown in Section 3.4.3, *Maximum Temperatures and Pressures*, the effects of an exposure of a bare SFC to the thermal conditions of 10 CFR §71.73(c)(4) is essentially equivalent to the heat test of 10 CFR §71.75(b)(4), in which the capsule is heated to 1,475 °F for 10 minutes. Although the duration of the test is slightly different between the two cases (the test specimen is exposed to the 1,475 °F environment for 30 minutes in §71.73(c)(4), whereas the SFC is heated explicitly to 1,475 °F for 10 minutes in §71.75(b)(4)), the maximum temperature in each case is essentially equal to the fire temperature of 1,475 °F. Since the special form heat test of 10 CFR §71.75(b)(4) was sustained by the tested capsules without loss of leaktight condition, then the SFC will remain leaktight following the HAC thermal test.

The possible retention of the SFC within an intact pipe component during the HAC thermal test is not of concern. In that case, the polyethylene shielding material would begin to decompose due to the elevated temperature. Gases which could form as a result of decomposition would partially escape through the pipe component lid vent, and after decomposition of the lid O-ring dust seal, which would occur shortly after the beginning of the fire, gases could also escape past the lid closure joint. Any pressurization of the pipe component which might occur would be external to the SFC. Since that would drive the tapered sealing plug further into its seat, it would have the tendency to enhance, rather than degrade, the sealing of the capsule.

2.7.5 Immersion – Fissile Material

10 CFR §71.73(c)(5) requires performance of the immersion test for packages containing fissile material. The criticality evaluation presented in Chapter 6.0, *Criticality Evaluation*, assumes optimum hydrogenous moderation of single SFCs and arrays of SFCs, thereby conservatively addressing the effects and consequences of water in-leakage.

2.7.6 Immersion – All Packages

10 CFR §71.73(c)(6) requires performance of an immersion test under a head of water of at least 50 ft. Since the test package may be undamaged, the condition applied to the SFC is merely one of external water pressure. Any effects on the S300 packaging components would be immaterial. The test water pressure of 21.7 psi would have a negligible effect on the relatively small, thick-walled SFC. The direction of pressure would also have the effect of driving the sealing plug deeper into its seat. Therefore, the immersion test is not of concern.

2.7.7 Deep Water Immersion Test

The S300 package is a Type AF package; hence, this requirement does not apply.

2.7.8 Summary of Damage

The discussions of sections 2.7.1, *Free Drop*, through 2.7.7, *Deep Water Immersion Test*, demonstrate that the S300 package in conjunction with the SFC payload prevents release or dispersal of the radioactive contents of the SFC when subjected to all applicable hypothetical accident tests. In particular, the criteria established in Section 2.1.2, *Design Criteria*, namely that the S300 package protect the SFC from conditions more severe than those experienced in the special form qualification 30-ft free drop, percussion, and heat tests of the SFC, were met.

The results of the special form qualification tests are discussed in Section 2.10, *Special Form*. The shielding and criticality control consequences of the separation of the SFC and contents from the rest of the S300 packaging under HAC is discussed in Chapter 5, *Shielding Evaluation*, and Chapter 6, *Criticality Evaluation*.

2.8 Accident Conditions for Air Transport of Plutonium

The S300 will not be transported by air in any airspace which is subject to the laws and regulations of the United States. Therefore, evaluation of the accident conditions specified in 10 CFR §71.74 is not required.

2.9 Accident Conditions for Air Transport of Fissile Material Packages

10 CFR §71.55(f) requires that the package be subcritical subsequent to the application of a series of accident condition tests specifically applicable to the transport of fissile materials by air. The effects of these tests on the S300 have not been specifically evaluated. Instead, for purposes of the criticality evaluation, a worst-case reconfiguration of the package and contents materials is assumed. Under the bounding assumption, all of the materials of the package and of the contents are assumed to reconfigure into a spherical shape. Materials which moderate or reflect neutrons are placed in positions which lead to the greatest reactivity of the system. Materials whose presence reduce system reactivity are removed. The sphere is surrounded by 20 cm of water as required by 10 CFR §71.55(f)(1). Details of the criticality analysis are given in Section 6.7, *Fissile Material Packages for Air Transport*. The S300 package meets the requirements of 10 CFR §71.55(f)(1) and TS-R-1, §680 for the air transport contents stated in Table 1-3.

2.10 Special Form

The radioactive contents of the SFC consist of neutron sources, alpha reference standards, foils (e.g., threshold detectors), and other similar source configurations containing plutonium. The contents are contained within special form capsules of two specific types: Model II and Model III. Each capsule is approved by the U.S. Competent Authority, is of similar design, and differ primarily only in dimensions. The sealing technique is the same for both models.

The Model II SFC, illustrated in Figure 1-3, is fabricated of Type 304 stainless steel, with a nominal wall thickness of almost 1/2 inch, and bottom and top threaded cap thicknesses of 3/4 inch. The contents are located below a snap ring that holds an impact plug in place axially, followed by a tapered sealing plug nominally 3/4 inch thick. The threaded cap is designed with a shearable stem to preclude removal of the cap once installed. The outer length of the closed Model II is 11-3/4 inches (excluding the shearable cap stem), and the outer diameter is three inches. The interior cavity length is 8-3/4 inches, and the interior cavity diameter is 2-1/16 inches. The Model II SFC meets the requirements of 10 CFR §71.75 and is certified by the U.S. Department of Transportation. Manufactured to AEA Technology QSA, Inc. Drawing No. R20047, Rev. B, it carries the IAEA Certificate of Competent Authority Special Form Radioactive Materials Certificate Number USA/0696/S-96.

The Model III SFC, illustrated in Figure 1-4, is fabricated of Type 304 stainless steel, with a nominal wall thickness of 1/2 inch, and bottom and top threaded cap thicknesses of 3/4 inch. The contents are located below a tapered sealing plug nominally 3/4 inch thick. The threaded cap is designed with a shearable stem to preclude removal of the cap once installed. The outer length of the closed Model III is seven inches (excluding the shearable cap stem), and the outer diameter is 2-1/2 inches. The interior cavity length is 4-1/2 inches, and the interior cavity diameter is 1-1/2 inches. The Model III SFC meets the requirements of 10 CFR §71.75 and is certified by the U.S. Department of Transportation. Manufactured to AEA Technology QSA, Inc. Drawing No. R20048, Rev. B, it carries the IAEA Certificate of Competent Authority Special Form Radioactive Materials Certificate Number USA/0695/S-96.

Both capsules are assembled and tested according to written procedures. To ensure proper assembly, each capsule is checked with a gauge that measures how far the tapered plug has been inserted into the capsule body. Measurements of the tapered plug insertion are made both before and after the final tightening and shear-off of the cap stem. These measurements are recorded on the data sheet belonging to each capsule. If the measurements meet the standards established for the capsule design, proper assembly is assured.

2.11 Fuel Rods

The S300 package does not carry fuel rods; hence, this section does not apply.

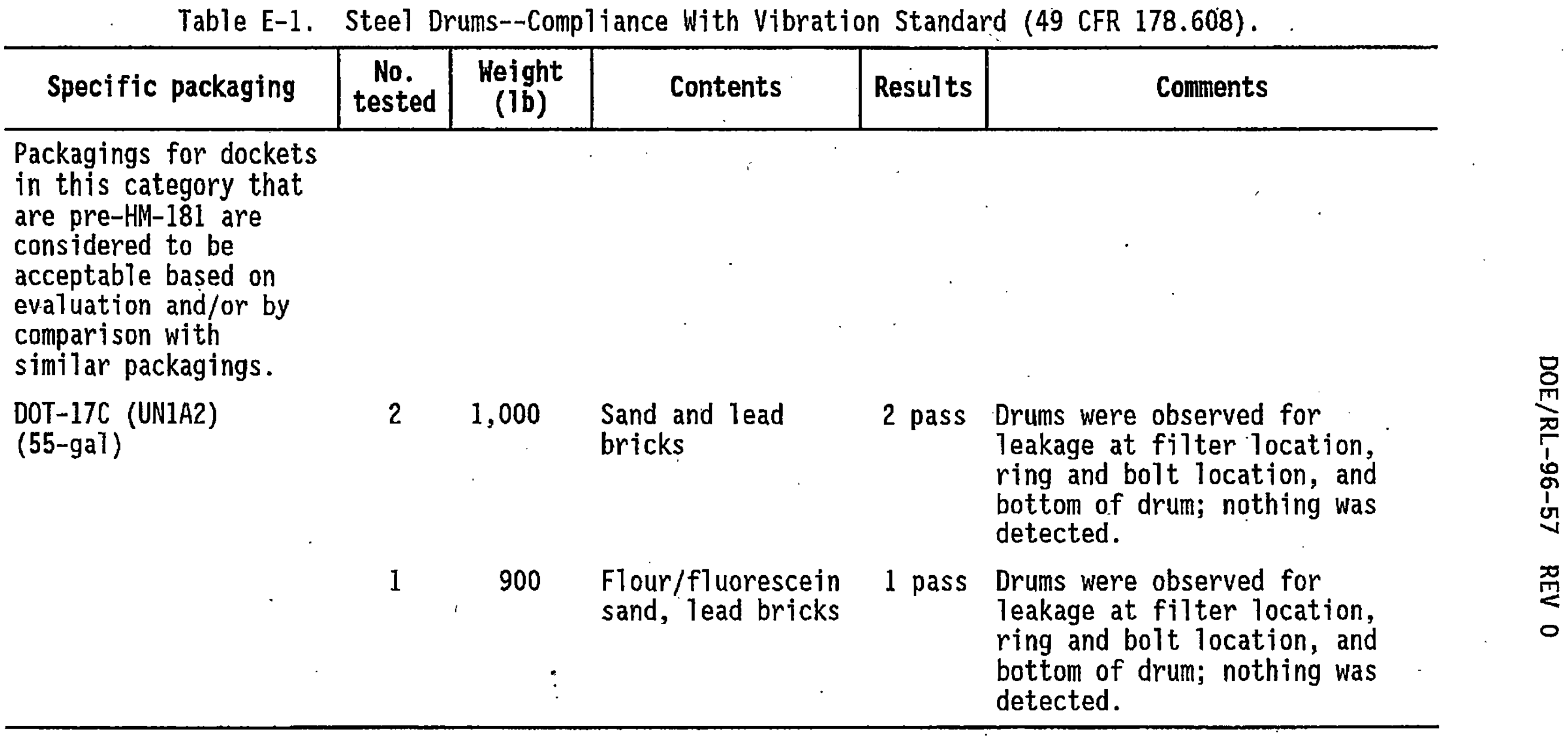

Table E-1. Steel Drums--Compliance With Vibration Standard (49 CFR 178.608).

Specific packaging	No. tested	Weight (lb)	Contents	Results	Comments
Packagings for dockets in this category that are pre-HM-181 are considered to be acceptable based on evaluation and/or by comparison with similar packagings.					
DOT-17C (UN1A2) (55-gal)	2	1,000	Sand and lead bricks	2 pass	Drums were observed for leakage at filter location, ring and bolt location, and bottom of drum; nothing was detected.
	1	900	Flour/fluorescein sand, lead bricks	1 pass	Drums were observed for leakage at filter location, ring and bolt location, and bottom of drum; nothing was detected.

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Figure 2-1 - Vibration Test Results for a DOT-17C Steel Drum
(Table E-1 from U.S. Department of Energy, *Test and Evaluation Document for DOT Specification 7A Type A Packaging*, DOE/RL-96-57, Revision 0)

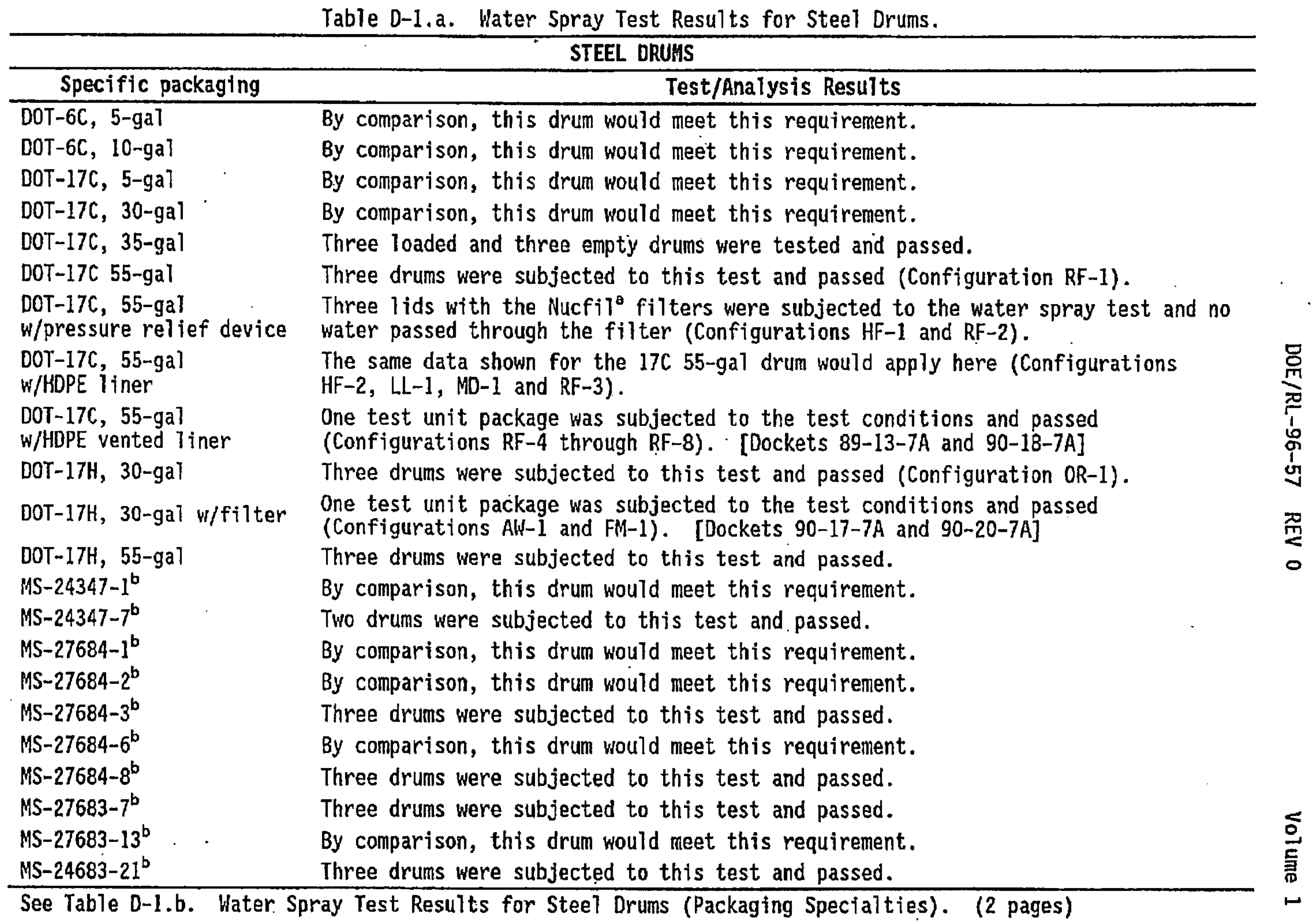

Table D-1.a. Water Spray Test Results for Steel Drums.

STEEL DRUMS	
Specific packaging	Test/Analysis Results
DOT-6C, 5-gal	By comparison, this drum would meet this requirement.
DOT-6C, 10-gal	By comparison, this drum would meet this requirement.
DOT-17C, 5-gal	By comparison, this drum would meet this requirement.
DOT-17C, 30-gal	By comparison, this drum would meet this requirement.
DOT-17C, 35-gal	Three loaded and three empty drums were tested and passed.
DOT-17C 55-gal	Three drums were subjected to this test and passed (Configuration RF-1).
DOT-17C, 55-gal w/pressure relief device	Three lids with the Nucfil® filters were subjected to the water spray test and no water passed through the filter (Configurations HF-1 and RF-2).
DOT-17C, 55-gal w/HDPE liner	The same data shown for the 17C 55-gal drum would apply here (Configurations HF-2, LL-1, MD-1 and RF-3).
DOT-17C, 55-gal w/HDPE vented liner	One test unit package was subjected to the test conditions and passed (Configurations RF-4 through RF-8). [Dockets 89-13-7A and 90-18-7A]
DOT-17H, 30-gal	Three drums were subjected to this test and passed (Configuration OR-1).
DOT-17H, 30-gal w/filter	One test unit package was subjected to the test conditions and passed (Configurations AW-1 and FM-1). [Dockets 90-17-7A and 90-20-7A]
DOT-17H, 55-gal	Three drums were subjected to this test and passed.
MS-24347-1^b	By comparison, this drum would meet this requirement.
MS-24347-7^b	Two drums were subjected to this test and passed.
MS-27684-1^b	By comparison, this drum would meet this requirement.
MS-27684-2^b	By comparison, this drum would meet this requirement.
MS-27684-3^b	Three drums were subjected to this test and passed.
MS-27684-6^b	By comparison, this drum would meet this requirement.
MS-27684-8^b	Three drums were subjected to this test and passed.
MS-27683-7^b	Three drums were subjected to this test and passed.
MS-27683-13^b	By comparison, this drum would meet this requirement.
MS-24683-21^b	Three drums were subjected to this test and passed.

See Table D-1.b. Water Spray Test Results for Steel Drums (Packaging Specialties). (2 pages)

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Figure 2-2 - Water Spray Test Results for a DOT-17C Steel Drum
(Table D-1.a from U.S. Department of Energy, *Test and Evaluation Document for DOT Specification 7A Type A Packaging*, DOE/RL-96-57, Revision 0)

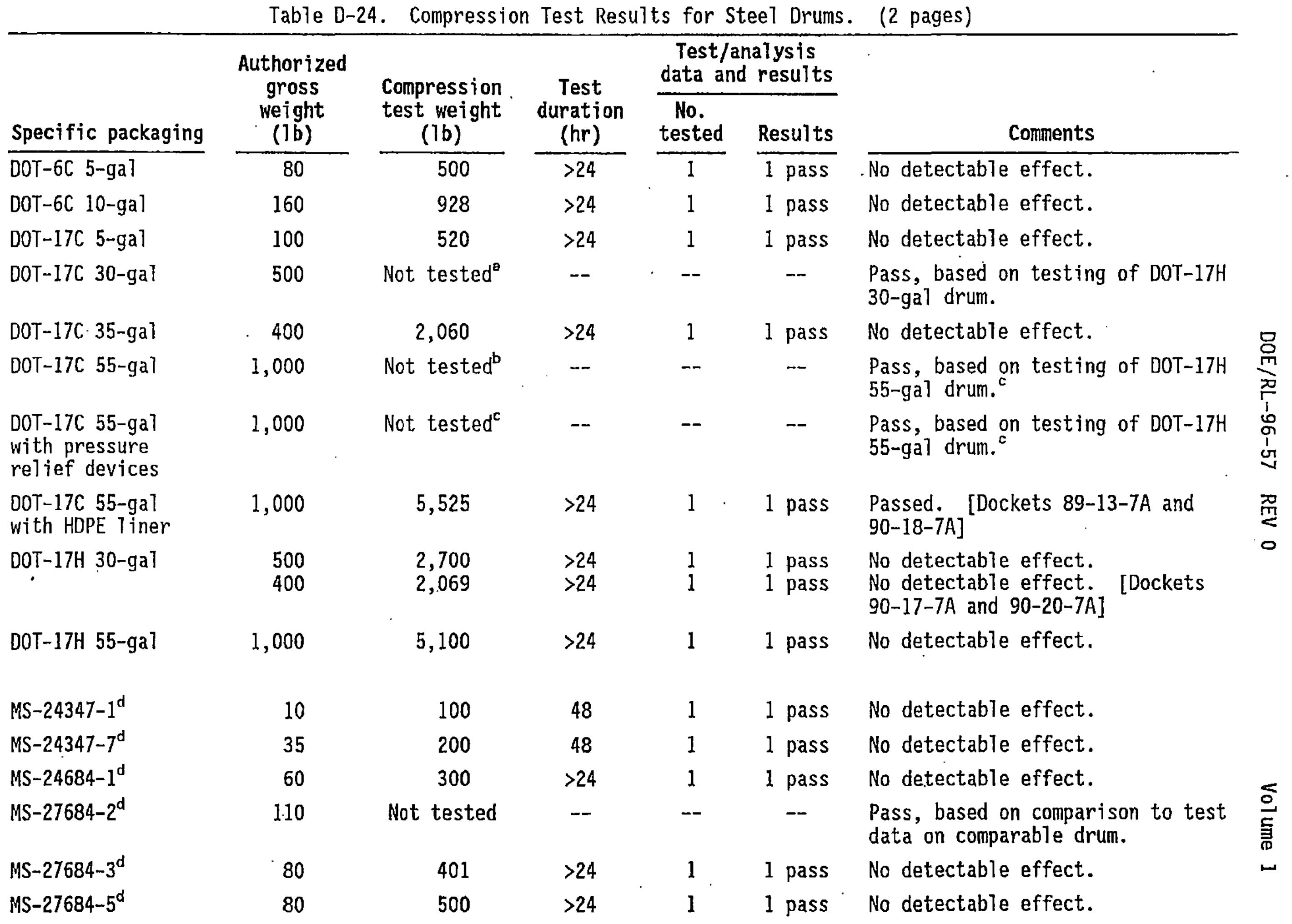

Table D-24. Compression Test Results for Steel Drums. (2 pages)

Specific packaging	Authorized gross weight (lb)	Compression test weight (lb)	Test duration (hr)	Test/analysis data and results		Comments
				No. tested	Results	
DOT-6C 5-gal	80	500	>24	1	1 pass	No detectable effect.
DOT-6C 10-gal	160	928	>24	1	1 pass	No detectable effect.
DOT-17C 5-gal	100	520	>24	1	1 pass	No detectable effect.
DOT-17C 30-gal	500	Not tested[a]	--	--	--	Pass, based on testing of DOT-17H 30-gal drum.
DOT-17C 35-gal	400	2,060	>24	1	1 pass	No detectable effect.
DOT-17C 55-gal	1,000	Not tested[b]	--	--	--	Pass, based on testing of DOT-17H 55-gal drum.[c]
DOT-17C 55-gal with pressure relief devices	1,000	Not tested[c]	--	--	--	Pass, based on testing of DOT-17H 55-gal drum.[c]
DOT-17C 55-gal with HDPE liner	1,000	5,525	>24	1	1 pass	Passed. [Dockets 89-13-7A and 90-18-7A]
DOT-17H 30-gal	500 400	2,700 2,069	>24 >24	1 1	1 pass 1 pass	No detectable effect. No detectable effect. [Dockets 90-17-7A and 90-20-7A]
DOT-17H 55-gal	1,000	5,100	>24	1	1 pass	No detectable effect.
MS-24347-1[d]	10	100	48	1	1 pass	No detectable effect.
MS-24347-7[d]	35	200	48	1	1 pass	No detectable effect.
MS-24684-1[d]	60	300	>24	1	1 pass	No detectable effect.
MS-27684-2[d]	110	Not tested	--	--	--	Pass, based on comparison to test data on comparable drum.
MS-27684-3[d]	80	401	>24	1	1 pass	No detectable effect.
MS-27684-5[d]	80	500	>24	1	1 pass	No detectable effect.

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Figure 2-3 - Compression Test Results for a DOT 17-C Steel Drum
(Table D-24 from U.S. Department of Energy, *Test and Evaluation Document for DOT Specification 7A Type A Packaging*, DOE/RL-96-57, Revision 0)

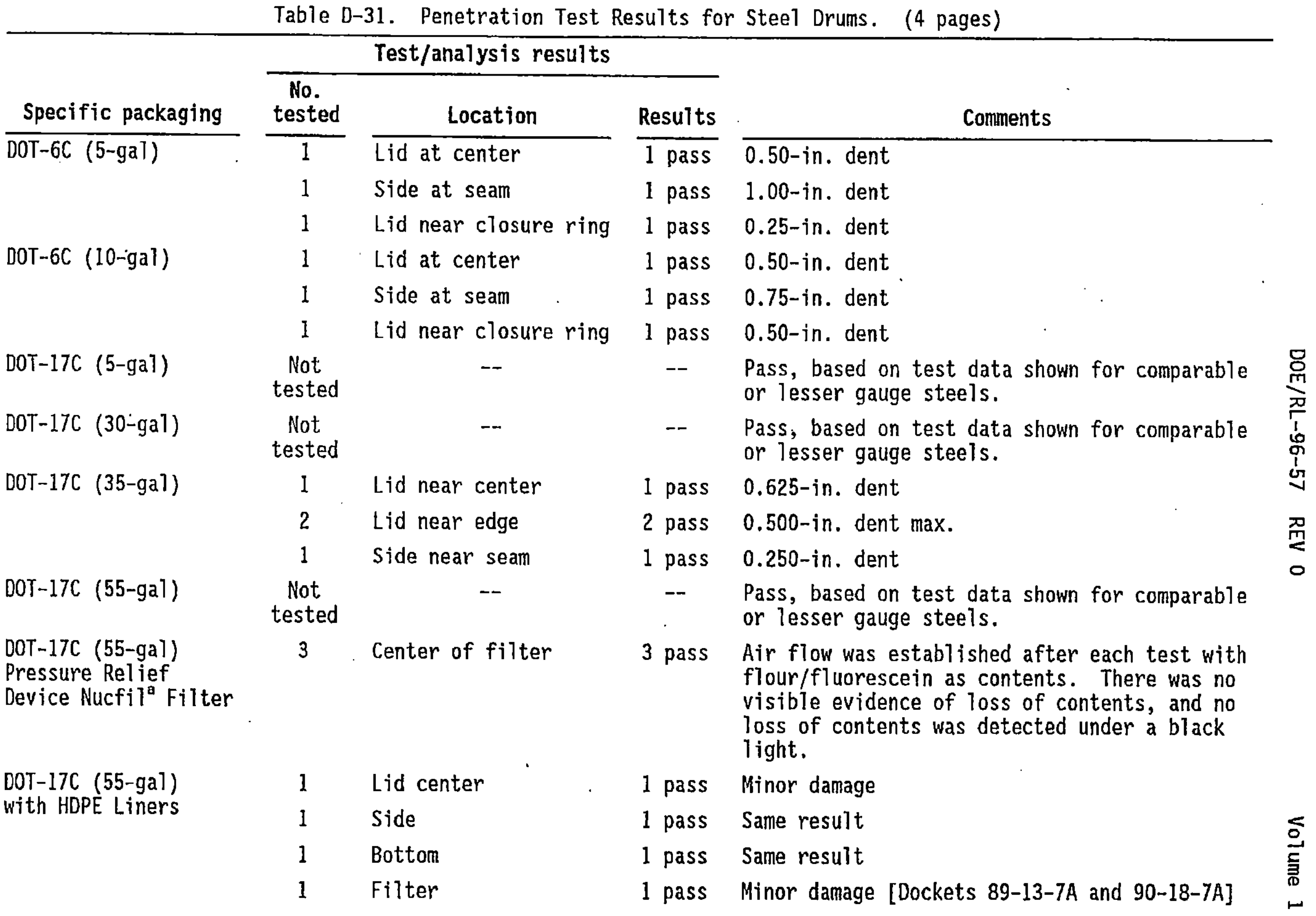

Table D-31. Penetration Test Results for Steel Drums. (4 pages)

Specific packaging	Test/analysis results No. tested	 Location	 Results	Comments
DOT-6C (5-gal)	1	Lid at center	1 pass	0.50-in. dent
	1	Side at seam	1 pass	1.00-in. dent
	1	Lid near closure ring	1 pass	0.25-in. dent
DOT-6C (10-gal)	1	Lid at center	1 pass	0.50-in. dent
	1	Side at seam	1 pass	0.75-in. dent
	1	Lid near closure ring	1 pass	0.50-in. dent
DOT-17C (5-gal)	Not tested	--	--	Pass, based on test data shown for comparable or lesser gauge steels.
DOT-17C (30-gal)	Not tested	--	--	Pass, based on test data shown for comparable or lesser gauge steels.
DOT-17C (35-gal)	1	Lid near center	1 pass	0.625-in. dent
	2	Lid near edge	2 pass	0.500-in. dent max.
	1	Side near seam	1 pass	0.250-in. dent
DOT-17C (55-gal)	Not tested	--	--	Pass, based on test data shown for comparable or lesser gauge steels.
DOT-17C (55-gal) Pressure Relief Device Nucfil[a] Filter	3	Center of filter	3 pass	Air flow was established after each test with flour/fluorescein as contents. There was no visible evidence of loss of contents, and no loss of contents was detected under a black light.
DOT-17C (55-gal) with HDPE Liners	1	Lid center	1 pass	Minor damage
	1	Side	1 pass	Same result
	1	Bottom	1 pass	Same result
	1	Filter	1 pass	Minor damage [Dockets 89-13-7A and 90-18-7A]

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Figure 2-4 - Penetration Test Results for a DOT-17C Steel Drum
(Table D-31 from U.S. Department of Energy, *Test and Evaluation Document for DOT Specification 7A Type A Packaging*, DOE/RL-96-57, Revision 0)

2.12 Appendix

2.12.1 Type A Testing

This appendix will detail testing that was performed on the S300 to qualify it as a DOT Type A package. Both vibration and free drop testing were performed on a S300 prototype in 2002.

Three test units were tested, having the serial numbers and overall weights listed in Table 2.12.1-1 below. Each test unit conformed to the drawings given in Appendix 1.3.1, *Packaging General Arrangement Drawings,* with the exception of the two, two-inch thick shield insert end plugs. Absence of those components would have no material effect on the test results. The payload consisted of a solid steel bar having a diameter of three inches, a length of 11.13 inches, and a weight of 22.5 lb. The steel bar provided an adequate simulation of the SFC, which, when loaded, is essentially solid metal. For testing, the test units were assembled and closed according to the packaging general arrangement drawings.

Table 2.12.1-1 - S300 Test Unit Serial Numbers and Weights

Test Unit Serial No.	Weight, lb
1T	444
2T	448
3T	448

2.12.1.1 Vibration Testing

A vibration test is required to qualify packages as DOT Type A packages, as stated in 49 CFR 173.24a(5): *"Vibration. Each non-bulk package must be capable of withstanding, without rupture or leakage, the vibration test procedure specified in Sec. 178.608 of this subchapter."* The vibration test requirements are found in 49 CFR 178.608. In fulfillment of this requirement, the three units were tested on a vibrating platform.

The vibration test machine was based on a wide flange I-beam, simply supported at each end, with a platform holding the test unit located at its center. A simple pivoting link provided lateral stability. Also mounted on the platform was a variable speed electric motor with a significant imbalance attached. By varying the speed of the motor and the amount of the imbalance, the beam was driven at resonance in a first mode of vibration. The test unit motion was not limited vertically, and was only limited horizontally by passive barriers which kept the unit from falling off of the platform. The amplitude of the motion was measured by tracing the platform motion using a pen attached to the platform against stationary paper. The peak-to-peak amplitude was one inch. The degree of vibration was such that a 1/16-inch thick steel strap could be passed between the test unit and the platform during oscillation, as required by 49 CFR 178.608. The frequency of the machine at resonance was approximately 4 – 5 Hz. The test setup is shown in Figure 2.12.1-1.

Each test was conducted for one full hour after the amplitude and the 1/16-inch bounce requirements were achieved. Upon completion of each test, the drum was moved to the floor and inspected. All tests had identical results. There was no evidence of cracking or other distress of the drum sidewall. The drum lid clamping ring bolt and all of the bolts of the pipe components were still snug. There was no damage to the shield insert components. The only change which occurred was a minor enlargement of the recesses in the upper dunnage. The recesses are provided to clear the bolt heads on the pipe component. No other damage to the upper or lower dunnage was found. This very slight damage could have no effect on the ability of the package to survive any other required tests. Therefore, the S300 passed the vibration testing.

2.12.1.2 Free Drop Testing

A free drop test is required to qualify packages as DOT Type A, as stated in 49 CFR 178.350(a): *"Each packaging must...be designed and constructed so that it meets the requirements of §§173.403, 173.410, 173.412, 173.415, and 173.465 of this subchapter for Type A packaging."* The acceptance criteria is found in 49 CFR 173.412(j): *"When evaluated against the performance requirements of this section and the tests specified in Sec. 173.465 or using any of the methods authorized by Sec. 173.461(a), the packaging will prevent--*

(1) Loss or dispersal of the radioactive contents; and

(2) A significant increase in the radiation levels recorded or calculated at the external surfaces for the condition before the test."

The free drop requirements are found in 49 CFR 173.465. In fulfillment of this requirement, one S300 test unit (serial no. 3TD, see Table 2.12.1-2) was tested using a drop pad having a weight of approximately 50,000 lbs and a steel impact surface. Since the test units weighed just over 500 lbs each, the weight of the drop pad is well in excess of 10 times the test unit weight, and qualifies as an unyielding surface.

The test series consisted of a one-foot drop sequence and a four-foot drop sequence. The one-foot drops were performed an accordance with 49 CFR 173.465(c)(2), since the payload is fissile, and consisted of a drop onto each quarter of each rim in the center-of-gravity (CG) over corner orientation. One of the drops was directly on the clamping ring bolt. The one-foot drops were followed by two, four-foot drops according to 49 CFR 173.465(c)(1). One drop was in the CG over corner orientation, and the second was in the drum axis horizontal orientation. In both cases, the clamping ring bolt was at the point of impact. Each drum was dropped a total of ten times (eight, one-foot, and two, four-foot drops).

Damage to the packages due to the drop testing was very modest, particularly in the case of the one-foot drops, for which damage was negligible. Damage due to the one-foot drops consisted in a small amount of bending of the upper or lower rims, but no deformation occurred in the wall of the drum proper.

The four-foot, CG over corner drops deformed the area of the clamping ring joint by an amount which was less than one inch in each case. Subsequent impact on the side at the same location drove the clamping ring legs in toward the center of the drum, but they still protruded from the side of the drum by at least 3/4 inches. There was also minor damage to the rolling hoops from side impact. However, the clamping rings were still snug to the drum in each case, and the clamping ring bolts were tight after all drops. Damage was modest enough that adequate wrench clearance remained to allow removal of the clamping ring bolt. Inside the drum, all components were in near-new condition. The only evidence of impact was some chips and dust from the cane fiberboard dunnage. The drum wall at the clamping ring bolt location was bent radially inward by approximately 7/8 inch, such that the drum poly liner was trapped in place. The bolts on the pipe component were tight, and there was no damage to the shield insert.

In summary, the drop damage was limited to minor deformations of the drum and lid in the near vicinity of the impact point. Deformations are summarized in Table 2.12.1-2. Photographs of the free drop test results are given in Figure 2.12.1-2 through Figure 2.12.1-7. There could be no loss or dispersal of the payload contents, and any increase in external radiation levels would be negligible. Therefore, the S300 passed the free drop testing.

Table 2.12.1-2 - Free Drop Impact Deformations, inches

Serial No.	Leg	Height
3TD	15/16	3/4

Notes:

1. The serial number for the drop tests is carried over from the vibration testing; thus drop test serial number 3TD is the same package as vibration test unit 3T.
2. The Leg dimension is measured from the original flat extreme top end of the drum to the top edge of the deformed clamping ring at the maximum deformation point, measured parallel to the drum axis, *before* the horizontal drop.
3. The Height dimension is measured from the drum cylindrical wall surface to the outermost protrusion of the bolting components at the clamping ring joint, measured along a radius *after* the horizontal drop.

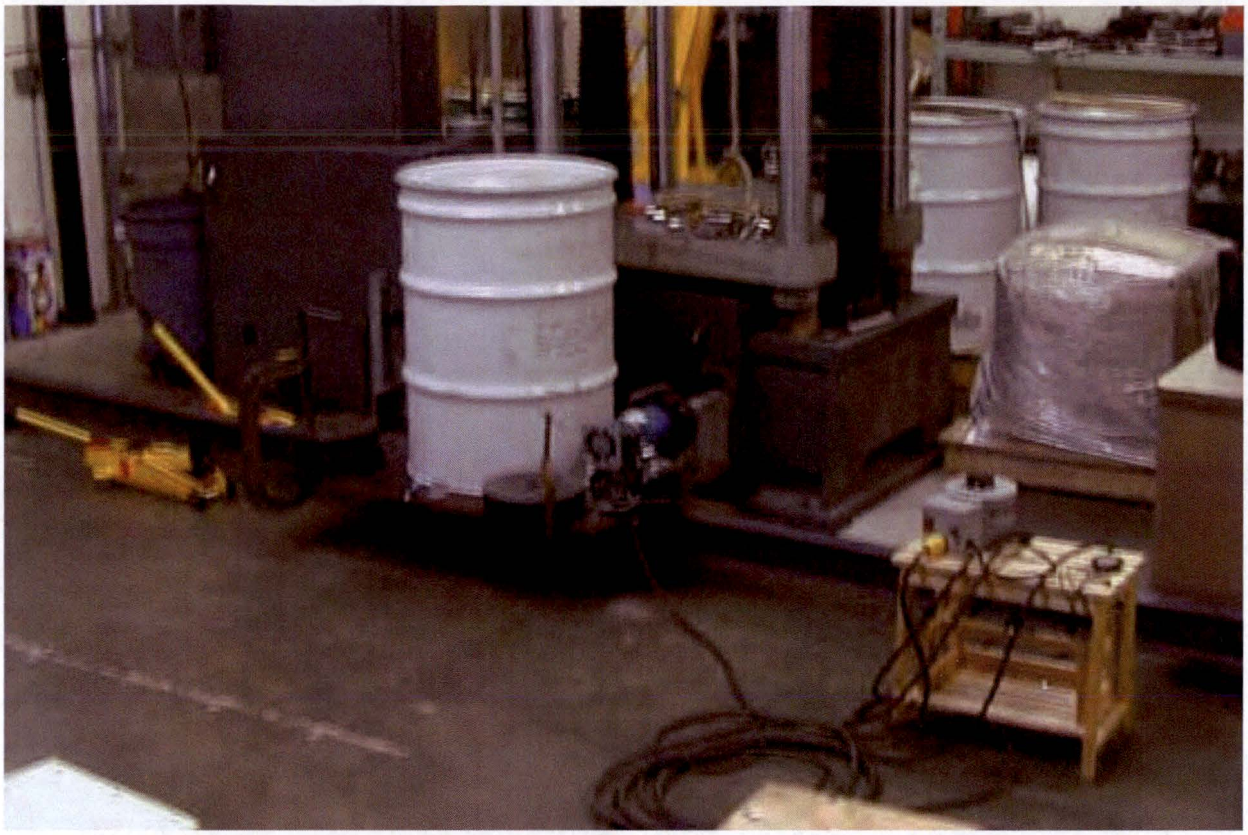

Figure 2.12.1-1 - Vibration Test Setup

Figure 2.12.1-2 - S300 CG over Corner Four-Foot Free Drop

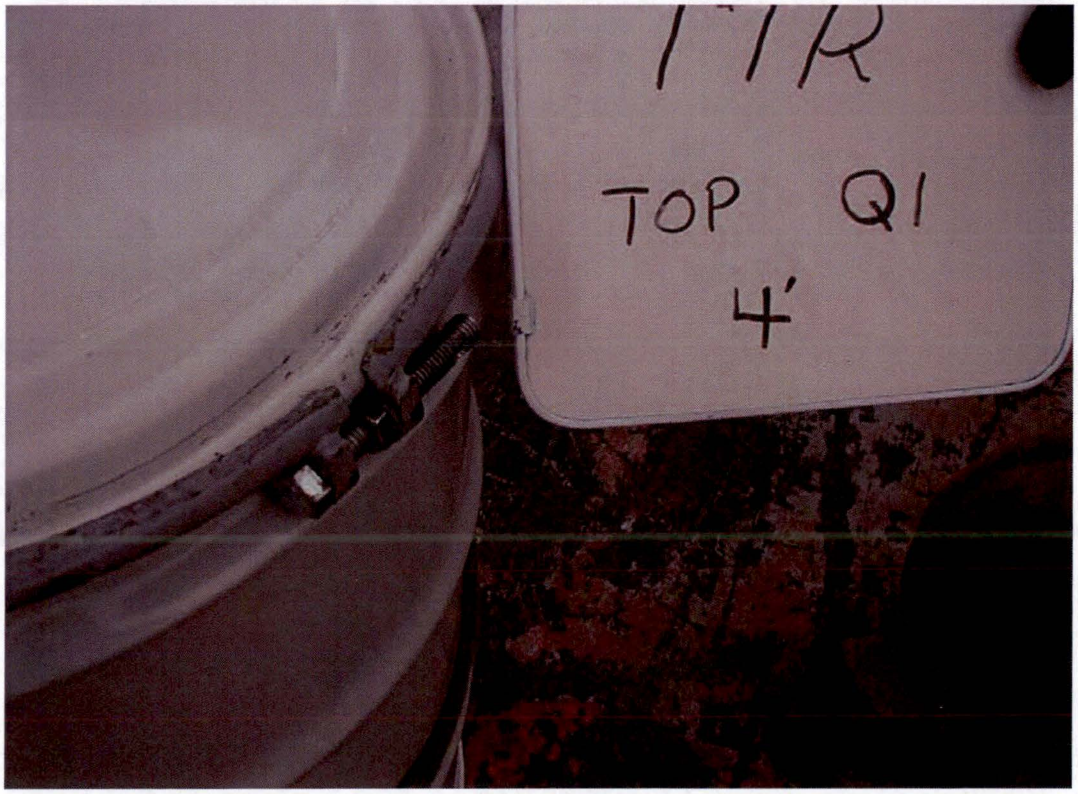

Figure 2.12.1-3 - Damage from CG over Corner Four-Foot Free Drop

Figure 2.12.1-4 - S300 Side Four-Foot Free Drop

Figure 2.12.1-5 - Damage from Side Four-Foot Free Drop

Figure 2.12.1-6 - Lid Removed After All Drops

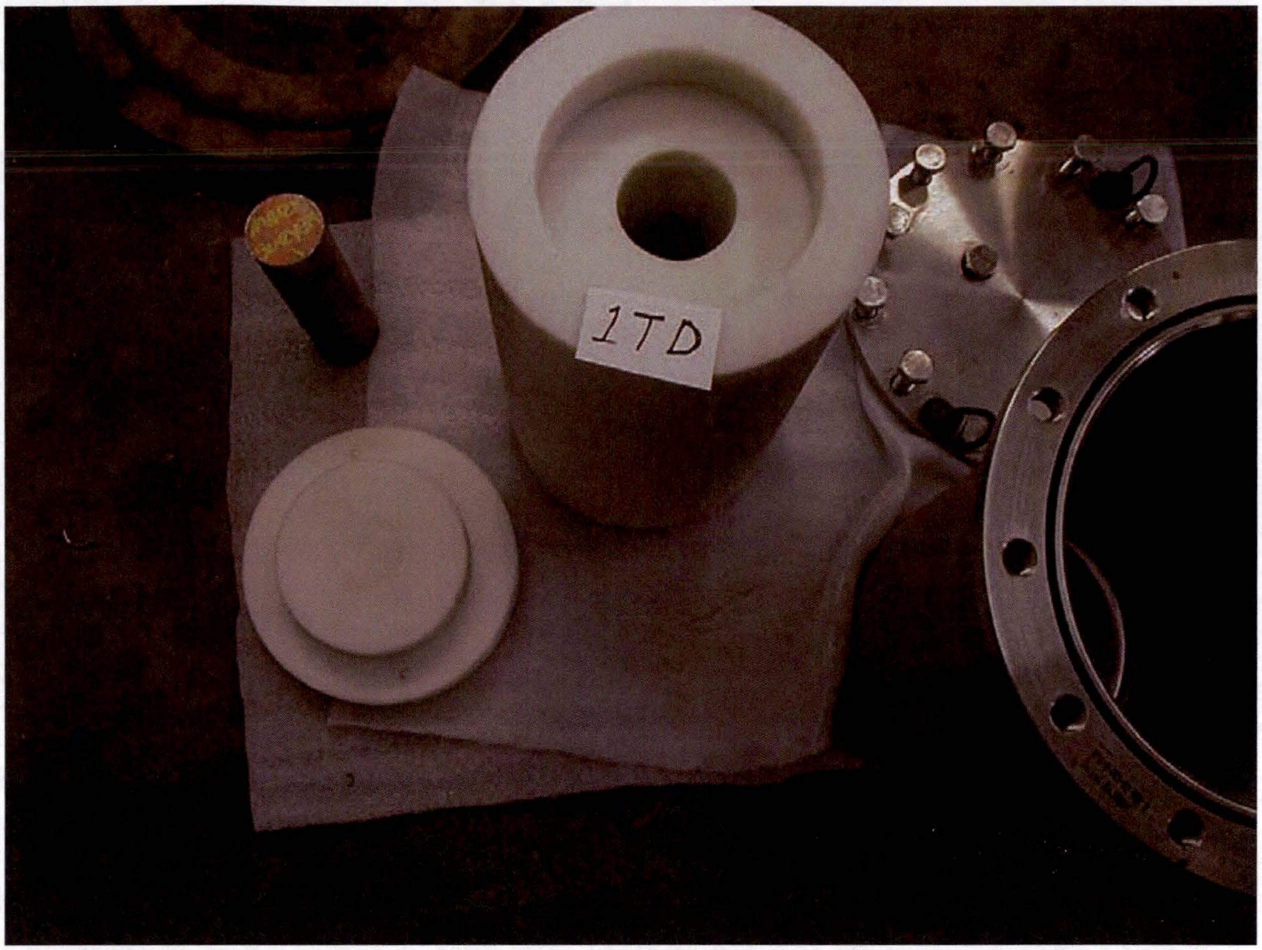

Figure 2.12.1-7 - Pipe Component Internals After All Drops

2.12.2 HAC Crush Test Evaluation

As discussed in Section 2.7.2, *Crush*, a crush test is required for the S300 package. Since a conservative evaluation of the free drop test concludes that the pipe component may become separated from the overpack components (as discussed in Section 2.7.1, *Free Drop*), the crush test will be considered to occur on the pipe component, resting on an unyielding surface. This is a conservative approach to the requirement, since a considerable amount of energy-absorbing structure is neglected, and thus damage to the pipe component or possibly the SFC will be potentially greater.

In this section, the crush test is evaluated using analysis. The SFC has been qualified as special form under the requirements of 10 CFR §71.75, thus it provides a containment function under the severe conditions of a bare, 30-ft free drop (§71.75(b)(1)). This analysis will demonstrate that the impact of a 1,100 lb mass falling from a height of 30 ft, and striking the pipe component so as to suffer the maximum damage, will not impart significant forces to the SFC. Thus, the crush test will not present any conditions that could compromise the containment function of the SFC.

2.12.2.1 Methodology

This analysis uses a half-symmetric FEA model using LS-Dyna (Version LS971S R2) to show that the cavity in the shielding insert for the SFC does not collapse as a result of the crush test, and does not apply any pressure or squeezing forces to the SFC. The dimensional output results of the payload cavity will be used to demonstrate that the cavity remains sufficiently large enough to accommodate the SFC during the crush test.

2.12.2.2 Assumptions

The deformation of the pipe component will be greatest at the maximum temperature. A conservative temperature of 180 °F is used for material properties, which bounds by a significant margin the maximum NCT temperature calculated in Section 3.3, *Thermal Evaluation for Normal Conditions of Transport*. At lower temperatures, the materials will be stronger and more resistant to deformation.

Friction is set to zero, which consequently directs most of the kinetic energy of the falling plate into deformation. A portion of the falling plate energy manifests as kinetic energy as the S300 package accelerates in the horizontal plane. Applying friction to the model will reduce this kinetic energy and the acceleration, but it will also decrease the deformation of the pipe component. Therefore, the frictionless setting results in a more conservative deformation model.

Of the two types of SFC, the larger Model II is used for this analysis, since less overall deformation of the pipe component and shielding insert would be needed to reach and apply load to the Model II SFC.

2.12.2.3 Model Description

The finite element model is shown in Figure 2.12.2-1. The model is constructed according to the drawings in Appendix 1.3.1, *Packaging General Arrangement Drawings*. The payload consists of a single Model II Special Form Capsule (SFC) within the shielding insert. The assembled pipe component rests on an unyielding drop pad. A solid mild steel crush plate is positioned above the pipe component.

The model takes advantage of the symmetrical design to reduce computation time. The model is symmetrically divided along its long axis, with the plane of symmetry perpendicular to the drop pad surface. The mass of each component in the half-symmetric model is one half of the full geometry mass. The masses and weights of the model components are summarized in Table 2.12.2-1.

The model, including the drop pad and crush plate, consists of 12 parts, constructed from six material definitions. Over one million nodes are used to construct over nine hundred thousand solid elements. Constant stress solid elements with hourglass control are defined for all parts. Hourglass control for the solid elements is by the stiffness form of the Type 5 Flanagan-Belytschko method.

Element mesh density throughout the model is balanced to allow observation of the high strain regions of the model without unduly increasing computation time. For example, the pipe component is modeled using 6 to 8 elements through the wall thickness, while the shielding insert uses 13 to 26 elements through the thickness.

The model uses automatic single surface contact control, where every surface can have contact with all adjacent surfaces. As stated above, both static and dynamic friction coefficients are set to zero.

2.12.2.4 Model Loads and Constraints

The initial loads on the simulation model consist of the bolt preload, initial velocity of the crush plate, and force of gravity on all parts. Appropriate displacement constraints are applied to the symmetry plane and rigid drop pad. A bolt preload is applied to represent the 65 ft-lb tightening torque of the lid bolts. The preload is equal to approximately 11,000 psi tensile stress applied to each bolt using the *INITIAL_STRESS_SOLID command with dynamic relaxation.

The initial velocity of the crush plate, established by a free drop through 30 ft, is 527.5 in/s. All parts in the simulation are under a gravitational load of 386.4 in/s^2. The gravitational load is applied to the model using the *DEFINE_CURVE and *LOAD_BODY_Y cards. The plane of symmetry is in the x-y plane through the center of the package along its length. All nodes in this plane are constrained from moving out of this plane. The bottom surface nodes in the drop pad are constrained from all translational and rotational movement. The drop pad is an immovable, rigid object.

2.12.2.5 Material Properties

The S300 Pipe Component is fabricated from Type 304/304L stainless steel, and the shielding insert is fabricated from High Density Polyethylene (HDPE).

2.12.2.5.1 HDPE Material Properties

The temperature dependent material properties for HDPE are based on information from a research document by N. Merah, F. Saghir, Z. Kahn, and A. Bazoune, *Effect of Temperature on Tensile Properties of HDPE Pipe Material*, Plastics, Rubber and Composites, 2006, Vol. 35, No. 5, 226-230. Yield strength vs. temperature and elastic modulus vs. temperature, taken from this document, are plotted in Figure 2.12.2-3 and Figure 2.12.2-4, respectively.

As seen from the trend line in Figure 2.12.2-3, the yield strength is predicted to decrease linearly to a value of approximately 700 psi at 180°F. Conservatively, 500 psi will be used as the true yield strength of the material.

The slope of the curve of elastic modulus in Figure 2.12.2-4 is shown to decrease over the span of the plot indicating a trend to a shallow slope as the temperature approaches 180°F. Only the last two data points in the plot are used to calculate the elastic modulus, which is:

$$E = -277.98(180) + 75{,}922 = 25.9 \text{ ksi}$$

As shown in *Merah*, the stress-strain curves tend to be quite flat after yield with essentially no strain hardening. Therefore, the material model used in the analysis has a tangent modulus of 15.5 psi, which is approximately 0.06% of the elastic modulus. The HDPE properties are summarized in Table 2.12.2-2.

2.12.2.5.2 Steel Material Properties

Since either Type 304 or 304L stainless steel may be used in the construction of the pipe component, the conservative approach is to use the lower allowable values of 304L material. The crush plate is modeled as mild steel. Material properties for the crush plate are taken from A36 steel. Material properties for 304L and A36 are shown in Table 2.12.2-3.

The published density for carbon steel and 300 series stainless steel is given as 0.280 lb/in^3 and 0.290 lb/in^3, respectively. The actual model densities are modified to achieve the component weights listed in Section 2.1.3, *Weights and Centers of Gravity*.

The engineering stress and strain listed in Table 2.12.2-3 are converted to true stress-strain for input in the LS-DYNA material models (the *MAT_PLASTIC_KINEMATIC input card). The true stress and strain values for both yield and ultimate strength are calculated for both steels below.

The common engineering relation between engineering and true strain is:

$$\varepsilon_t = \ln\left(\frac{L}{L_0}\right) = \ln(1+e)$$

where true strain is equivalent to the natural logarithm of the ratio between the strain length (L) and the original length (L_0) and e is the engineering strain. The relationship between engineering and true stress is:

$$S_t = S(1+e)$$

where S_t and S denote the true stress and engineering stress values respectively. Since the modulus of elasticity is calculated from the linear 0.2 percent stress-strain curve to the yield stress value, the engineering yield strain is therefore:

$$e_y = \frac{S_y}{E} + 0.002$$

where S_y and E are the engineering yield stress and modulus of elasticity. The tangent modulus is equivalent to the slope of the plastic region of the true stress-strain curve. Therefore the tangent modulus is calculated from the ratio between the difference of the true ultimate and yield stress and the difference of the true ultimate and yield strain. From these relations, and the values in Table 2.12.2-3, the true yield stress and strain for the two metals are calculated below.

The drop pad is defined as a rigid body (LS-DYNA material card *MAT_RIGID).

304L Stainless Steel

True Yield Strength: $S_{yt} = S_y\left(1+\left(\frac{S_y}{E}+0.002\right)\right) = (21.9)\left(1+\left(\frac{21.9}{27.6e3}+0.002\right)\right) = 22.0 \text{ ksi}$

True Ultimate Strength: $S_{ut} = S_u(1+e_u) = (66.9)(1+0.40) = 93.7 \text{ ksi}$

True Yield Strain: $\varepsilon_{yt} = \ln(1+e_y) = \ln\left(1+\left(\frac{21.9}{27.6e3}+0.002\right)\right) = 0.00279$

True Ultimate Strain: $\varepsilon_{ut} = \ln(1+e_u) = \ln(1+0.40) = 0.336$

Tangent Modulus: $E_{tan} = \frac{S_{ut}-S_{yt}}{\varepsilon_{ut}-\varepsilon_{yt}} = \frac{93.7-22.0}{0.336-0.00279} = 215 \text{ ksi}$

A36 Carbon Steel:

True Yield Strength: $S_{yt} = S_y\left(1+\left(\frac{S_y}{E}+0.002\right)\right) = (33.3)\left(1+\left(\frac{33.3}{28.9e3}+0.002\right)\right) = 33.4 \text{ ksi}$

True Ultimate Strength: $S_{ut} = S_u(1+e_u) = (58.0)(1+0.23) = 71.3 \text{ ksi}$

True Yield Strain: $\varepsilon_{yt} = \ln(1+e_y) = \ln\left(1+\left(\frac{33.3}{28.9e3}+0.002\right)\right) = 0.00315$

True Ultimate Strain: $\varepsilon_{ut} = \ln(1+e_u) = \ln(1+0.230) = 0.207$

Tangent Modulus: $E_{tan} = \frac{S_{ut}-S_{yt}}{\varepsilon_{ut}-\varepsilon_{yt}} = \frac{71.3-33.4}{0.207-0.00315} = 186 \text{ ksi}$

2.12.2.6 Results

The LS-DYNA simulation ran continuously for approximately 18 hours. For the 24 millisecond simulation, there were 50 distinct time steps recorded at an average interval of 0.5 milliseconds.

Figure 2.12.2-5 shows the time step for maximum crush of the package. The plastic deformation of the crush plate was negligible, thus virtually all of the energy went into the pipe component and shielding insert. Figure 2.12.2-6 shows the maximum bolt strain. Figure 2.12.2-7 shows the payload cavity during the crushing event. Table 2.12.2-4 and Figure 2.12.2-8 through Figure 2.12.2-13 illustrate the time-based changes in the diameter. Figure 2.12.2-9, Figure 2.12.2-11, and Figure 2.12.2-13 show the deformation at the time point of minimum diameter.

The maximum effective strain on the lid bolts of 0.3628 in/in is found in the lowest bolt pictured in Figure 2.12.2-5. This value is approximately equal to the true ultimate strain of the stainless steel used in for the bolts. The next highest bolt strain is found in the top bolt pictured in Figure 2.12.2-5, having a maximum effective plastic strain of 0.2044 in/in, which is well below the true ultimate strain of the material. Therefore, loss of more than one lid bolt during the crush test is unlikely, and the lid remains part of the structural load path absorbing some of the energy of the crush plate. The peak effective strain of the worst-case bolt shown in Figure 2.12.2-6.

The analysis shows that the central payload cavity resists collapsing in on the SFC. The pipe body and end plate show noticeable deformation from the crush plate, but do not fail. The pipe flange, lid and lid bolts survive the impact event intact, retaining the shielding insert and SFC within the package.

The load transmitted to the HDPE shielding material is insufficient to collapse the payload cavity, and a gap between the cavity and the SFC is maintained at all times. The gap is monitored at each end and at the middle of the SFC throughout the event. The initial nominal clearance between the cavity and the SFC is 0.5 inches. The minimum clearance is 0.38 inches. Therefore, the SFC is protected by the S300 packaging from the direct effects of the crush load.

Local permanent increase in the payload cavity is also seen to occur, for example, in Figure 2.12.2-7. This results from "rattling" contact between the SFC and the relatively soft shielding insert cavity during the crush plate impact event.

The S300 model energy is shown in Figure 2.12.2-14. The energy in the model behaves much as the energy in the benchmark model as shown in Figure 2.12.2-16. The energy of the system is 198,669 lb-in due to the kinetic energy of the crush plate. The final kinetic and potential energy of the system is 16,800 in-lb and 179,484 in-lb, respectively, for a total system energy of 196,284 lb-in. The 2,385 lb-in of energy lost represents approximately 1 percent of the total energy, similar to the results of the benchmark model in Section 2.12.2.8, *Benchmark Model*.

2.12.2.7 Conclusions

As shown in Section 2.12.2.6, *Results*, the payload cavity does not collapse onto the SFC payload. Since compression of the SFC by deformation of the shielding insert does not occur, the crush test cannot compromise the containment integrity of the SFC.

2.12.2.8 Benchmark Model

A benchmark simulation was performed to assess the relative performance of the specimen material (HDPE) within the bounds of the problem set. To do this, a simplified crush model with similar characteristics to the S300 crush test was created. The plastic deformation and global energy profile of the model were recorded for comparison to the S300 simulation model.

2.12.2.8.1 Simplified Crush Model

The benchmark model represents a simplified version of the crush model used in the analysis of the S300 and is shown in Figure 2.12.2-15. A quarter symmetric model of a solid bar of HDPE material is crushed between a mild steel crush plate and a rigid steel plate representing an unyielding surface. The crush plate has the initial velocity of a 30 ft drop. A gravitational body acceleration of 386.4 in/sec^2 is applied to the model. In its reduced symmetry form, the dimensions of the test specimen are 10.0 in x 10.0 in x 10.0 in.

The mesh is similar to that used in the S300 calculation. The model consists of the crush plate, test specimen, and drop pad. The only energy term in the initial state of the model is the kinetic energy of the plate. The material properties, element material representation, hourglass control, friction, and contact definitions are all the same as the main S300 crush model.

2.12.2.8.2 Results

During the simulation, the kinetic energy of the plate is transferred to the test specimen as internal energy. Energy used to cause elastic strain is available to return to the system as kinetic energy. The remaining energy will be absorbed by the HDPE due to plastic strain. The exchange of energy in the model is shown in Figure 2.12.2-16.

Inspection of the global energy curves of the model initially shows a decrease in kinetic energy proportional to the increase in potential energy. The final portion of the simulation demonstrates a proportional relation as well, but with only a small increase in kinetic energy and a small decrease in potential energy. The total energy of the system remains nearly constant, with some minor loss (approximately 1%) as expected due to hourglass effects or computational error due to single precision floating point calculations.

The initial kinetic energy of the system is 99,000 lb-in due to the crush plate. The final kinetic and potential energy of the system are 4,892 lb-in and 93,181 lb-in, respectively, for total system energy of 98,073 lb-in. The 927 lb-in of energy lost represents a negligible 1 percent of the total energy.

2.12.2.8.3 Deformation

Figure 2.12.2-17 shows the center maximum deformation of the test specimen. The deformation of the test specimen due to the crushing load is due to both plastic and elastic deformation (strain.) Given the shape of the simplified model, the stress and strain can be assumed to be nearly uniform over the test specimen.

Using the center thickness as a basis of measurement the average strain for the package is (see Figure 2.12.2-17):

$$\varepsilon = \frac{L_0 - L}{L_0} = 0.1804 \text{ in/in}$$

where L = 8.1961 inches is the maximum deformation and L_0 = 10.0 inches is the initial length of the span. The average strain exceeds the yield strain by a large margin; therefore the strain is primarily plastic. Deformation in the HDPE for a given crush test should be expected to be permanent in nature.

From the final time step the average plastic strain for the package is (see Figure 2.12.2-18):

$$\varepsilon = \frac{L_0 - L}{L_0} = 0.1632 \text{ in/in}$$

where $L = 8.3681$ is the maximum deformation and $L_0 = 10.0$ is the initial length of the span. Thus, the benchmark model provides reasonable assurance that the results of the crush analysis of the S300 pipe component are accurate.

Table 2.12.2-1 Model Weight Summary

Component	Part ID	Part Mass, $lb\text{-}s^2/in$	Full Geometry Weight, lb	Target Weight,* lb	Diff. (%)
Special Form Capsule	1	0.0388302	30.008	30	+0.027
Pipe Component (empty)			180.056	180	+0.031
	2	0.1010420	78.085		
	3	0.0303894	23.485		
	4	0.0777609	60.094		
	5	0.0160645	12.415		
	6	0.00773467	5.977		
Shielding insert			90.137	90	+0.152
	11	0.1005960	77.741		
	12	0.0143962	11.125		
	13	0.000822243	0.635		
	14	0.000822243	0.635		
Drop Pad	15	49.6916	38,401.7		
Crush Plate	16	1.42817	1,103.7	1,100	+0.34

* Target weight taken from Table 2-1.

Table 2.12.2-2 Material Properties for HDPE at 180°F

Property	HDPE
Elastic Modulus (psi)	25,900
True Yield Stress (psi)	500
Poisson's Ratio	0.46
Density (lb/in^3)	0.035
Tangent Modulus (psi)	15.5

Table 2.12.2-3 Material Properties for Steel at 180°F

Property	304L	A36
Elastic Modulus[1] (psi)	27.6(10^6)	28.9(10^6)
Engineering Ultimate Stress[2] (psi)	66.9(10^3)	58.0(10^3)
Engineering Yield Stress[3] (psi)	21.9(10^3)	33.3(10^3)
Total Elongation[4]	0.40	0.23
Poisson's Ratio[5]	0.31	0.30
Density[5] (lb/in^3)	0.290	0.280

Notes:

1. ASME B&PV Code, Section II, Part D, Table TM-1, Material Group G (Note 7) and Carbon Steel (C[0.30%). Linearly interpolated from values for 70°F and 200°F.
2. ASME B&PV Code, Section II, Part D, Table U. Linearly interpolated from values for 100°F and 200°F.
3. ASME B&PV Code, Section II, Part D, Table Y-1. Linearly interpolated from values for 150°F and 200°F.
4. ASME B&PV Code, Section II, Part A.
5. ASME B&PV Code, Section II, Part D, Table PR

Table 2.12.2-4 Payload Cavity Deformation Summary

SFC Location Description	Nodes	Minimum Dia. (in)	Remaining Margin (in)
Bottom	933351 - 997977	3.3802	0.3802
Middle	933373 - 997999	3.4438	0.4438
Top	933394 - 998020	3.4106	0.4106

Note: The Model II SFC is 3.0 inches in diameter.

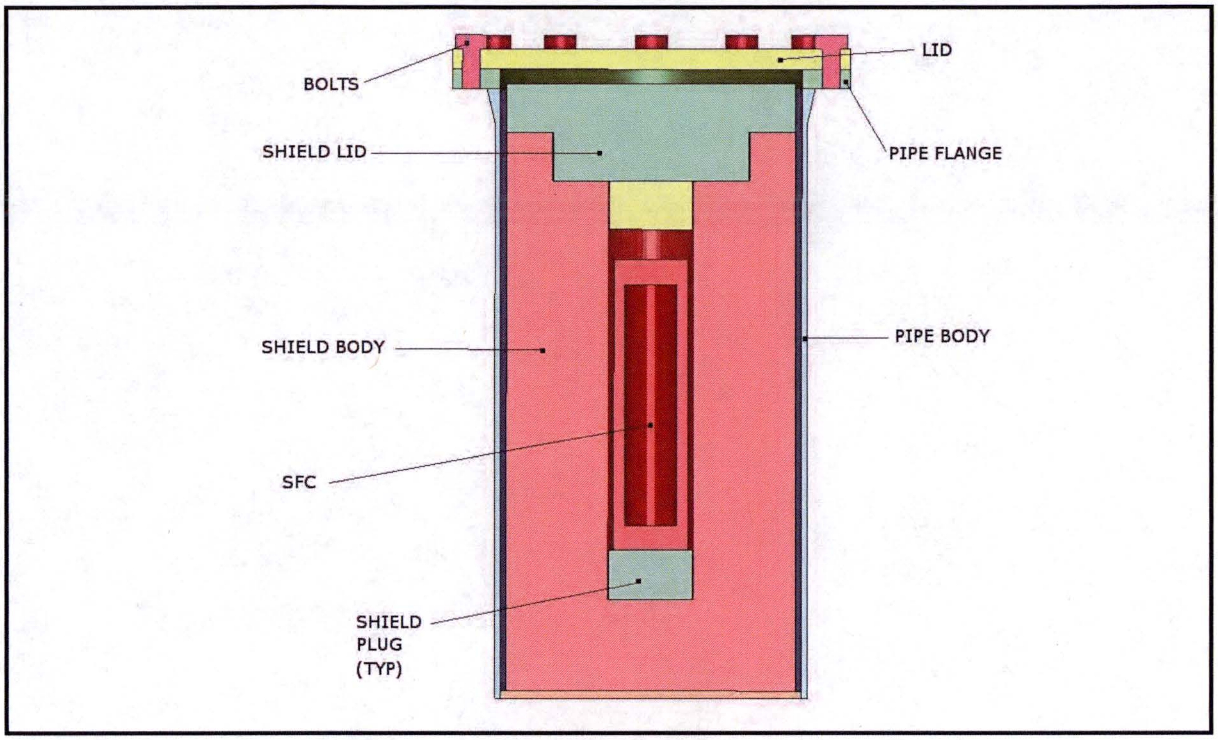

Figure 2.12.2-1 – S300 Pipe Component

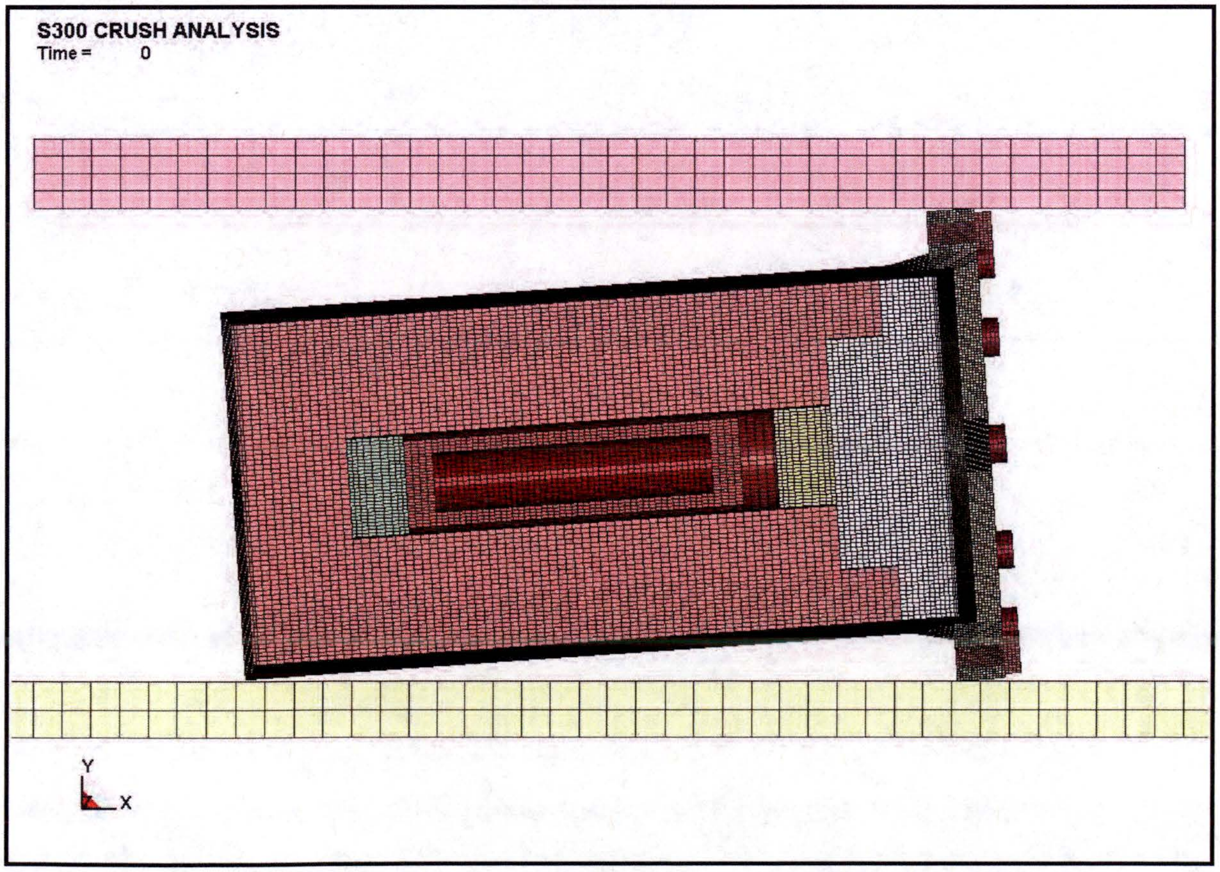

Figure 2.12.2-2 – S300 Crush Test Finite Element Model Mesh

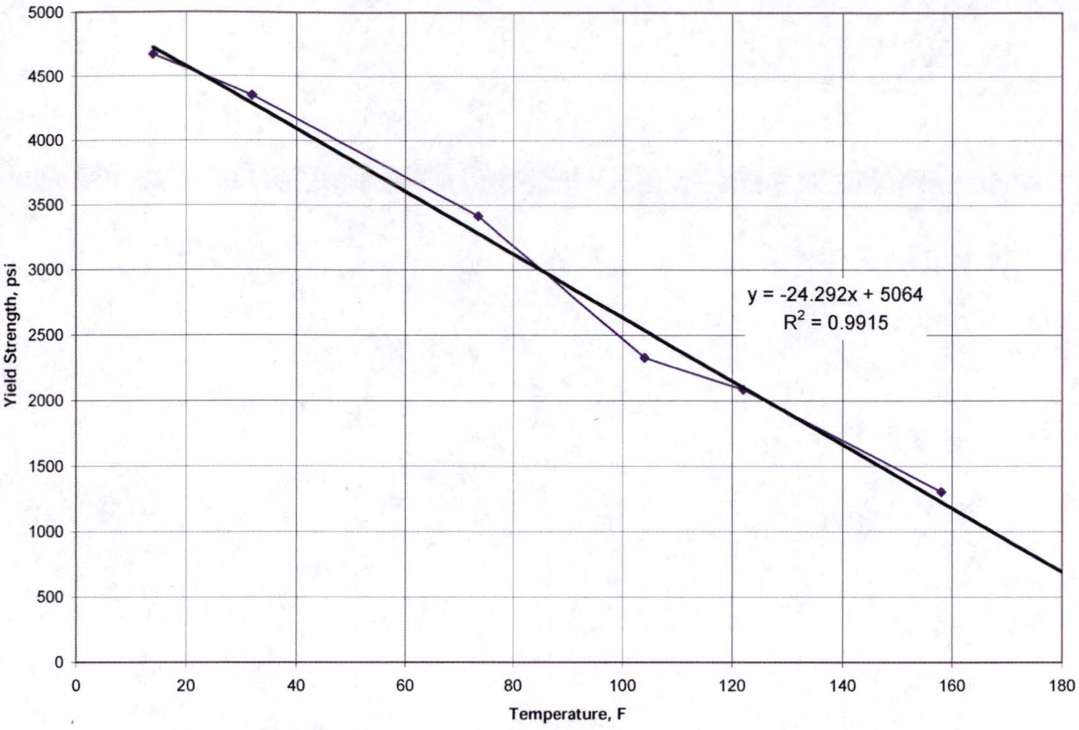

Figure 2.12.2-3 – HDPE Yield Strength vs. Temperature

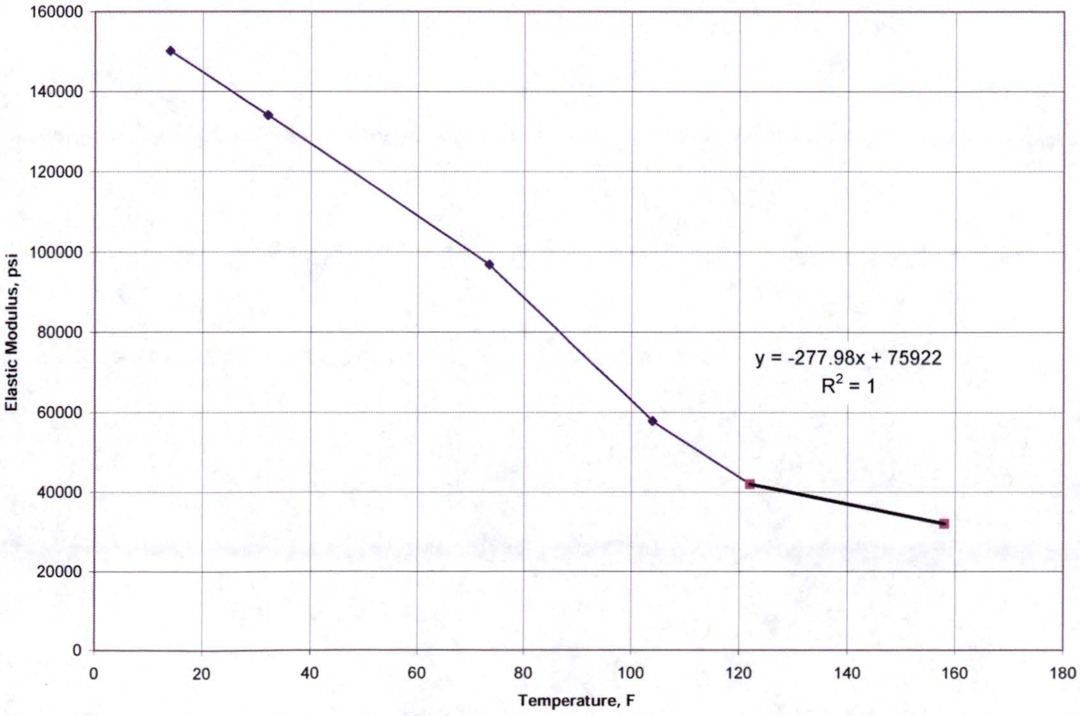

Figure 2.12.2-4 – HDPE Elastic Modulus vs. Temperature

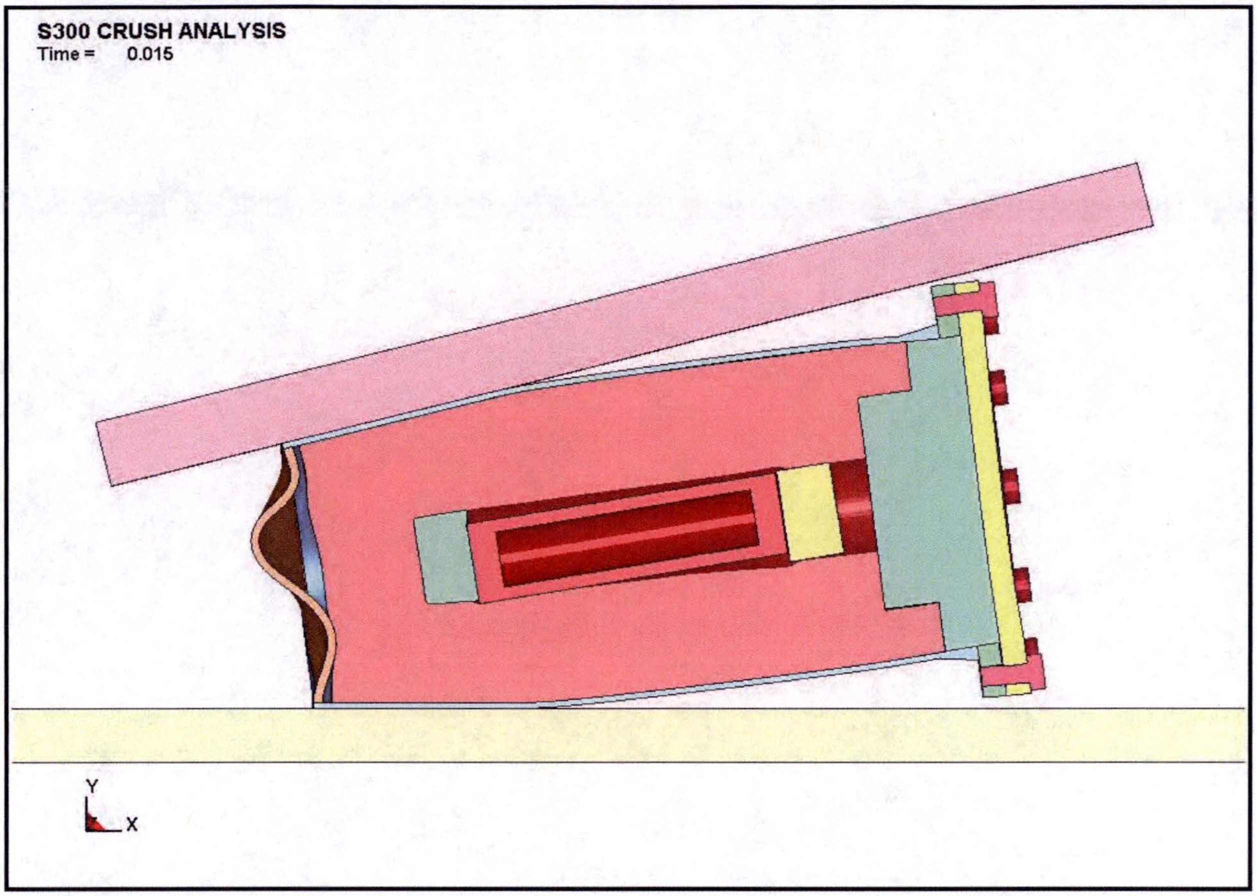

Figure 2.12.2-5 – S300 Pipe Assembly Under Crushing Load

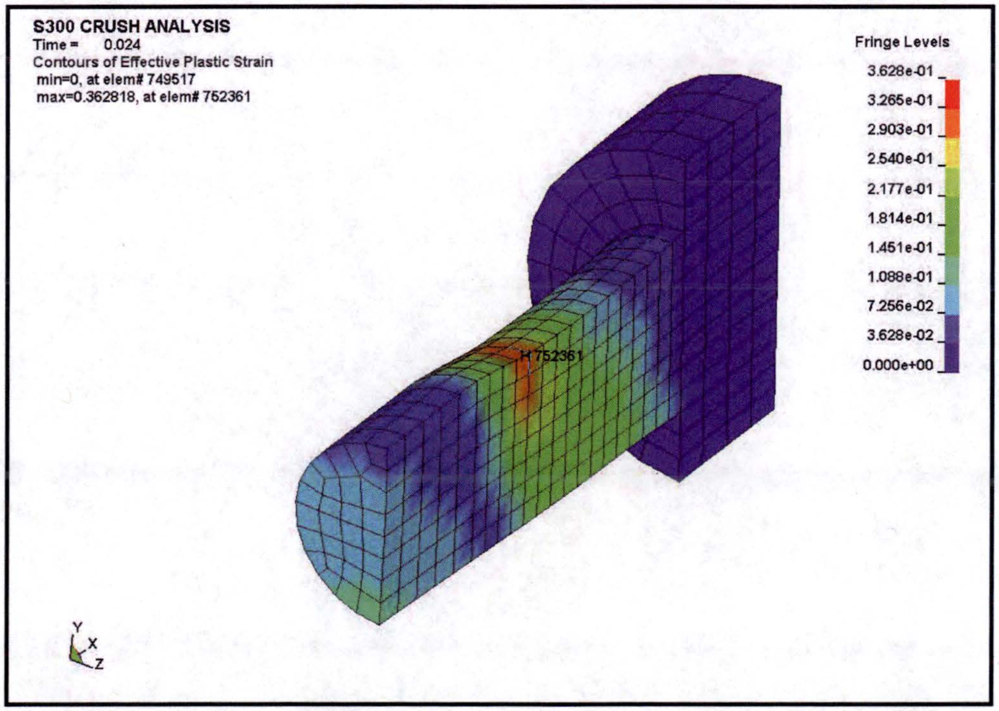

Figure 2.12.2-6 – Maximum Effective Strain of Lid Bolts

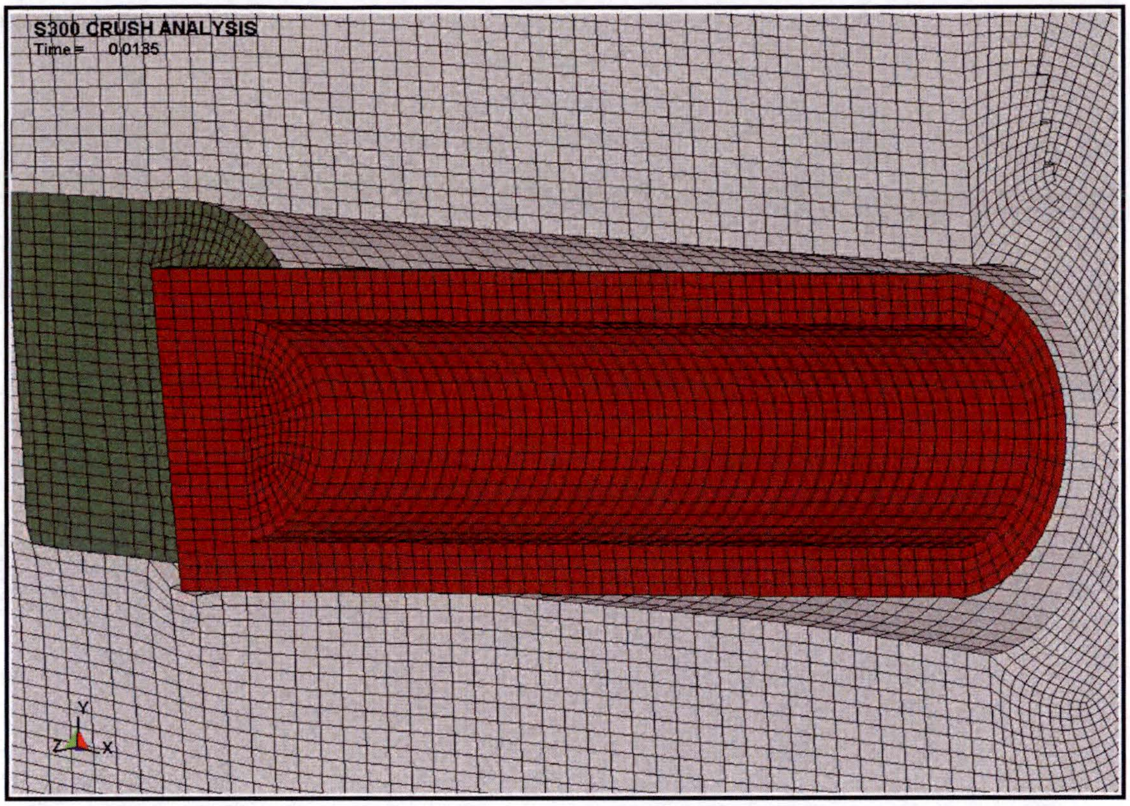

Figure 2.12.2-7 – Cutaway View of Payload Cavity

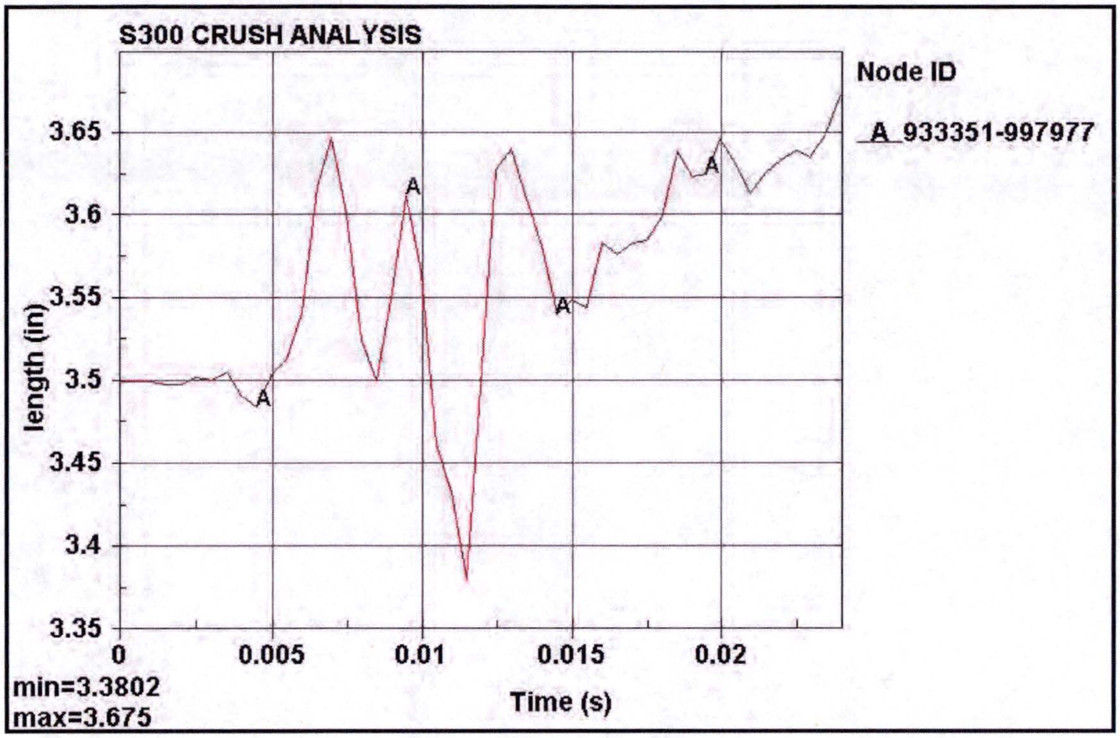

Figure 2.12.2-8 – Payload Cavity Bottom Diameter

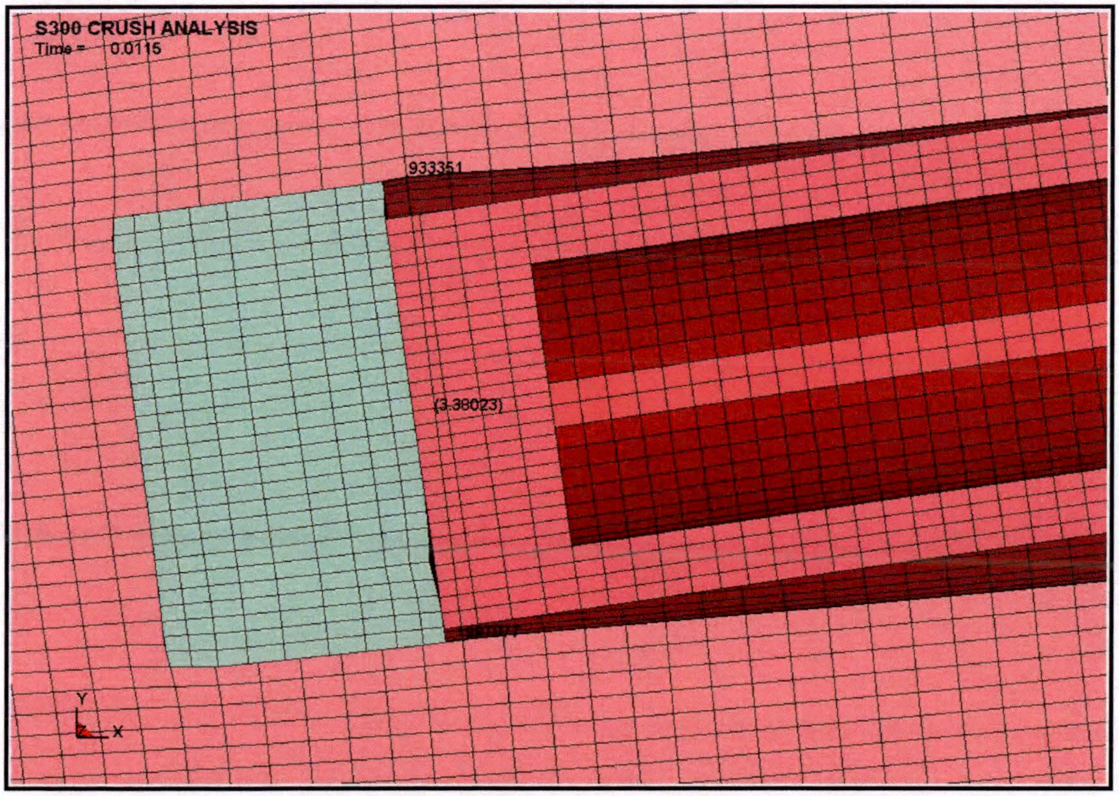

Figure 2.12.2-9 – Payload Cavity Bottom Deformation

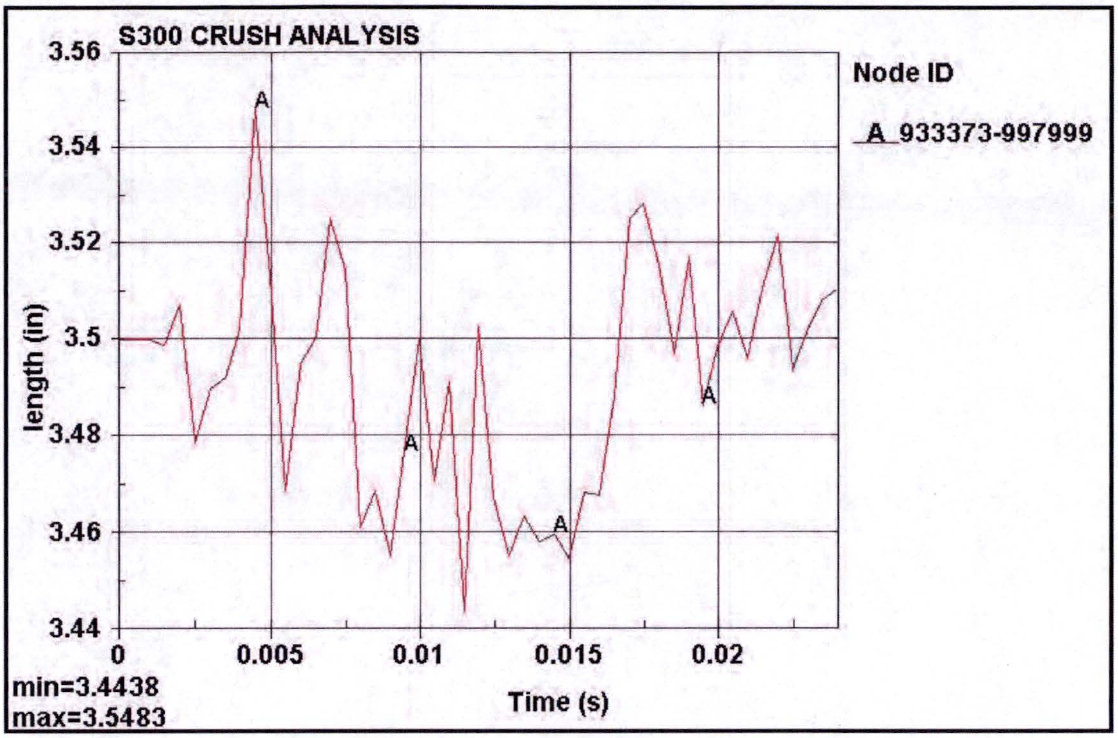

Figure 2.12.2-10 – Payload Cavity Middle Diameter

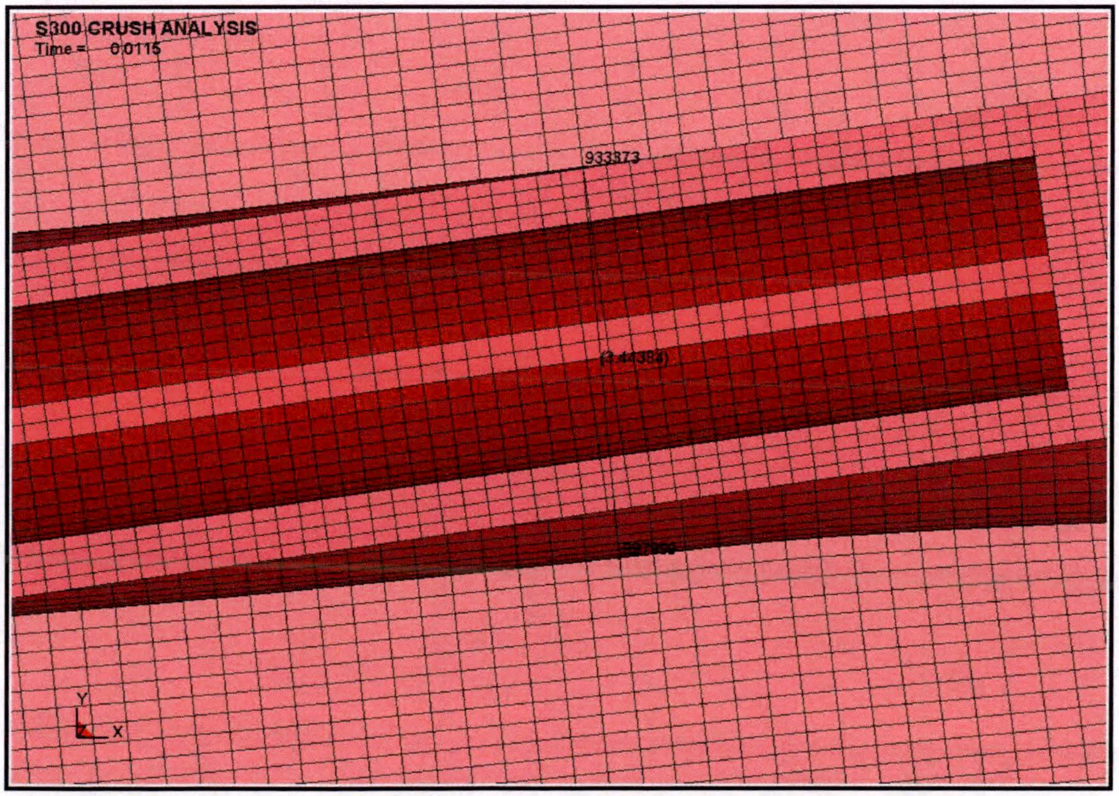

Figure 2.12.2-11 – Payload Cavity Middle Deformation

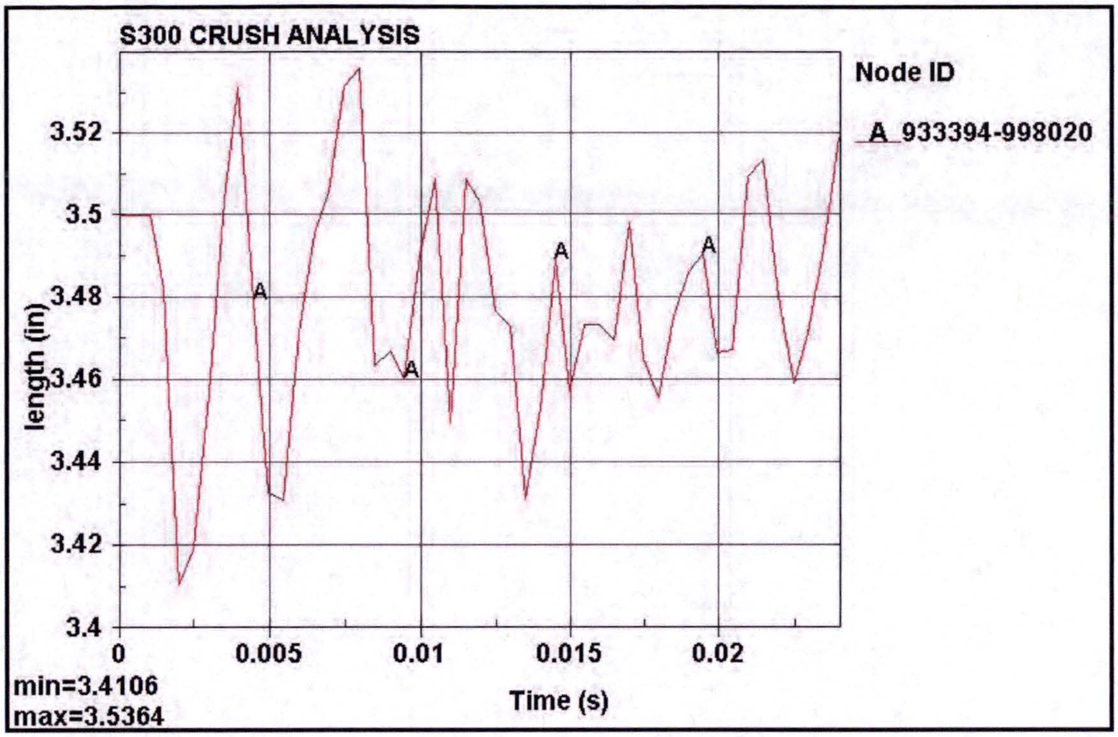

Figure 2.12.2-12 – Payload Cavity Top Diameter

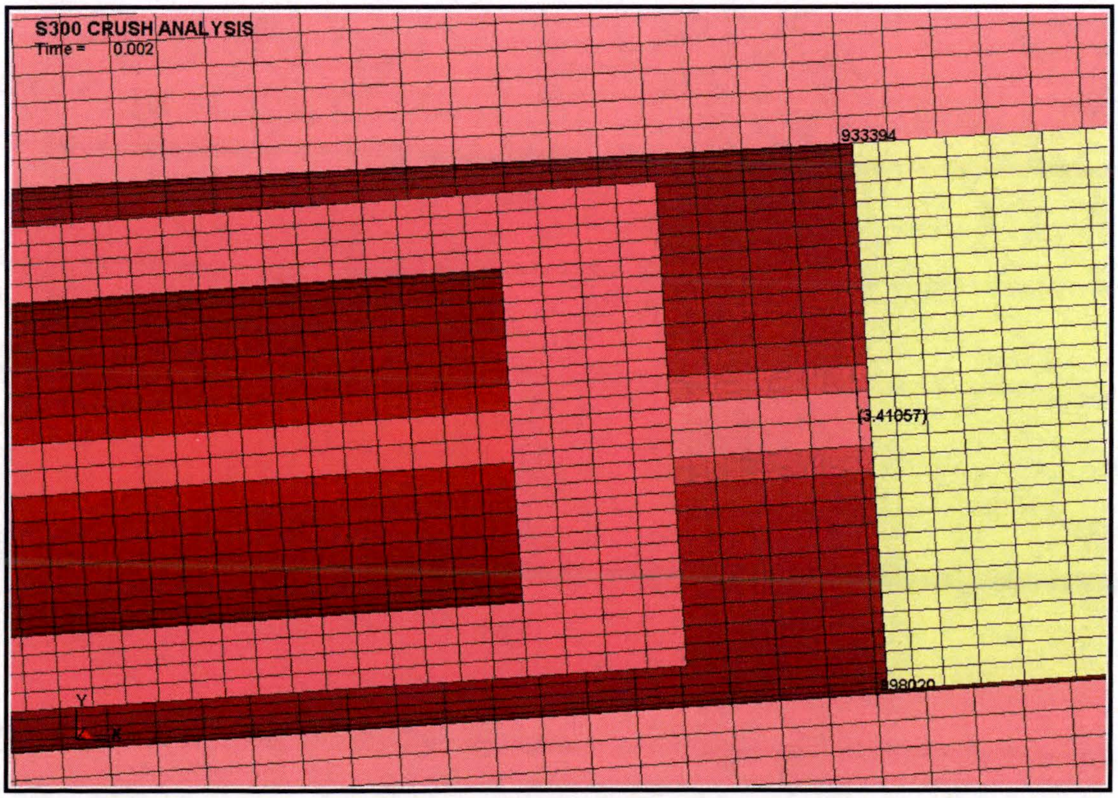

Figure 2.12.2-13 – Payload Cavity Top Deformation

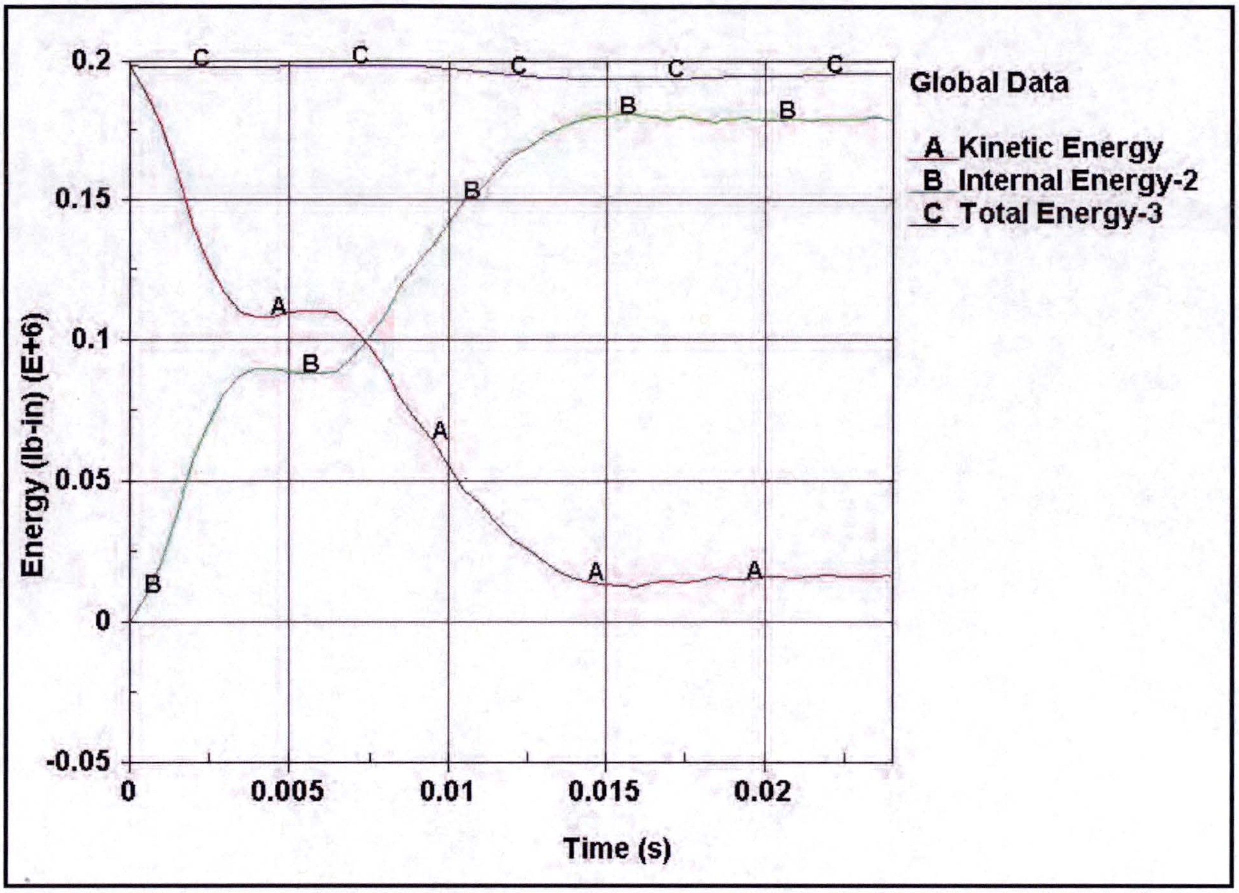

Figure 2.12.2-14 – S300 Model Global Energy

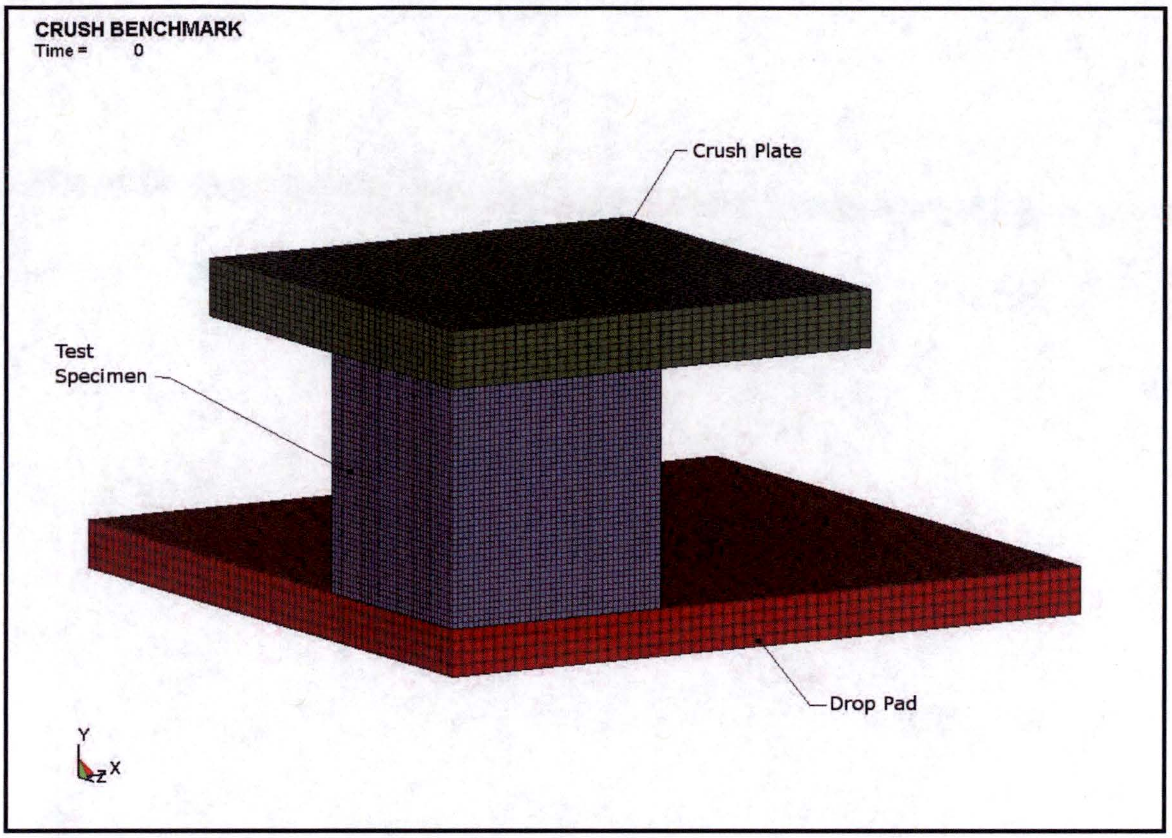

Figure 2.12.2-15 – Benchmark Crush Specimen Model

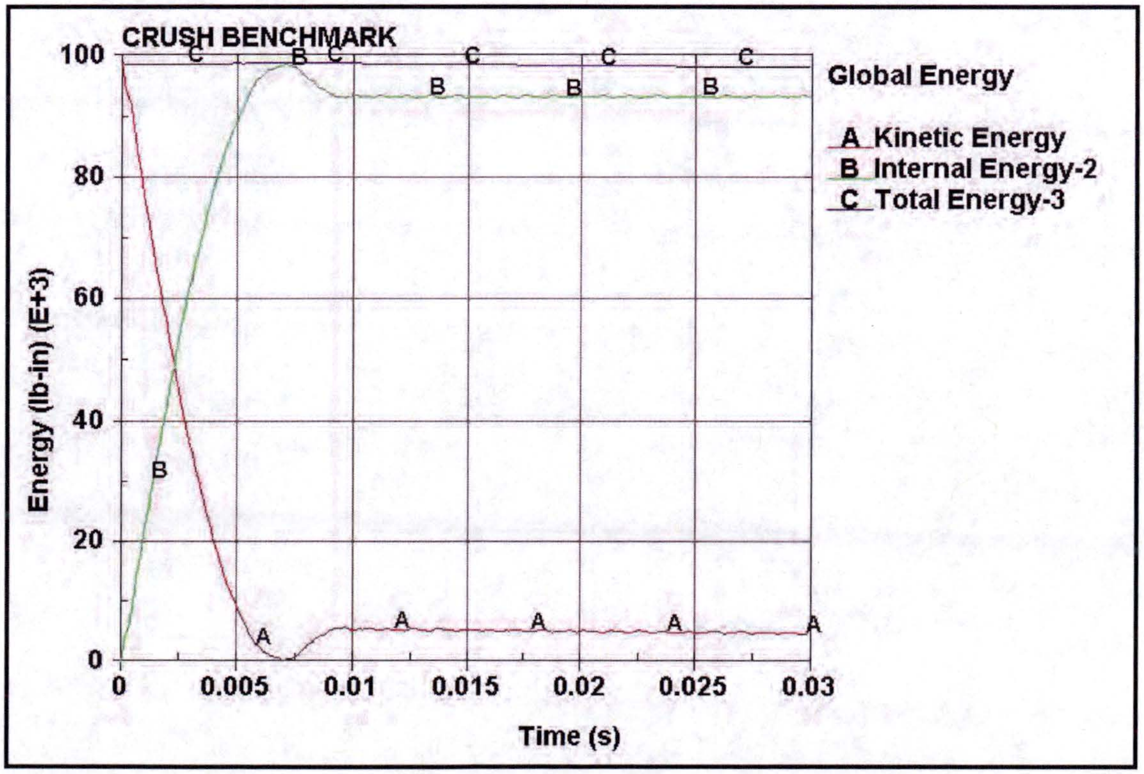

Figure 2.12.2-16 – Benchmark Model Global Energy

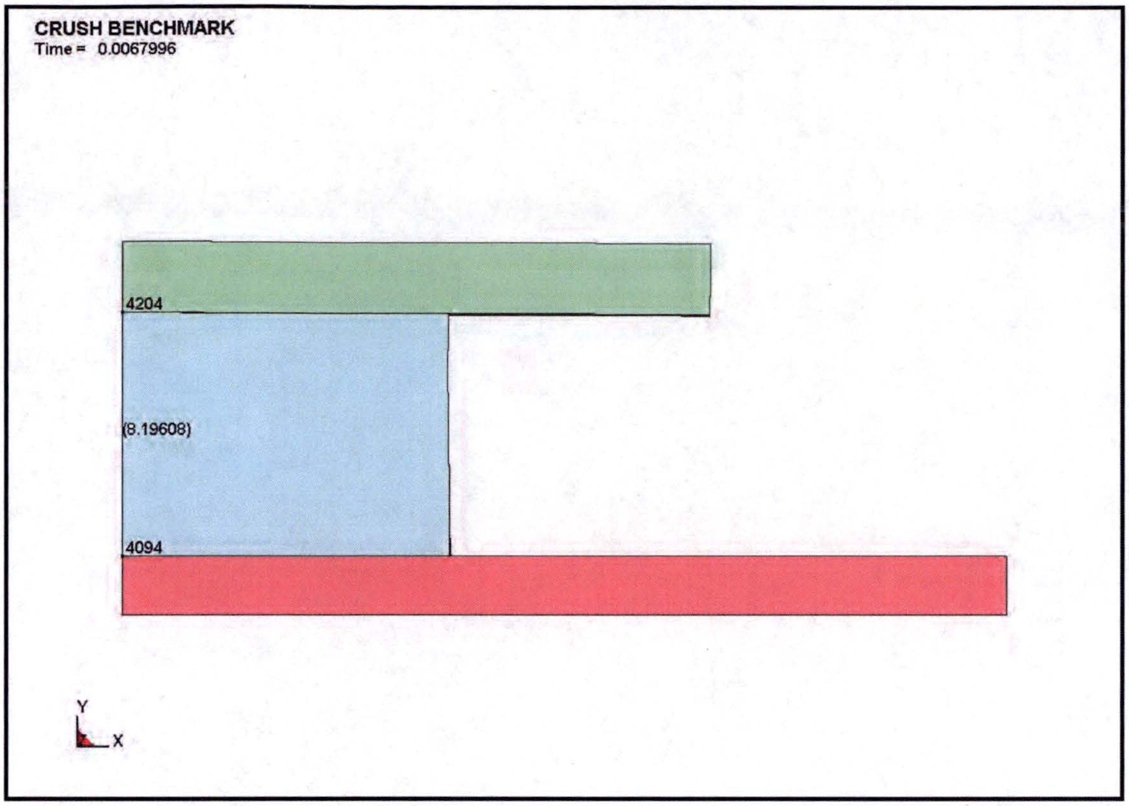

Figure 2.12.2-17 – Maximum Center Deformation (t = 6.8 ms)

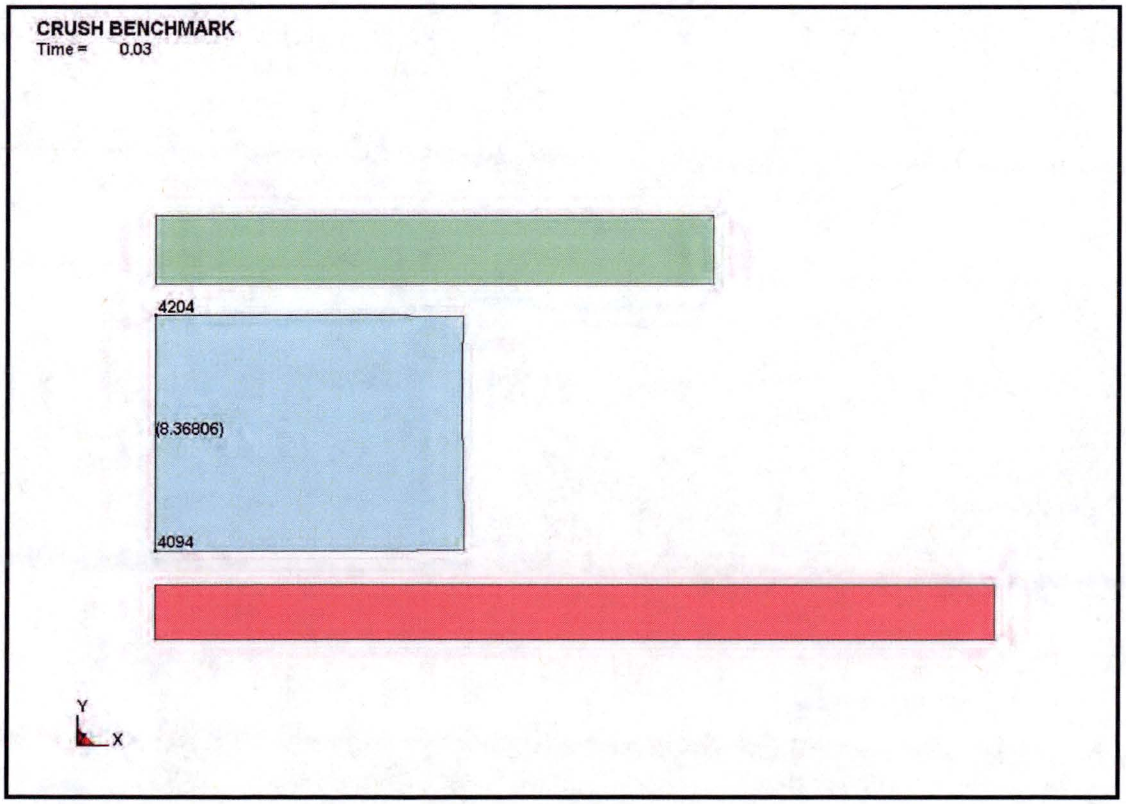

Figure 2.12.2-18 – Maximum Plastic Deformation (t = 30 ms)

3. THERMAL EVALUATION

This chapter identifies and describes the principal thermal design aspects of the S300 package, and further demonstrates the thermal safety of the packaging system and compliance with the thermal requirements of 10 CFR 71.

3.1 Description of Thermal Design

3.1.1 Design Features

The S300 packaging is a pipe overpack design contained within a 55-gallon drum that was developed as a safe means for transporting a single Los Alamos Special Form Capsule (SFC). The major components of the S300 package, as discussed in Section 1.2.1, *Packaging*, are: 1) the impact-absorbing protection provided by the 55-gallon drum and cane fiberboard dunnage, 2) the confinement vessel consisting of the pipe component, and 3) the neutron shielding provided by the high density polyethylene (HDPE) shielding insert. Containment and criticality control are provided by the SFC. Detailed drawings of the package design are presented in Section 1.3.1, *Packaging General Arrangement Drawings*. The S300 package has a maximum gross shipping weight of 480 pounds and is transported with the 55-gallon drum overpack in the vertical orientation.

Since the radioactive contents are in special form, the S300 package does not include any features specifically designed to enhance or control thermal performance.

3.1.2 Content's Decay Heat

The payload for the S300 package is a single Special Form Capsule (SFC) that is housed within the shielding insert. Two SFC models, designated Model II and Model III, are used. Each is fabricated of Type 304 stainless steel, with a nominal wall thickness of 0.5 inch and with bottom and threaded top cap thicknesses of 0.75 inches. As stated in Section 5.2.2, *Neutron Source*, the decay heat for the maximum payload of 350g of plutonium is bounded by 1.1W. This value includes the conservative assumption that all of the Pu-241 has decayed to Am-241. The decay heat is applied as an equivalent surface heat flux to the inside surface of the SFC. For conservatism, the smaller SFC is used as the basis for this evaluation.

3.1.3 Summary of Temperatures

The maximum temperature of the S300 package payload and HDPE shielding under NCT is bounded by 151 °F, while the maximum temperature of the fiberboard dunnage is bounded by 214 °F. Under HAC, the maximum temperature of the SFC is bounded by the HAC thermal test flame temperature of 1,475 °F.

3.1.4 Summary of Maximum Pressures

Since all cavities of the S300 packaging are vented, there is no internal pressure under NCT or HAC.

3.2 Material Properties and Component Specifications

3.2.1 Material Properties

A standard 55-gallon drum is used as the outer container for the S300 package. The drum may be fabricated of plated or painted carbon steel, or bare stainless steel. Table 3.2-1 presents the thermal properties for Type 304 stainless steel and A36 carbon steel. The thermal properties are taken from the ASME material properties database[1] and the density is taken from an on-line database[2]. Properties for temperatures between the tabulated values are calculated via linear interpolation within the heat transfer code. The thermal properties of Type 304 stainless steel are also applicable to the SFC.

The thermal properties of the HDPE material used as the shield inserts within the pipe component is based on a prototypic HDPE material[3,4] (see product data sheets in Appendix 3.5.3, *Material Data Sheets*). The thermal properties of the material presented in Table 3.2-2 are taken from the Handbook of Polyethylene Pipe[5], while its density is obtained from the product datasheet.

Cane fiberboard is used in the package for dunnage and impact protection. This material is typically used as sheathing material for building construction. The thermal properties under NCT conditions presented in Table 3.2-3 were obtained from testing conducted at the Savannah River National Laboratory[6]. The thermal conductivity of the material is anisotropic in that the conductivity perpendicular to the fibers is lower than the conductivity parallel to the fibers.

The thermal properties for air, presented in Table 3.2-4, are derived from the curve fits provided in Rohsenow, et. al.[7] Because the gas thermal conductivity varies significantly with temperature, the computer model calculates the thermal conductivity across the gas filled spaces and between the package and the ambient as a function of the mean film temperature. All void spaces within the S300 package are assumed to be filled with air at atmospheric pressure since the package is vented to the ambient.

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[1] ASME B&PV Code, Section II, Part D.

[2] Matweb, Online Material Data Sheets, www matweb.com.

[3] Neutron Shielding Material Catalog No. 201, Product Specifications 2003, Thermo-Electron Corporation, Santa Fe, NM, www.thermo.com.

[4] DriscoPlex® PE3608/(PE3408) *Pipe, Pipe and Fittings Data Sheet*, Bulletin PP 109, September 2006.

[5] *Handbook of Polyethylene Pipe*, Second Edition, Plastic Pipe Institute, Irving, TX, 75062, www.plasticpipe.org.

[6] Vormelker, P.R. and Daugherty, W.L., *Thermal Properties of Fiberboard Overpack Materials in the 9975 Shipping Package*, presented at the 2005 ASME Pressure Vessels and Piping Conference in Denver, CO, Paper No. WSRC-MS-2005-00001.

[7] Rohsenow, Hartnett, and Choi, *Handbook of Heat Transfer*, 3rd edition, McGraw-Hill, 1998.

The emissivity of 'as-received' Type 304 stainless steel has been measured as 0.25 to 0.28[8], while the emissivity of weathered Type 304 stainless steel has been measured as being between 0.46 to 0.50[9]. For the purpose of this analysis, an emissivity of 0.25 is assumed for the emittance from the SFC surfaces to account for the surface finish required for decontamination considerations. The exterior and interior surfaces of a standard 55-gallon drum fabricated of stainless steel are assumed to be 0.46 and 0.30, respectively. The drums fabricated of carbon steel are assumed to have a minimum emissivity of 0.8 on the interior and exterior surfaces to account for the coating used.

The solar absorptivity of Type 304 stainless steel is approximately 0.52[10], while the solar absorptivity of coated carbon steel is conservatively assumed to be 0.90.

The surfaces of the cane fiberboard are assumed to have an emissivity of 0.85[10] to account for both the surface roughness and color of the material. The same emissivity is assumed for the HDPE shielding material.

3.2.2 Component Specifications

Type 304 stainless steel has a melting point above 2,700 °F[2], but in compliance with the ASME B&PV Code[11], its allowable temperature is limited to 800°F if the component serves a structural purpose (e.g., the material's structural properties are relied on for loads postulated to occur in the respective operating mode or accidental free drop condition). As such, the appropriate upper temperature limit under normal conditions is 800 °F for stainless steel components.

Similarly, while carbon steel has a melting temperature of approximately 2,750 °F, its allowable temperature is limited to 700°F in compliance with the ASME B&PV Code[11]. The presence of a coating on the surface of the carbon steel drum will further restrict its temperature limit under NCT conditions. The typical coating is resistant to long term temperature exposure up to 250 °F and for intermittent exposure up to 275 °F[12].

A continuous use temperature limit of 250 °F is applied to the cane fiberboard material based on thermal testing conducted in support of nuclear material packaging[13].

The HDPE used in the shield insert has a manufacturer's recommended operating temperature limit of 180 °F and a melting temperature of approximately 210 °F, based on the product data sheet in Appendix 3.5.3, *Material Data Sheets*. In contrast, the standard HDPE material used

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[8] Frank, R., and Plagemann, W., *Emissivity Testing of Metal Specimens,* Boeing Analytical Engineering coordination sheet No. 2-3623-2-RF-C86-349, 1986.

[9] Azzazy, M., *Emissivity Measurements of 304 Stainless Steel,* prepared for Southern California Edison, September 6, 2000, Transnuclear File No. SCE-01.0100.

[10] Gubareff, G., Janssen, J., and Torborg, R., *Thermal Radiation Properties Survey,* 2nd edition, Honeywell Research Center, 1960.

[11] American Society of Mechanical Engineers (ASME) Boiler & Pressure Vessel Code, Section III, Rules for Construction of Nuclear Facility Components, Division 1, Subsection NB, Class 1 Components, & Subsection NG, Core Support Structures, 2001 Edition, 2002 Addendum.

[12] *Series 66 and 73 Product Data Sheets,* Tnemec Company, Inc. 6800 Corporate Drive Kansas City, MO, www.tnemec.com.

[13] Varble, J.L., Watkins, R.W., and Gunter, A.H., *Demonstration of Equivalency of Cane and Softwood Based CelotexTM for Model 9975 Shipping Package,* Savannah River National Laboratory Packaging Technology, Aiken SC.

for the drum liner has a higher melting point of approximately 260 °F[2,4]. This temperature limit is appropriate for the HDPE drum liner since its loss is not important to the safety of the package.

A rubber gasket may be used between the 55-gallon drum lid and body. Since the 55-gallon drum only serves to provide a protective overpack for the pipe component, loss of the rubber gasket is of no safety consequence. Because the payload is in special form, the elastomeric O-ring dust seal used in the pipe component performs no safety function.

The minimum allowable service temperature for all S300 package components is below -40 °F.

Table 3.2-1 – Thermal Properties of Metallic Materials

Material	Temperature (°F)	Thermal Conductivity (Btu/hr-ft-°F)	Specific Heat (Btu/lb_m-°F)	Density (lb_m/in^3)
Stainless Steel① Type 304	70	8.6	0.114	0.289
	100	8.7	0.115	
	150	9.0	0.117	
	200	9.3	0.119	
	250	9.6	0.122	
	300	9.8	0.123	
Carbon Steel② Type A36	70	27.3	0.105	0.284
	100	27.6	0.108	
	150	27.8	0.112	
	200	27.8	0.116	
	250	27.6	0.119	
	300	27.3	0.122	

Notes:

① ASME B&PV Code, Section II, Part D, Material Group J.

② ASME B&PV Code, Section II, Part D, Material Group B.

Table 3.2-2 – Thermal Properties of HDPE

Temperature (°F)	Density (lb_m/in^3)	Thermal Conductivity (Btu/hr-ft-°F)	Specific Heat (Btu/lb_m-°F)
-	0.034	0.25	0.46

Table 3.2-3 – Thermal Properties of Cane Fiberboard

Temperature (°F)	Density (lb_m/in^3)	Thermal Conductivity, (Btu/hr-ft-°F)		Specific Heat (Btu/lb_m-°F)
		'Perpendicular to Fiber'	'Parallel to Fiber'	
77	0.0107	0.0341	0.0595	0.1433
125.6		0.0364	0.0618	0.1481
195.8		0.0422	0.0659	0.1665

Table 3.2-4 – Thermal Properties of Air

Temperature (°F)	**Density lb$_m$/in^3)①**	**Specific Heat (Btu/lb$_m$-°F)**	**Dynamic Viscosity (lb$_m$ /ft-hr)**	**Thermal Conductivity (Btu/hr-ft-°F)**	**Prandtl Number②**	**Coef. Of Thermal Exp. (°R^{-1})③**
-40	Use Ideal Gas Law w/ Molecular wt = 28.966	0.240	0.03673	0.0121	Compute as $Pr = c_p\mu / k$	Compute as $\beta = 1/(°F+459.67)$
0		0.240	0.03953	0.0131		
50		0.240	0.04288	0.0143		
100		0.241	0.04607	0.0155		
200		0.242	0.05207	0.0178		
300		0.243	0.05764	0.0199		
400		0.245	0.06286	0.0220		
500		0.248	0.06778	0.0240		
600		0.251	0.07242	0.0259		
700		0.253	0.07680	0.0278		
800		0.256	0.08098	0.0297		
900		0.259	0.08500	0.0315		
1000		0.262	0.08887	0.0333		
1200		0.269	0.09620	0.0366		
1400		0.274	0.10306	0.0398		
1500		0.277	0.10633	0.0412		

Table Notes:

① Density computed from ideal gas law as $\rho = PM/RT$, where R= 1545.35 ft-lbf/lb-mole-R, T= temperature in °R, P= pressure in lbf/ft^2, and M= molecular weight of air. For example, at 100 °F and atmospheric pressure of 14.69lbf/in^2, ρ = (14.69*144 in^2/ft^2*28.966 lbm/lb-mole)/1545.35*(100+459.67) = 0.071 lbm/ft^3 = 4.099x10^{-5} lbm/in^3.

② Prandtl number computed as $Pr = c_p\mu / k$, where c_p = specific heat, μ = dynamic viscosity, and k = thermal conductivity. For example, at 100 °F, Pr = 0.241*0.04607/0.0155 = 0.72.

③ Coefficient of thermal expansion is computed as the inverse of the absolute temperature. For example, at 100 °F, β = 1/(100+459.67) = 0.00179.

3.3 Thermal Evaluation under Normal Conditions of Transport

This section presents the thermal evaluation of the S300 package for normal conditions of transport (NCT). Under NCT, the S300 package will be transported in a vertical orientation. This establishes the orientation of the exterior surfaces of the package for determining the free convection heat transfer coefficients and insolation loading. The NCT evaluations conservatively assume an adiabatic condition for the bottom surface of the vertically oriented drum (i.e. there is no heat transfer to or from the ambient).

3.3.1 Heat and Cold

3.3.1.1 Heat

The thermal performance of the S300 package under NCT is determined using a two-dimensional, axisymmetric thermal model of the packaging and its enclosed payload. Details of the thermal models and analysis methodology for NCT conditions are provided in Appendix 3.5.2, *Analytical Thermal Model.*

Table 3.3-1 presents the predicted peak S300 package temperatures under NCT conditions for the transportation of a SFC dissipating 1.1W of decay heat. The evaluation was conducted for both carbon steel and stainless steel 55-gallon drum overpacks to ensure that the bounding transportation configuration was identified. The results with solar are derived from a transient modeling of the diurnal variation in the insolation loading, while the results without solar are obtained from a steady-state analysis.

The results in Table 3.3-1 demonstrate that positive thermal margins exist for all packaging components. A minimum thermal margin of 30 °F (i.e., 180 - 150 °F for the HDPE shielding) exists for the packaging components. The temperature margins are adequate to cover potential modeling uncertainty, especially in light of the fact that the axisymmetric modeling approach used effectively applies the solar loading around the entire circumference of the 55-gallon drum overpack instead of only one-half of the circumference as occurs in actual operations.

Figure 3.3-1 illustrates the typical heat up of the S300 package under NCT conditions and assuming a diurnal variation of solar loads. The transient results show that approximately 6 days are required to approach repeatable temperature cycles within the S300 package after its assumed loading at a uniform temperature of 68 °F. While the exterior shell of the drum overpack essentially reaches its peak temperature points after the first diurnal cycle, the insulating effects of the cane fiberboard dunnage and the HDPE shielding material delays the heat up of the payload for about 144 hours, with true temperature repeatability not occurring until approximately 300 hours after the start of the diurnal analysis.

Figure 3.3-2 present the predicted temperature distribution within the S300 package at the point when the peak drum temperature is achieved, which occurs at the center of the drum's top. Figure 3.3-3 presents the predicted temperature distribution at the point when the peak HDPE shield material temperature is achieved.

Evaluation of the package for an ambient air temperature of 100 °F without insolation loads demonstrates that the peak temperature of the accessible exterior surfaces of the packaging are just slightly above 100 °F and well below the maximum temperature of 122 °F permitted by 10 CFR §71.43(g) for accessible surface temperature in an non-exclusive use shipment.

3.3.1.2 Cold

With an internal decay heat load of zero, no insolation, and an ambient temperature of -40 °F, the average package temperature will be -40 °F per 10 CFR §71.71(c)(2). As discussed in Section 3.2.2, *Component Specifications*, the -40 °F temperature is within the allowable operating temperature range for all package components. None of the materials of construction (i.e., thin carbon steel comprising the 55-gallon drum, austenitic stainless steel comprising the pipe component and special form capsules, HDPE shielding, and cane fiberboard and wood dunnage) undergo a ductile-to-brittle transition at temperatures of -40 °F or higher. Therefore, the NCT cold event is of negligible consequence.

3.3.2 Maximum Normal Operating Pressure

Since all cavities of the S300 packaging are vented, the internal pressure is equal to ambient pressure at all times.

Table 3.3-1 – NCT Temperatures for S300 Packaging

Component	Temperature (°F) ①			
	NCT Hot	**NCT Hot without Solar**	**NCT Hot Stainless Steel Drums**	**Max. Allowable**
SFC	151	116	145	800
HDPE Shielding				
- Max.	150	115	144	180 ③
- Avg. ②	141	104	134	180 ③
Pipe Component	152	103	142	800
Cane Fiberboard Dunnage				
- Max.	214	103	185	250
- Avg. ②	169	101	156	250
HDPE Drum Liner	222	101	191	260 ③
55-Gallon Walls				
- Side	189	100.2	173	250 ④
- Lid	233	100.1	206	250 ④

Notes: ① Results assume a payload of 1.1W.

② Average temperatures computed using a mass weighted average of the model nodes.

③ Recommended temperature limit of 180°F assumed for HDPE used as shielding given its importance to safety. The melting point of approximately 260°F is used for the standard HDPE material used for the drum liner since its loss is not important to safety.

④ Temperature criterion based on long term temperature limit for typical drum coatings versus the nominal 700°F limit for carbon steel under NCT conditions.

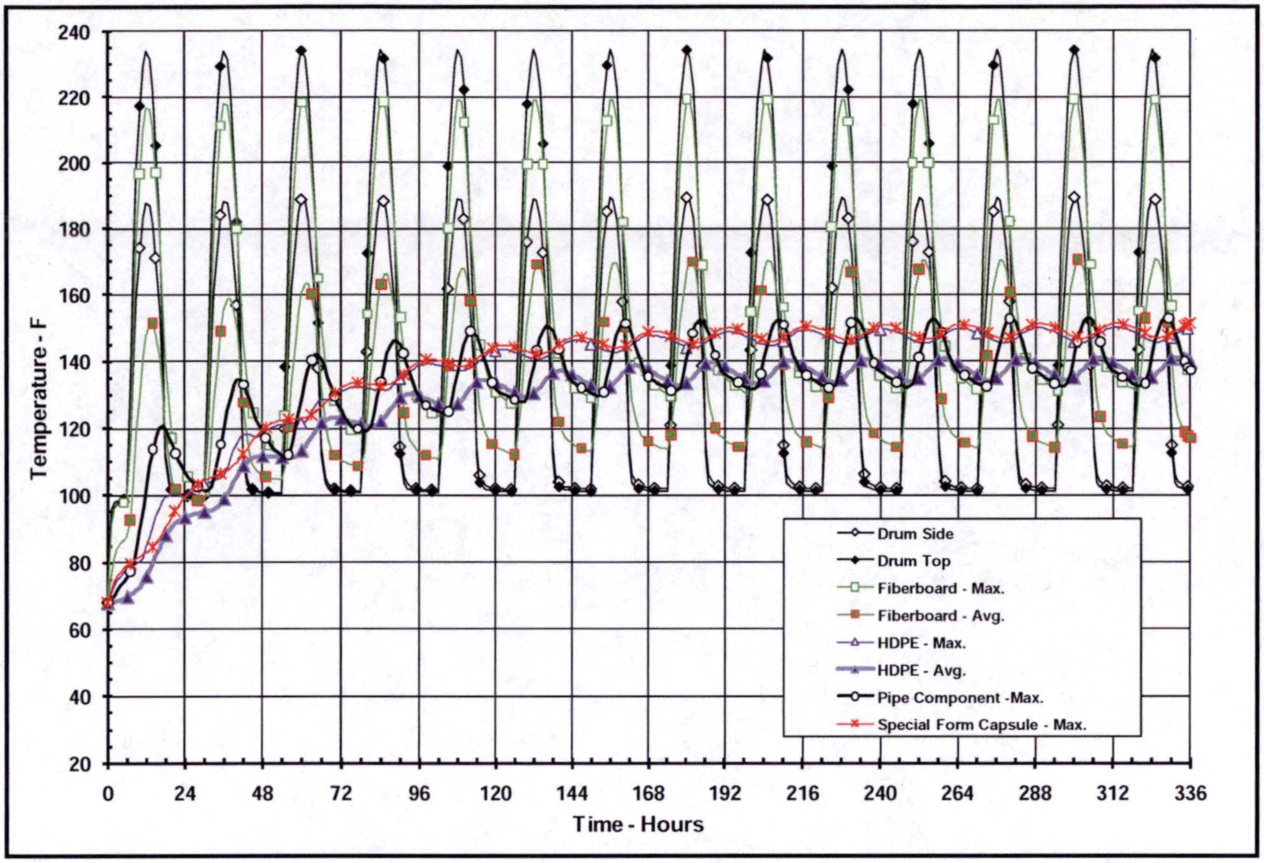

Figure 3.3-1 – S300 Package Transient Heat Up for NCT

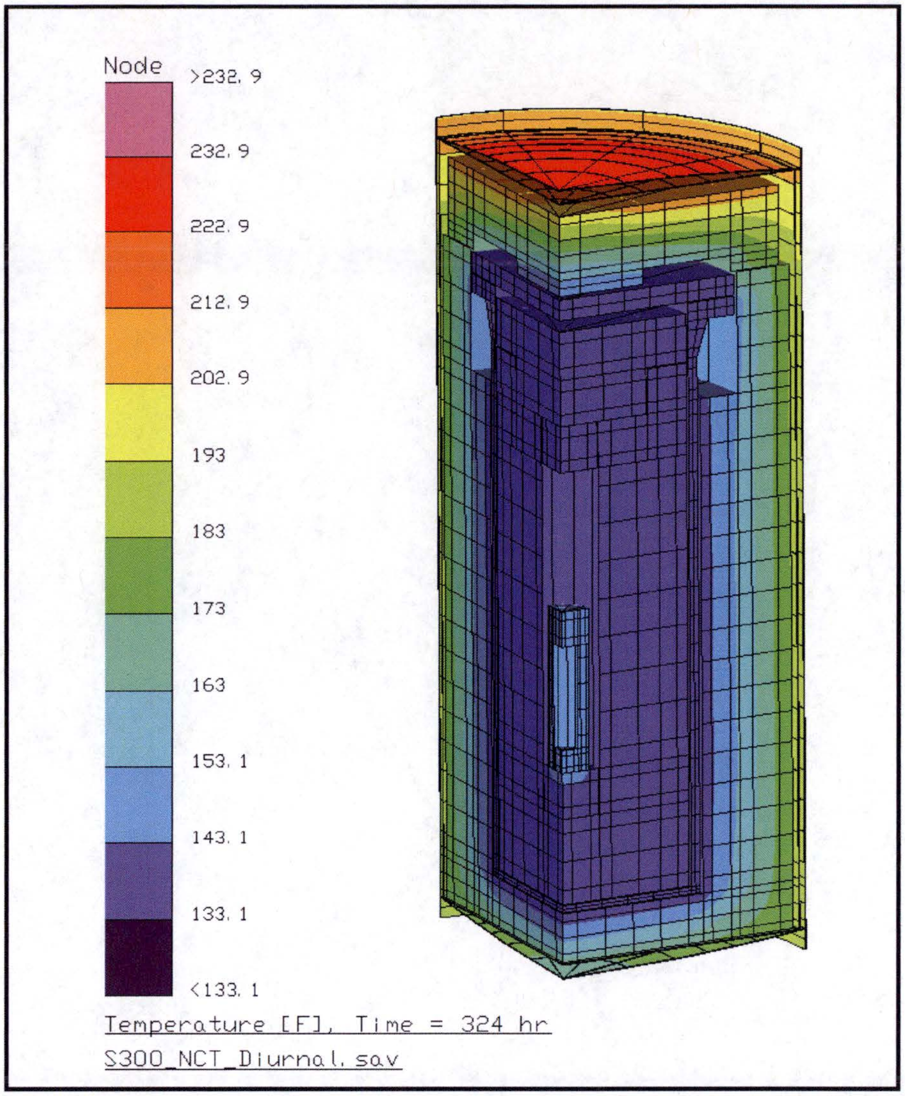

Figure 3.3-2 – NCT Temperature Distribution at Time of Peak Drum Temperature

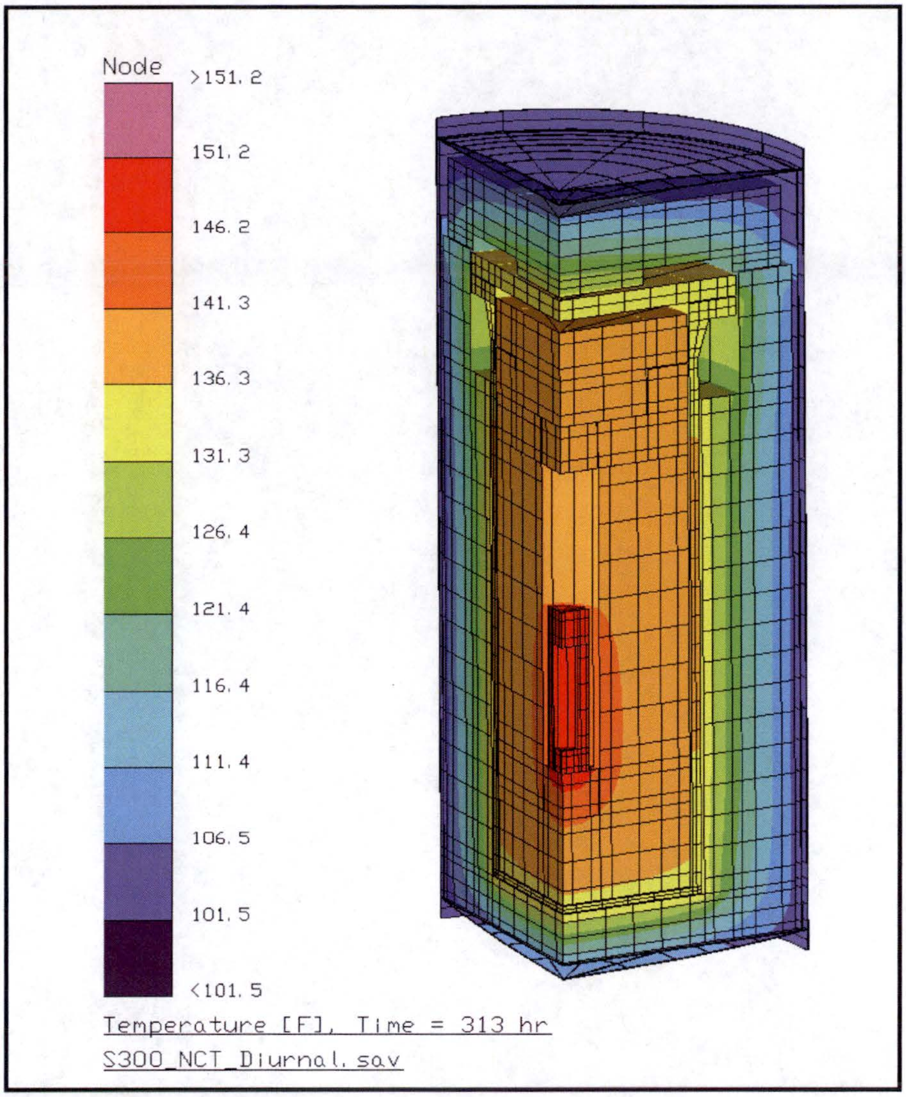

Figure 3.3-3 – NCT Temperature Distribution at Time of Peak HDPE Shielding Temperature

3.4 Thermal Evaluation under Hypothetical Accident Conditions

The most conservative assumption regarding the initial conditions of the S300 packaging before the fire is that due to the mechanical tests (free drop, crush, and puncture), the SFC has been separated entirely from the package and is exposed to the fire without any package components to shield it. 10 CFR §71.73(c)(4) requires that the package be exposed to a fire having an average temperature of 800 °C (1,475 °F) and a flame emissivity of 0.9 for 30 minutes. In the case of the S300, that would mean exposure of the SFC. The special form qualification testing, per 10 CFR §71.75, requires that the capsule be heated to 1,475 °F for 10 minutes. With regard to capsule temperature, these two requirements are essentially equivalent, as shown by a simple heat transfer calculation. Because it would have little effect on the results, the internal heat generation of 1.1W is neglected.

3.4.1 Initial Conditions

As discussed in Section 2.7.4, *Thermal*, the most conservative assumption concerning the initial conditions of the S300 package prior to the fire is that, due to the mechanical tests (free drop, crush, and puncture), the SFC has been separated entirely form the packaging and is exposed to the fire without any packaging components to shield it. The initial temperature of the SFC at the start of the fire is taken as 165 °F, which is conservatively higher than the temperature of 151 °F shown in Table 3.3-1.

As noted in Section 2.7.3, *Puncture*, the HAC free drop, crush, and puncture drop tests may not lead to full separation of the SFC from the other components of the S300 packaging. If the pipe component survived the HAC impact events intact, the SFC would be located within the polyethylene shielding, located within the steel pipe component. This scenario would be much more favorable than full exposure of the bare SFC to the hypothetical accident fire, due to the considerable protection from fire temperature which would be afforded by the pipe component and shielding materials. Any combustion of the polyethylene shield material which might occur would be quite limited compared to the full fire environment. Therefore, the most conservative condition for the HAC thermal event is exposure of the bare SFC to the fire.

3.4.2 Fire Test Conditions

The standard conditions required by 10 CFR §71.73(c)(4) were used in the analysis.

3.4.3 Maximum Temperatures and Pressures

Since the capsule is compact and made of thick steel (diameter between 2.5 and 3 inches, and wall thickness approximately 1/2 inches), its internal temperature during the hypothetical fire may be assumed to be uniform compared to the environment temperature. According to Kreith[14], Section 4-2,

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[14] Frank Kreith, Principles of Heat Transfer, 3rd edition, Intext Press, Inc., 1973.

Change in internal energy of the capsule during dθ	=	net heat flow from the environment during dθ

For a combination of convection and radiation, the transient heat transfer equation is (based on equation 4-1 of Kreith):

$$c\rho V dT = \left[\sigma A\varepsilon\left(T_\infty^4 - T^4\right) + hA\left(T_\infty - T\right)\right]d\theta$$

This can be rearranged for numerical solution as follows:

$$T_{NEW} = T_{OLD} + \frac{\sigma A\varepsilon\left(T_\infty^4 - T_{OLD}^4\right) + hA\left(T_\infty - T_{OLD}\right)}{c\rho V}\Delta\theta$$

According to 10 CFR §71.73(c)(4), the emissivity of the flame must be 0.9 and the temperature of the flame equal to 1,475 °F. Conservatively, a greater flame emissivity of $\varepsilon = 1.0$ will be used in this analysis.

The capsule which will reach the fire temperature the fastest is the one which has the largest surface area-to-mass ratio, or A/ρV, where A is the total surface area, and the quantity ρV is the weight, assuming solid steel. From the table in Section 1.2.2, *Contents*, and assuming a stainless steel density of 0.29 lb/in^3, the value of A/ρV for the Model II (larger) SFC is equal to 5.2 in^2/lb, while the corresponding value for the Model III (smaller) SFC is equal to 6.5 in^2/lb. Thus, the Model III SFC will heat up faster than the Model II, and will be used in the following demonstration.

A conservatively high convection coefficient of h = 10 Btu/hr-ft^2-°F is used, as developed in Section 3.4.3.2, *Forced Convection Heat Transfer Coefficient*. The emissivity of the capsule is 0.8, per 10 CFR §71.73(c)(4). The specific heat of the steel in the capsule has an average value of 0.13 Btu/hr-°F through the heat-up temperature range of 200 °F to 1,500 °F[15]. Using these parameters with a straightforward numerical solution of the equation for T_{NEW}, the capsule temperature would reach 99% of the environment temperature (i.e., approximately 1,460 °F) after an exposure of 19 minutes, as shown in Table 3.4-1 and depicted in Figure 3.4-1. The dwell time at the peak fire temperature would therefore be approximately (30 – 19) = 11 minutes before the end of the fire. Since 10 CFR §71.75 requires that the capsule be heated to 1,475 °F and held there for 10 minutes, the effects on containment of the requirements of 10 CFR §71.75 and §71.73(c)(4) are essentially equivalent. Therefore, the requirements for exposure of the package (in this case, the SFC) to the HAC fire have been met by the qualification testing of the SFC.

Since the test capsules were leaktight following the thermal qualification test (as documented in Section 2.10, *Special Form*), they will also be leaktight following the HAC, 30-minute fire test. In addition, it is noted that none of the materials of construction of the capsules would be affected by either the required temperature of 1,475 °F nor hold time at that temperature. Exposure to the combustion of any of the flammable materials of construction of the S300 package (cane fiberboard, polyethylene) could not create conditions that would exceed the ability of the stainless steel components of the SFC to remain leaktight. A discussion of the effects of

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[15] $C_p = k/\rho\alpha$, where k (thermal conductivity) and α (thermal diffusivity) are taken from the ASME B&PV Code, Section II, Part D, Table TCD, averaged using data at 200 °F and 1,500 °F. Density (ρ) is taken as 501 lb/ft^3.

the capsule temperature on the plutonium contents is given in Section 2.2.2.1, *Effect of Contents on the SFC.*

3.4.3.1 Post-fire Analysis

At the end of the hypothetical fire, the SFC will cool down under conditions of a 100 °F ambient temperature and full regulatory solar conditions. Due to the fire, the SFC is assumed to have an emissivity of 0.9 and a solar absorptivity of 0.9. It will lose heat to the surrounding air by radiation and convection in still air with an initial temperature of 1,475 °F. It will gain heat from insolation.

From 10 CFR §71.71(c)(1), the insolation for a curved surface is 10.24 Btu/in^2 (400 g cal/cm^2) per 12 hrs, or 122.9 Btu/ft^2-hr. Conservatively, the larger Model II capsule, which will cool more slowly than the smaller one per the reasoning stated above, will be used. The cylindrical area of the Model II is $A_C = 0.77$ ft^2. Assuming the SFC is in a horizontal orientation after the fire, the ends of the capsule are "flat surfaces not transported horizontally", having an insolation of 5.12 Btu/in^2 (200 g cal/cm^2) per 12 hrs, or 61.4 Btu/ft^2-hr. The flat area of the SFC ends is $A_E = 0.10$ ft^2. Thus, the total heat input from insolation, post-fire, is:

$$Q_I = (0.9)(A_C \times 122.9 + A_E \times 61.4) = 90.7 \text{ Btu/hr}$$

The heat balance equation used for the fire case above is now:

$$c\rho V dT = \left[\sigma A \varepsilon_{pf}\left(T_\infty^4 - T^4\right) + h_s A (T_\infty - T) + Q_I\right] d\theta$$

which can be written:

$$T_{NEW} = T_{OLD} + \frac{\sigma A \varepsilon_{pf}\left(T_\infty^4 - T_{OLD}^4\right) + h_s A\left(T_\infty - T_{OLD}\right) + Q_I}{c\rho V} \Delta\theta$$

For the post-fire analysis, σ, A, c, ρ, and V remain the same as in the fire case, $T_\infty = 100$ °F, $\varepsilon_{pf} = 0.9$, and the convection coefficient, h_s, is defined for still air rather than the forced fire convection case as follows.

From Guyer[16], equation 3-43, Chapter 1, the Nusselt number for a horizontal cylinder is:

$$Nu = \frac{h_s L}{k} = \left[0.60 + \frac{0.387 Ra^{1/6}}{\left(1 + (0.559/Pr)^{9/16}\right)^{8/27}}\right]^2$$

The Rayleigh number, Ra, is:

$$Ra = \left(\frac{\rho^2 g \beta L^3 \Delta T}{\mu^2}\right) Pr$$

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[16] Eric Guyer, *Handbook of Applied Thermal Design*, McGraw-Hill, Inc., 1989.

The convection coefficient may be expected to vary over the temperature range of the SFC during the cool-down; however, it does not vary widely, and may be conservatively bounded. A smaller value of convection will give the slowest (most conservative) cool-down rate. As time passes, the coefficient will differ only as a result of the differences in the temperature of the boundary layer air and of the temperature difference between the SFC and ambient, which at time $\theta = 0$, is equal to 1,475 – 100 = 1,375 °F, and when the SFC is nearly in equilibrium, say at a temperature of 200 °F, is equal to 200 – 100 = 100 °F. The appropriate value for the distance L is the SFC diameter, equal to 3.0 inches or 0.25 ft. The quantity $L^3 = 0.016$ ft^3. Properties of air are evaluated at the average film temperature and are taken from Table A-3 of Kreith. The evaluation of h_s for the two temperature extremes (hot SFC and near-ambient SFC) are compared in Table 3.4-2. As seen from the table, a value of still air convection of $h_s = 1.0$ Btu/hr-ft^2-°F may be used as a conservative lower bound. This convection is assumed to apply to the entire SFC, including the flat ends.

The solution to the time-dependent post-fire cool-down relation is shown in Table 3.4-3 and depicted in Figure 3.4-3. After 30 minutes, the temperature of the SFC falls to 594 °F. After one hour (shown in Figure 3.4-2 only), the temperature is 402 °F.

3.4.3.2 Forced Convection Heat Transfer Coefficient

The forced convection coefficient applied to the SFC during the HAC fire event is computed using the relationships in Table 6-5 of Kreith for a flat surface, where the characteristic dimension (L) is equal to the length along the surface and the free stream flow velocity is V. The average gas velocity is taken as 10 m/s (equivalent to V = 118,080 ft/hr) as found from Schneider[17]. The heat transfer coefficient is computed based on the local Reynolds number, defined as:

$$\mathrm{Re}_L = \frac{V \times \rho \times L}{\mu}$$

When the Reynolds number is less than $5(10)^5$ and $\mathrm{Pr} > 0.1$, $\mathrm{Nu} = 0.664 \times \mathrm{Re}_L^{0.5} \times \mathrm{Pr}^{0.33}$. A characteristic length of L = 0.208 feet is used, based on the capsule diameter of 2.5 inches. The properties of air (from Table A-3 of Kreith) are evaluated at the average of the fire temperature (1,475 °F) and the surface temperature at the start of the fire (165 °F), or 820 °F. At this temperature, the density, ρ, of air is 0.0309 lbm/ft^3, and the dynamic viscosity, μ, is 0.0818 lbm/ft-hr. Using these quantities, the Reynolds number is equal to 9,278. The Prandtl number at 820 °F is 0.699. Using the equation above, the Nusselt number can therefore be calculated as 56.8. The convection coefficient is therefore:

$$h_c = \frac{\mathrm{Nu} \times k}{L} = 7.92\ \mathrm{Btu/hr-ft^2-{}^\circ F}$$

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[17] Schneider, M.E., and Kent, L.A., *Measurements of Gas Velocities and Temperatures in a Large Open Pool Fire,* Heat and Mass Transfer in Fire – HTD Vol. 73, 1987, ASME, New York, NY.

where the thermal conductivity, k, is equal to 0.0290 Btu/hr-ft-°F. This value for the convection coefficient is conservatively rounded up to a value of 10.0 for the HAC fire evaluation in Section 3.4.3, *Maximum Temperatures and Pressures*.

3.4.4 Maximum Thermal Stresses

Direct exposure of the SFC to the fully engulfing fire has been shown to be equivalent to the qualification testing performed on the capsule. Since the SFC was leaktight after qualification testing, thermal stresses are not of concern.

3.4.5 Accident Conditions for Air Transport of Fissile Material

With regard to air transport of fissile material, 10 CFR §71.55(f) requires that the package be subcritical subsequent to the application of a series of accident condition tests, including a thermal test. A criticality analysis of the worst-case geometric configuration is performed in Section 6.7, *Fissile Material Packages for Air Transport*, which considers the presence of all of the moderating and reflecting material in the package. The effect of the thermal test on the criticality analysis is nil, since the fire cannot increase the amount of moderating or reflecting material, nor cause it to be located in a more reactive position than already assumed in the criticality analysis. The fire would in fact tend to decrease the availability of moderating material due to combustion. For these reasons, the effects of the fire test of 10 CFR §71.55(f)(1)(iv) do not need to be specifically evaluated.

Table 3.4-1 – Heating of SFC in Fire Event

Time, min.	Temp, °F	Time, min.	Temp, °F	Time, min.	Temp, °F	Time, min.	Temp, °F
0.00	165	7.50	1,166	15.00	1,435	22.50	1,471
0.25	211	7.75	1,185	15.25	1,438	22.75	1,471
0.50	257	8.00	1,202	15.50	1,440	23.00	1,471
0.75	302	8.25	1,219	15.75	1,443	23.25	1,471
1.00	346	8.50	1,234	16.00	1,445	23.50	1,472
1.25	389	8.75	1,249	16.25	1,447	23.75	1,472
1.50	431	9.00	1,263	16.50	1,449	24.00	1,472
1.75	473	9.25	1,277	16.75	1,451	24.25	1,472
2.00	513	9.50	1,289	17.00	1,453	24.50	1,473
2.25	553	9.75	1,301	17.25	1,454	24.75	1,473
2.50	592	10.00	1,312	17.50	1,456	25.00	1,473
2.75	630	10.25	1,323	17.75	1,457	25.25	1,473
3.00	667	10.50	1,333	18.00	1,458	25.50	1,473
3.25	703	10.75	1,342	18.25	1,460	25.75	1,473
3.50	739	11.00	1,351	18.50	1,461	26.00	1,473
3.75	773	11.25	1,359	18.75	1,462	26.25	1,474
4.00	806	11.50	1,367	19.00	1,463	26.50	1,474
4.25	839	11.75	1,374	19.25	1,464	26.75	1,474
4.50	870	12.00	1,381	19.50	1,464	27.00	1,474
4.75	900	12.25	1,387	19.75	1,465	27.25	1,474
5.00	929	12.50	1,393	20.00	1,466	27.50	1,474
5.25	958	12.75	1,399	20.25	1,466	27.75	1,474
5.50	985	13.00	1,404	20.50	1,467	28.00	1,474
5.75	1,011	13.25	1,409	20.75	1,468	28.25	1,474
6.00	1,036	13.50	1,414	21.00	1,468	28.50	1,474
6.25	1,060	13.75	1,418	21.25	1,469	28.75	1,474
6.50	1,083	14.00	1,422	21.50	1,469	29.00	1,474
6.75	1,106	14.25	1,425	21.75	1,470	29.25	1,474
7.00	1,127	14.50	1,429	22.00	1,470	29.50	1,474
7.25	1,147	14.75	1,432	22.25	1,470	29.75	1,474

Table 3.4-2 – Evaluation of Post-fire Convection Coefficient

Input Parameter	Hot SFC	Near-Ambient SFC
T_{surf}. °F	1,475	200
ΔT, °F	1,375	100
Film Temp., °F*	788	150
$\rho^2 g\beta/\mu^2$, 1/°F ft^3	52,272	1,305,000
Pr	0.696	0.720
k, But/hr-ft-°F	0.0284	0.0164
Ra, $\rho^2 g\beta/\mu^2 L^3\ \Delta T(Pr)$	800,389	1,503,360
Nusselt (see above)	13.62	16.34
h_s, Btu/hr-ft^2-°F	1.55 (max)	1.07 (min)

*Film temperature is equal to ½ × ($T_{surf} + T_\infty$), where T_∞ = 100 °F.

Table 3.4-3 – Cooling of SFC After Fire Event

Time, min.	Temp, °F	Time, min.	Temp, °F	Time, min.	Temp, °F	Time, min.	Temp, °F
0.00	1,475	7.50	1,012	15.00	806	22.50	681
0.25	1,449	7.75	1,003	15.25	801	22.75	677
0.50	1,424	8.00	994	15.50	796	23.00	674
0.75	1,400	8.25	985	15.75	791	23.25	671
1.00	1,377	8.50	977	16.00	786	23.50	667
1.25	1,356	8.75	969	16.25	782	23.75	664
1.50	1,335	9.00	960	16.50	777	24.00	661
1.75	1,316	9.25	952	16.75	772	24.25	658
2.00	1,297	9.50	945	17.00	768	24.50	655
2.25	1,279	9.75	937	17.25	763	24.75	652
2.50	1,261	10.00	930	17.50	759	25.00	649
2.75	1,245	10.25	922	17.75	754	25.25	646
3.00	1,229	10.50	915	18.00	750	25.50	643
3.25	1,213	10.75	908	18.25	746	25.75	640
3.50	1,198	11.00	901	18.50	741	26.00	637
3.75	1,184	11.25	894	18.75	737	26.25	634
4.00	1,170	11.50	888	19.00	733	26.50	631
4.25	1,156	11.75	881	19.25	729	26.75	628
4.50	1,143	12.00	875	19.50	725	27.00	625
4.75	1,130	12.25	869	19.75	721	27.25	622
5.00	1,118	12.50	862	20.00	717	27.50	620
5.25	1,106	12.75	856	20.25	713	27.75	617
5.50	1,094	13.00	850	20.50	710	28.00	614
5.75	1,083	13.25	845	20.75	706	28.25	612
6.00	1,072	13.50	839	21.00	702	28.50	609
6.25	1,062	13.75	833	21.25	698	28.75	606
6.50	1,051	14.00	828	21.50	695	29.00	604
6.75	1,041	14.25	822	21.75	691	29.25	601
7.00	1,031	14.50	817	22.00	688	29.50	599
7.25	1,022	14.75	812	22.25	684	29.75	596

Note: at time = 30 minutes, T = 594 °F.

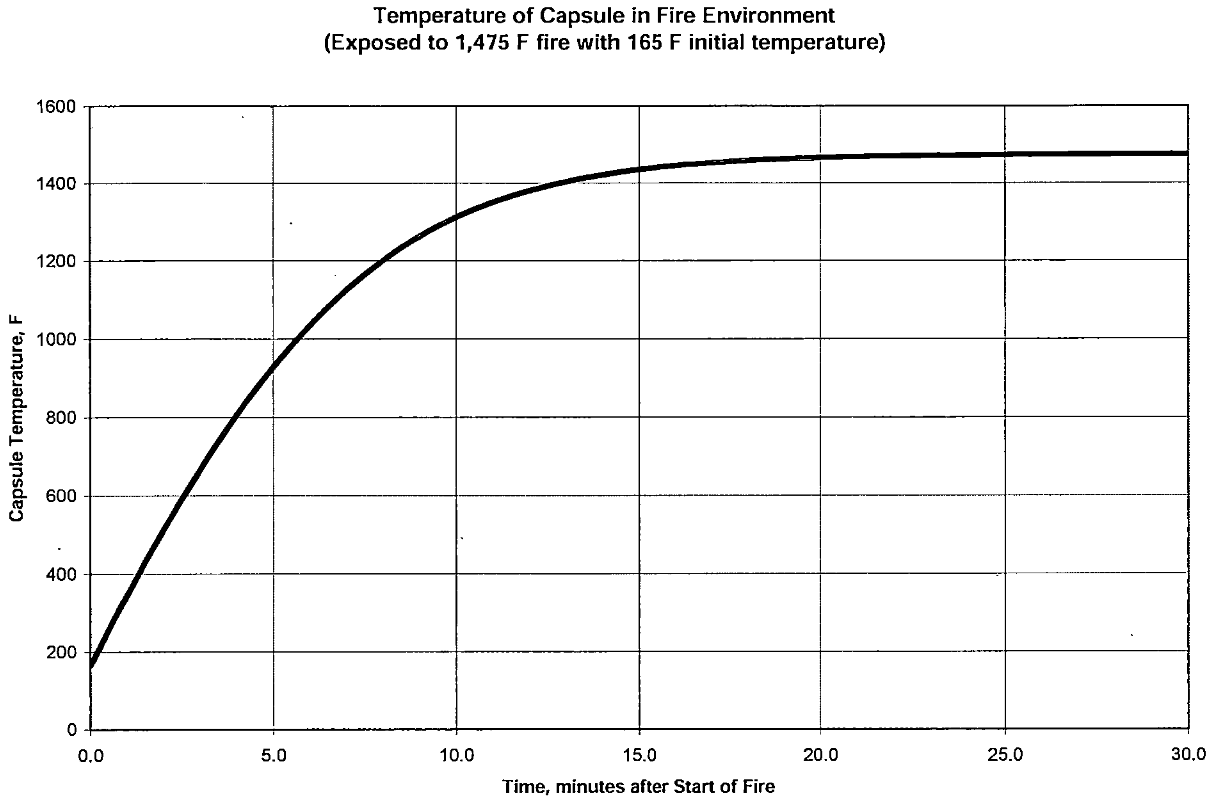

Figure 3.4-1 - Heating of SFC During Fire Event

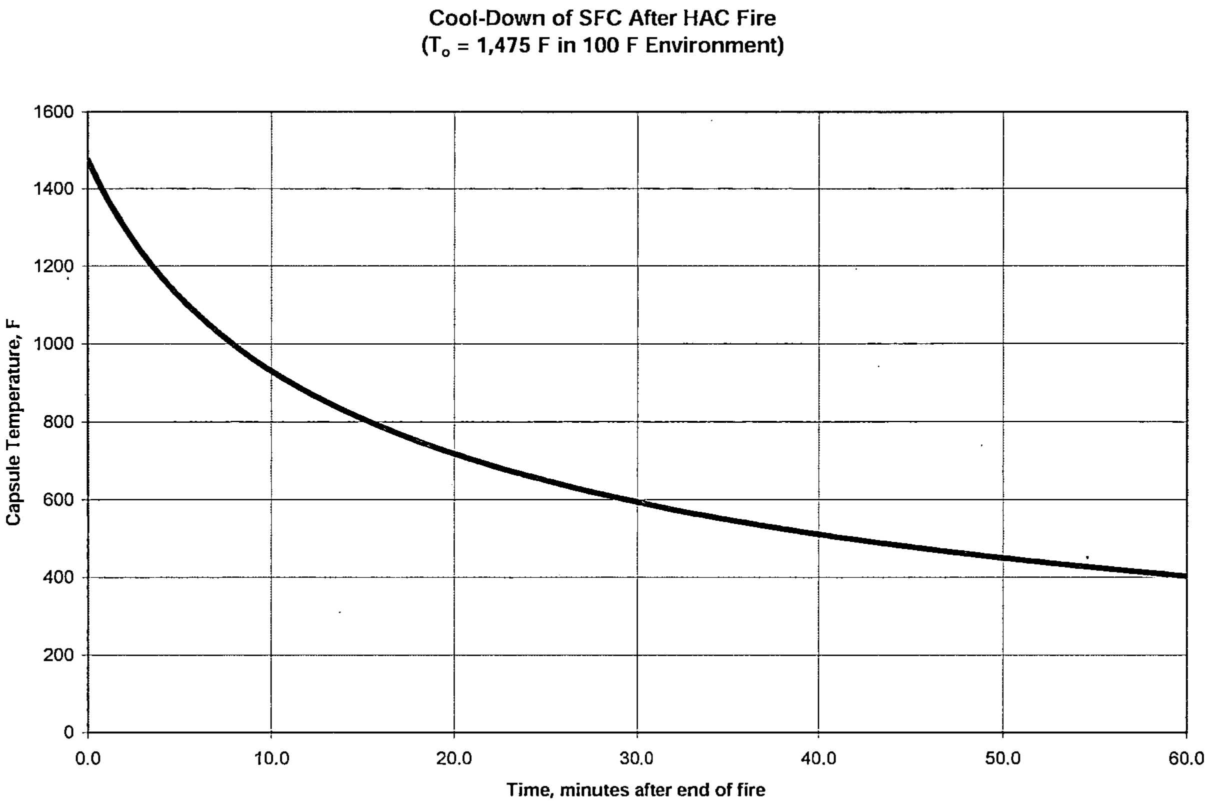

Figure 3.4-2 - Cooling of SFC After Fire Event

3.5 Appendices

3.5.1 Computer Analysis Results

Due to the size and number of the output files associated with each analyzed condition, results from the computer analysis are provided on a CD-ROM.

3.5.2 Analytical Thermal Model

The analytical thermal model of the S300 packaging and its authorized payload is developed for use with the Thermal Desktop®[18] and SINDA/FLUINT[19] computer programs. These programs work together to provide the functions needed to build, exercise, and post-process a thermal model. The Thermal Desktop® computer program provides graphical input and output display functions, as well as computing the thermal mass, conduction, and radiation exchange conductors for the defined geometry and thermal/optical properties. Thermal Desktop® is designed to run as an application module within the AutoCAD™ design software. As such, all of the CAD tools available for generating geometry within AutoCAD™ can be used for generating a thermal model. In addition, the use of the AutoCAD™ layers tool presents a convenient means of segregating the thermal model into its various elements.

The SINDA/FLUINT computer program is a general purpose code that handles problems defined in finite difference (i.e., lumped parameter) and/or finite element terms and can be used to compute the steady-state and transient behavior of the modeled system. Although the code can be used to solve any physical problem governed by diffusion-type equations, specialized functions used to address the physics of heat transfer and fluid flow make the code primarily a thermal code.

The SINDA/FLUINT and Thermal Desktop® computer programs have been validated for safety basis calculations for nuclear related projects[20].

Together, the Thermal Desktop® and SINDA/FLUINT codes provide the capability to simulate steady-state and transient temperatures using temperature dependent material properties and heat transfer via conduction, convection, and radiation. Complex algorithms may be programmed into the solution process for the purposes of computing heat transfer coefficients as a function of the local geometry, gas thermal properties as a function of species content, temperature, and pressure.

3.5.2.1 Description of S300 Packaging NCT Thermal Model

The S300 packaging is represented by a 2-dimensional, axisymmetric thermal model for the NCT evaluation. The various packaging components are defined using a combination of planar and

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[18] Thermal Desktop®, Version 5.3, Cullimore & Ring Technologies, Inc., Littleton, CO, 2010.

[19] SINDA/FLUINT, *Systems Improved Numerical Differencing Analyzer and Fluid Integrator*, 5.3, Cullimore & Ring Technologies, Inc., Littleton, CO, 2010.

[20] AFS Report AFS-TR-VV-013, Rev. 0, *Thermal Desktop® and SINDA/FLUINT Testing and Acceptance Report*, Version 5.3, AREVA Federal Services, LLC, 2010.

solid elements. Program features within the Thermal Desktop® computer program automatically compute the various areas, lengths, thermal conductors, and view factors involved in determining the individual elements that make up the thermal model of the complete assembly. While axisymmetric conditions are assumed, the actual thermal modeling presents a 90° segment of the package since the Thermal Desktop® code does not provide an explicit option for axisymmetric modeling and to provide clearer graphical depictions of the modeling and the temperature distribution within the package.

Figure 3.5-1 to Figure 3.5-4 illustrate 'solid' views of the S300 packaging thermal model. The model is composed of solid and planar type elements representing the various packaging components. Thermal communication between the various components is via conduction, radiation, and surface-to-surface contact. A total of approximately 1,940 nodes, 12 planar elements, and 37 finite difference solid cylindrical shapes are used to simulate the modeled components. The solid cylindrical shapes are a Thermal Desktop® computer program feature (i.e., FD solids) that permits a group of solid elements to be represented by a single entity. As such, the number of individual solid 'bricks' utilized in the modeling is actually significantly larger than the 37 value indicated above.

As seen from Figure 3.5-1, the modeling accurately captures the geometry of the various components of the packaging, including the cane fiberboard used for dunnage and impact protection, the pipe component, the HDPE shielding material, and the special form capsule (SFC) payload. The minimal spatial resolution provided by the thermal modeling is approximately 1.25 inches in the radial direction and 1.6 inches in the axial direction. All void spaces within the packaging are assumed to be filled with air at one atmosphere. The heat transfer across all air gaps is computed as a combination of conduction and radiation.

Figure 3.5-2 illustrates the thermal modeling used for the 55-gallon drum and drum liner. Planar elements are used for these components since the temperature difference across these thin components will be small. The drum liner is assumed to be radially centered between the cane fiberboard and 55-gallon drum surfaces. This assumption leads to an approximate 0.23-inch airspace between the liner and the drum wall and between the liner and cane fiberboard surfaces. The liner is assumed to be supported around the ID of the 55-gallon drum with a varying air gap thickness between the liner and the dished end of the drum. A similar gap variation exists between the liner lid and the drum lid. For modeling purposes, a mean 0.25-inch air gap of is assumed at the bottom, while a 0.4-inch is assumed for the top air gap. The liner is assumed to be in direct contact with the base of the fiberboard dunnage, while an approximate 0.5-inch air gap exists between the lid of the dunnage and the inside surface of the liner lid.

Figure 3.5-3 illustrates the 'solids' thermal modeling of the cane fiberboard and the pipe component. The figure demonstrates that the geometry of these package components is accurately captured by the thermal modeling. The fibers of the dunnage material is assumed to be oriented vertically for the sides of the dunnage and horizontally for the base and lid segments. These assumed orientations are used in the application of the anisotropic properties for this material. The potential presence of buffer sheet of exterior plywood at the base of the dunnage cavity is ignored for simplicity in the modeling of the dunnage. This modeling simplification is seen as conservative under NCT conditions since the higher thermal conductivity of plywood will act to lower the internal temperatures of the package.

Similarly, the thermal modeling of the bolts and lift rings of the pipe component is not considered to be necessary for the determination of the peak temperatures within the S300 package.

A nominal 0.15-inch air space exists between the ID of the cane fiberboard and the sides of the pipe component. This gap is increased to an estimated mean of 1.8-inches at the top of the dunnage cavity. An air gap of 0.15 to 0.7-inches is used between the lid of the pipe component and the lid of the dunnage. Direct contact is assumed between the base of the pipe component and the base of the dunnage cavity.

Figure 3.5-4 illustrates the modeling used for the HDPE shielding and the SFC. Again, the geometry of these package components is accurately captured by the thermal modeling. Based on the nominal design dimensions, an air gap of 0.1-inches is assumed between the sides of the shielding and the pipe component, 0.5-inches is used between the top of the shielding and the underside of the pipe component's lid, and direct contact is assumed at the base of the HDPE shielding.

The SFC is assumed to be centered radially within the shielding cavity and to be resting against the base of the cavity. Based on the conservative assumption of transportation of the small Type III SFC, a nominal radial air gap of 0.5-inches would exist. The SFC is assumed to rest on the shield end plug with the heat transfer from the base computed as a direct contact. Given that the air gap above the SFC could be large, the heat transfer via conduction across the air gap is conservatively ignored for this surface of the SFC.

3.5.2.2 Insolation Loads

The principal thermal loading on the S300 package during NCT arises from insolation on the outer shell of the package. Since the S300 package is characterized by a thin outer shell, a relatively thick layer of low conductivity fiberboard dunnage and HDPE shielding material, the exterior package temperature will respond rapidly to the daily variation in insolation loading, but the payload will experience a much lower temperature swing.

The 10 CFR §71.71(c)(1) specified insolation values provide the total insolation over a 12-hour period to horizontal, curved, and vertical surfaces. Application of these specified insolation values to the steady-state evaluation of the package's thermal performance requires converting the total insolation received on any surface to hourly averaged values (typically 12 or 24 hour averages). However, per IAEA Safety Guide TS-G-1.1 §654.4[21], the more precise way to model insolation is to use a time dependant sinusoidal heat flux . As such, the peak NCT temperatures for the S300 package are evaluated using a transient model and a diurnal cycle on insolation loading that provides the equivalent 10 CFR §71.71(c)(1) insolation over a 12 hour period.

A sine wave model is used to simulate the variation in the applied insolation on the surfaces of the package over a 24-hour period, except that when the sine function is negative, the insolation level is set to zero. The timing of the sine wave is set to achieve its peak at 12 pm and peak value of the curve is adjusted to ensure that the total energy delivered matched the regulatory values. As such, the total energy delivered in one day by the sine wave solar model is given by:

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[21] Safety Guide No. TS-G-1.1 (ST-2), *Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material*, IAEA Safety Standards Series, International Atomic Energy Agency, Vienna, Austria, 2002.

$$\int_{6\cdot hr}^{18\cdot hr} Q_{peak}\cdot\sin\left(\frac{\pi\cdot t}{12\cdot hr}-\frac{\pi}{2}\right)dt=\left(\frac{24\cdot hr}{\pi}\right)\cdot Q_{peak}$$

Using the expression above for the peak rate of insolation, the peak rates for top and side insolation on a vertically oriented 55-gallon drum may be calculated as follows:

$$Q_{top}=\left(800\frac{cal}{cm^2}\right)\cdot\left(\frac{\pi}{24\ hr}\right) \qquad Q_{top}=2.68\frac{Btu}{hr-in^2}\ =0.0447\frac{Btu}{min-in^2}$$

$$Q_{side}=\left(400\frac{cal}{cm^2}\right)\cdot\left(\frac{\pi}{24\ hr}\right) \qquad Q_{sside}=1.34\frac{Btu}{hr-in^2}\ =0.0223\frac{Btu}{min-in^2}$$

Conversion factors of 1 cal/cm^2-hr = 0.0256 Btu/hr-in^2 are used in the above calculations. These peak rates are multiplied by the sine function and the surface solar absorptivity to create the top and side insolation values as a function of time of day.

3.5.2.3 Description of Thermal Model for HAC Conditions

The thermal model used for HAC is described in Section 3.4.3, *Maximum Temperatures and Pressures*.

3.5.2.4 Convection Coefficient Calculation

The S300 package thermal model uses semi-empirical relationships to determine the level of convection heat transfer from the exterior package surfaces under the regulatory NCT conditions. The convective heat transfer coefficient, h_c, has a form of:

$$h_c=Nu\frac{k}{L}$$

where k is the thermal conductivity of the gas at the mean film temperature and L is the characteristic length of the vertical or horizontal surface. The convection coefficient is correlated via semi-empirical relationships against the local Rayleigh number and the characteristic length. The Rayleigh number is defined as:

$$Ra_L=\frac{\rho^2 g_c\,\beta\,L^3\Delta T}{\mu^2}\times Pr$$

where

g_c = gravitational acceleration, 32.174 ft/s^2
β = coefficient of thermal expansion, °R^{-1}
ΔT = temperature difference, °F
ρ = density of air at the film temperature, lb$_m$/ft^3
μ = dynamic viscosity, lb$_m$/ft-s
Pr = Prandtl number = $(c_p\,\mu)/k$
L = characteristic length , ft
k = thermal conductivity at film temp., Btu/ft-hr-°F
c_p = specific heat, Btu/ lb$_m$ -°F
Ra_L = Rayleigh #, based on length 'L'

Note that k, c_p, and μ are each a function of air temperature as taken from Table 3.2-4. Values for ρ are computed using the ideal gas law, β for an ideal gas is simply the inverse of the absolute temperature of the gas, and Pr is computed using the values for k, c_p, and μ from Table 3.2-4. Unit conversion factors are used as required to reconcile the units for the various properties used.

The natural convection from a discrete vertical surface is computed using Equations 4-13, 4-24, 4-31, and 4-33 of Rohsenow, et. al., which is applicable over the range 1 < Rayleigh number (Ra) < 10^{12}:

$$\mathrm{Nu}^{\mathrm{T}} = \overline{\mathrm{C}}_{\mathrm{L}}\mathrm{Ra}^{1/4}$$

$$\overline{\mathrm{C}}_{L} = \frac{0.671}{\left(1 + (0.492/\mathrm{Pr})^{9/16}\right)^{4/9}}$$

$$\mathrm{Nu}_{\mathrm{L}} = \frac{2.0}{\ln(1 + 2.0/\mathrm{Nu}^{\mathrm{T}})}$$

$$\mathrm{Nu}_{\mathrm{t}} = \mathrm{C}_{\mathrm{t}}^{\mathrm{V}}\mathrm{Ra}^{1/3} / \left(1 + 1.4 \times 10^{9}\,\mathrm{Pr/Ra}\right)$$

$$\mathrm{C}_{\mathrm{t}}^{\mathrm{V}} = \frac{0.13\,\mathrm{Pr}^{0.22}}{\left(1 + 0.61\,\mathrm{Pr}^{0.81}\right)^{0.42}}$$

$$\mathrm{Nu} = \frac{\mathrm{h_c L}}{\mathrm{k}} = \left[(\mathrm{Nu}_{\mathrm{L}})^{6} + (\mathrm{Nu}_{\mathrm{t}})^{6}\right]^{1/6}$$

The natural convection from a vertical cylindrical surface is computed by applying a correction factor to the laminar Nusselt number ($\mathrm{Nu_L}$) determined using the same methodology and $\mathrm{Nu_t}$ for a vertical plate (see above). The characteristic dimension, L, is the height of the vertical cylinder and D is the cylinder's diameter. The correction factor as defined by Equations 4-44 of Rohsenow, et. al., is:

$$\mathrm{Nu}_{\text{L-Cylinder}} = \frac{\delta}{\ln(1 + \delta)}\mathrm{Nu}_{\text{L-Plate}}$$

$$\delta = \frac{1.8 \times \mathrm{L/D}}{\mathrm{Nu}_{\text{Plate}}^{\mathrm{T}}}$$

$$\mathrm{Nu}_{\text{Vert Cylinder}} = \frac{\mathrm{h_c L}}{\mathrm{k}} = \left[(\mathrm{Nu}_{\text{L-Cylinder}})^{6} + (\mathrm{Nu}_{\text{t-Plate}})^{6}\right]^{1/6}$$

Natural convection from horizontal surfaces is computed from Equations 4-13, 4-25, 4-39, and 4-40 of Rohsenow, et. al., where the characteristic dimension (L) is equal to the plate surface area divided by the plate perimeter. For a heated surface facing upwards or a cooled surface facing downwards and Ra > 1:

$$\mathrm{Nu} = \frac{\mathrm{h_c L}}{\mathrm{k}} = \left[(\mathrm{Nu}_{\mathrm{L}})^{10} + (\mathrm{Nu}_{\mathrm{t}})^{10}\right]^{1/10}$$

$$\mathrm{Nu}_{\mathrm{L}} = \frac{1.4}{\ln\left(1 + 1.4/\left(0.835 \times \overline{\mathrm{C}}_{\mathrm{L}}\mathrm{Ra}^{1/4}\right)\right)}$$

$$\overline{C}_L = \frac{0.671}{\left(1+\left(0.492/\mathrm{Pr}\right)^{9/16}\right)^{4/9}}$$

$$\mathrm{Nu}_t = 0.14 \times \left(\frac{1+0.0107\times \mathrm{Pr}}{1+0.01\times \mathrm{Pr}}\right) \times \mathrm{Ra}^{1/3}$$

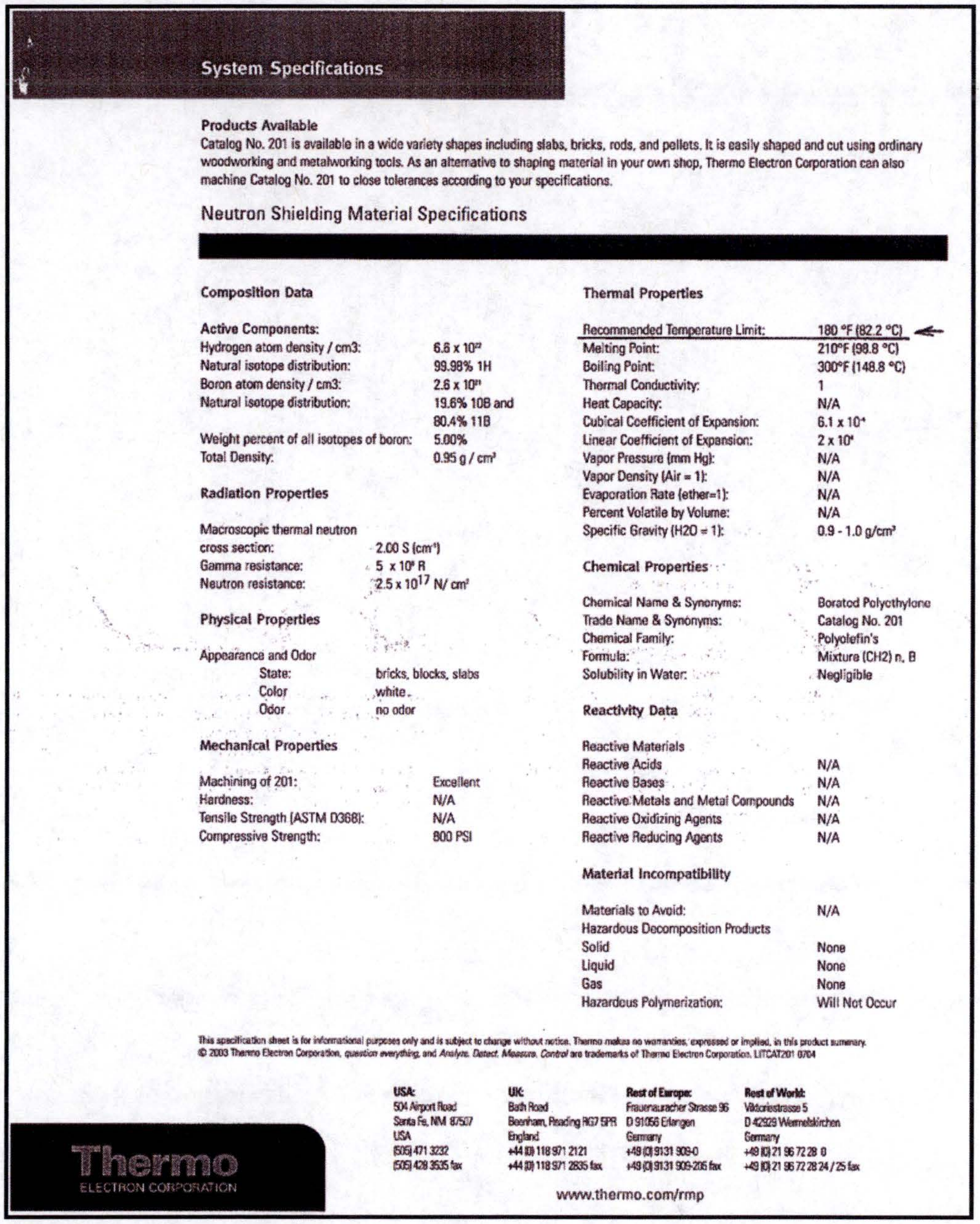
For a heated surface facing downwards or a cooled surface facing upwards and $10^3 < \mathrm{Ra} < 10^{10}$, the correlation is as follows:

$$\mathrm{Nu} = \mathrm{Nu}_L = \frac{2.5}{\ln\left(1+2.5/\mathrm{Nu}^T\right)}$$

$$\mathrm{Nu}^T = \frac{0.527}{\left(1+\left(1.9/\mathrm{Pr}\right)^{9/10}\right)^{2/9}} \mathrm{Ra}^{1/5}$$

3.5.3 Material Data Sheets

Neutron Shielding Material (Thermo-Electron Corp, Catalog No. 201 Product Specifications, 2003



System Specifications

Products Available

Catalog No. 201 is available in a wide variety shapes including slabs, bricks, rods, and pellets. It is easily shaped and cut using ordinary woodworking and metalworking tools. As an alternative to shaping material in your own shop, Thermo Electron Corporation can also machine Catalog No. 201 to close tolerances according to your specifications.

Neutron Shielding Material Specifications

Composition Data

Active Components:	
Hydrogen atom density / cm3:	6.6 x 10^{22}
Natural isotope distribution:	99.98% 1H
Boron atom density / cm3:	2.6 x 10^{21}
Natural isotope distribution:	19.6% 10B and 80.4% 11B
Weight percent of all isotopes of boron:	5.00%
Total Density:	0.95 g / cm^3

Radiation Properties

Macroscopic thermal neutron cross section:	2.00 S (cm^{-1})
Gamma resistance:	5 x 10^{8} R
Neutron resistance:	2.5 x 10^{17} N/ cm^2

Physical Properties

Appearance and Odor	
State:	bricks, blocks, slabs
Color	white
Odor	no odor

Mechanical Properties

Machining of 201:	Excellent
Hardness:	N/A
Tensile Strength (ASTM D368):	N/A
Compressive Strength:	800 PSI

Thermal Properties

Recommended Temperature Limit:	180 °F (82.2 °C) ←
Melting Point:	210°F (98.8 °C)
Boiling Point:	300°F (148.8 °C)
Thermal Conductivity:	1
Heat Capacity:	N/A
Cubical Coefficient of Expansion:	6.1 x 10^{-4}
Linear Coefficient of Expansion:	2 x 10^{-4}
Vapor Pressure (mm Hg):	N/A
Vapor Density (Air = 1):	N/A
Evaporation Rate (ether=1):	N/A
Percent Volatile by Volume:	N/A
Specific Gravity (H2O = 1):	0.9 - 1.0 g/cm^3

Chemical Properties

Chemical Name & Synonyms:	Boratod Polyethylone
Trade Name & Synonyms:	Catalog No. 201
Chemical Family:	Polyolefin's
Formula:	Mixture (CH2) n, B
Solubility in Water:	Negligible

Reactivity Data

Reactive Materials	
Reactive Acids	N/A
Reactive Bases	N/A
Reactive Metals and Metal Compounds	N/A
Reactive Oxidizing Agents	N/A
Reactive Reducing Agents	N/A

Material Incompatibility

Materials to Avoid:	N/A
Hazardous Decomposition Products	
Solid	None
Liquid	None
Gas	None
Hazardous Polymerization:	Will Not Occur

USA:
504 Airport Road
Santa Fe, NM 87507
USA
(505) 471 3232
(505) 428 3535 fax

UK:
Bath Road
Beenham, Reading RG7 5PR
England
+44 (0) 118 971 2121
+44 (0) 118 971 2835 fax

Rest of Europe:
Frauenauracher Strasse 96
D 91056 Erlangen
Germany
+49 (0) 9131 909-0
+49 (0) 9131 909-205 fax

Rest of World:
Viktoriastrasse 5
D 42929 Wermelskirchen
Germany
+49 (0) 21 96 72 28 0
+49 (0) 21 96 72 28 24 / 25 fax

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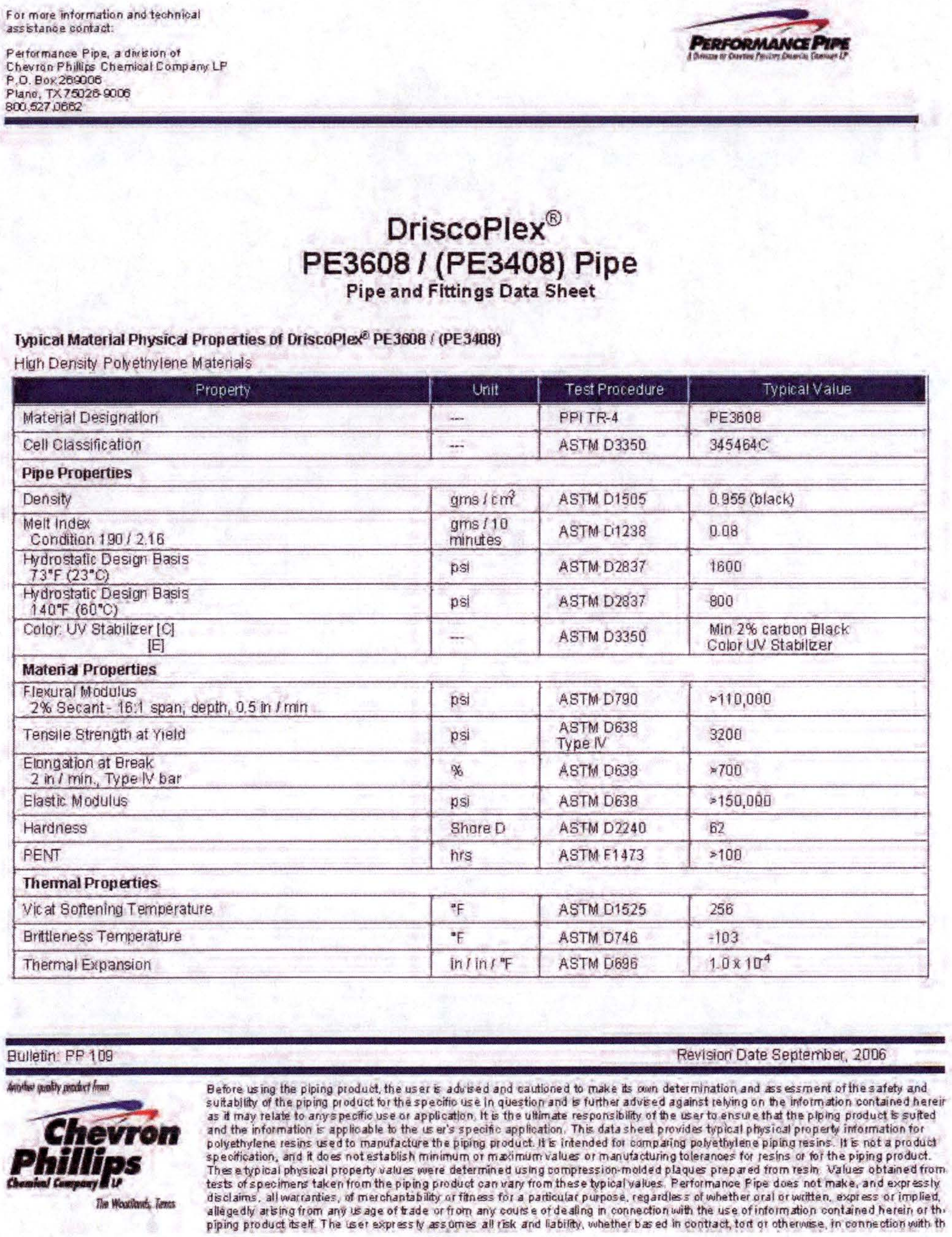
DriscoPlex® PE3608/(PE3408) Pipe, Pipe and Fittings Data Sheet, Bulletin PP 109



For more information and technical
assistance contact:

Performance Pipe, a division of
Chevron Phillips Chemical Company LP
P.O. Box 269006
Plano, TX 75026-9006
800.527.0662

DriscoPlex®
PE3608 / (PE3408) Pipe
Pipe and Fittings Data Sheet

Typical Material Physical Properties of DriscoPlex® PE3608 / (PE3408)

High Density Polyethylene Materials

Property	Unit	Test Procedure	Typical Value
Material Designation	---	PPI TR-4	PE3608
Cell Classification	---	ASTM D3350	345464C
Pipe Properties			
Density	gms / cm^3	ASTM D1505	0.955 (black)
Melt Index Condition 190 / 2.16	gms / 10 minutes	ASTM D1238	0.08
Hydrostatic Design Basis 73°F (23°C)	psi	ASTM D2837	1600
Hydrostatic Design Basis 140°F (60°C)	psi	ASTM D2837	800
Color; UV Stabilizer [C] [E]	---	ASTM D3350	Min 2% carbon Black Color UV Stabilizer
Material Properties			
Flexural Modulus 2% Secant - 16:1 span; depth, 0.5 in / min	psi	ASTM D790	>110,000
Tensile Strength at Yield	psi	ASTM D638 Type IV	3200
Elongation at Break 2 in / min., Type IV bar	%	ASTM D638	>700
Elastic Modulus	psi	ASTM D638	>150,000
Hardness	Shore D	ASTM D2240	62
PENT	hrs	ASTM F1473	>100
Thermal Properties			
Vicat Softening Temperature	°F	ASTM D1525	256
Brittleness Temperature	°F	ASTM D746	-103
Thermal Expansion	in / in / °F	ASTM D696	1.0×10^{-4}

Bulletin: PP 109 Revision Date September, 2006

Another quality product from
Chevron Phillips Chemical Company LP
The Woodlands, Texas

Before using the piping product, the user is advised and cautioned to make its own determination and assessment of the safety and suitability of the piping product for the specific use in question and is further advised against relying on the information contained hereir as it may relate to any specific use or application. It is the ultimate responsibility of the user to ensure that the piping product is suited and the information is applicable to the user's specific application. This data sheet provides typical physical property information for polyethylene resins used to manufacture the piping product. It is intended for comparing polyethylene piping resins. It is not a product specification, and it does not establish minimum or maximum values or manufacturing tolerances for resins or for the piping product. These typical physical property values were determined using compression-molded plaques prepared from resin. Values obtained from tests of specimens taken from the piping product can vary from these typical values. Performance Pipe does not make, and expressly disclaims, all warranties, of merchantability or fitness for a particular purpose, regardless of whether oral or written, express or implied, allegedly arising from any usage of trade or from any course of dealing in connection with the use of information contained herein or th piping product itself. The user expressly assumes all risk and liability, whether based in contract, tort or otherwise, in connection with th

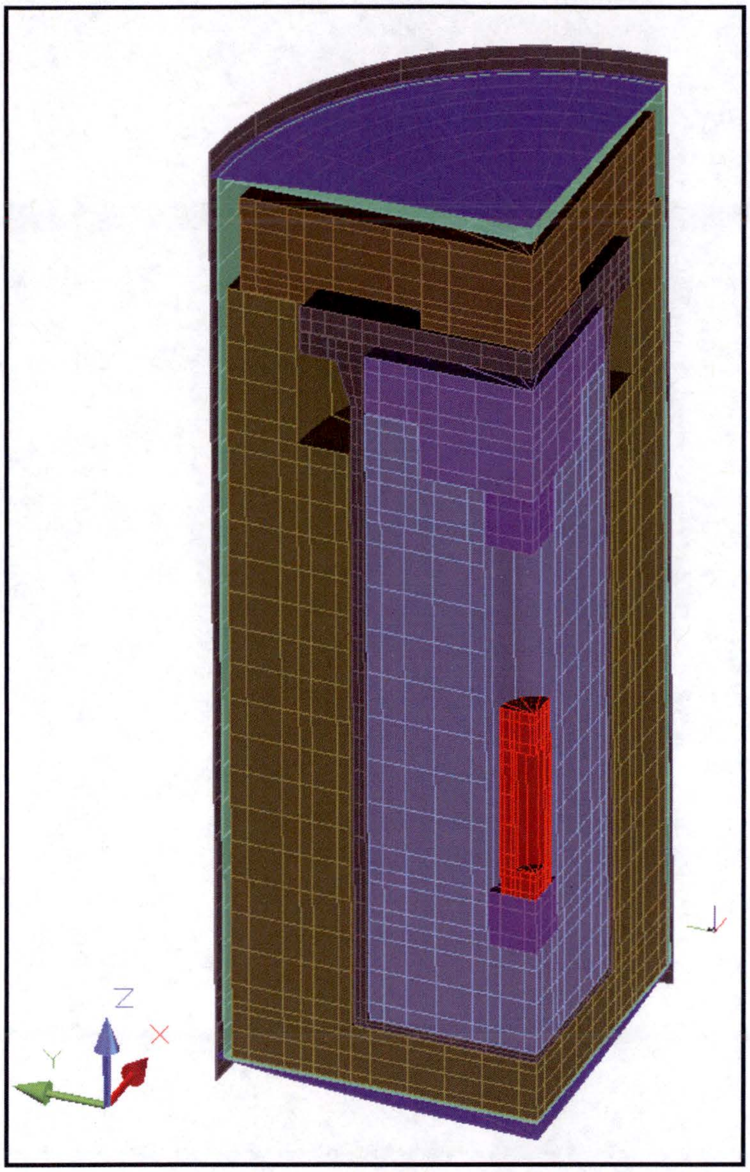


Figure 3.5-1 – Isometric View of 'Solids' Thermal Model for S300 Packaging

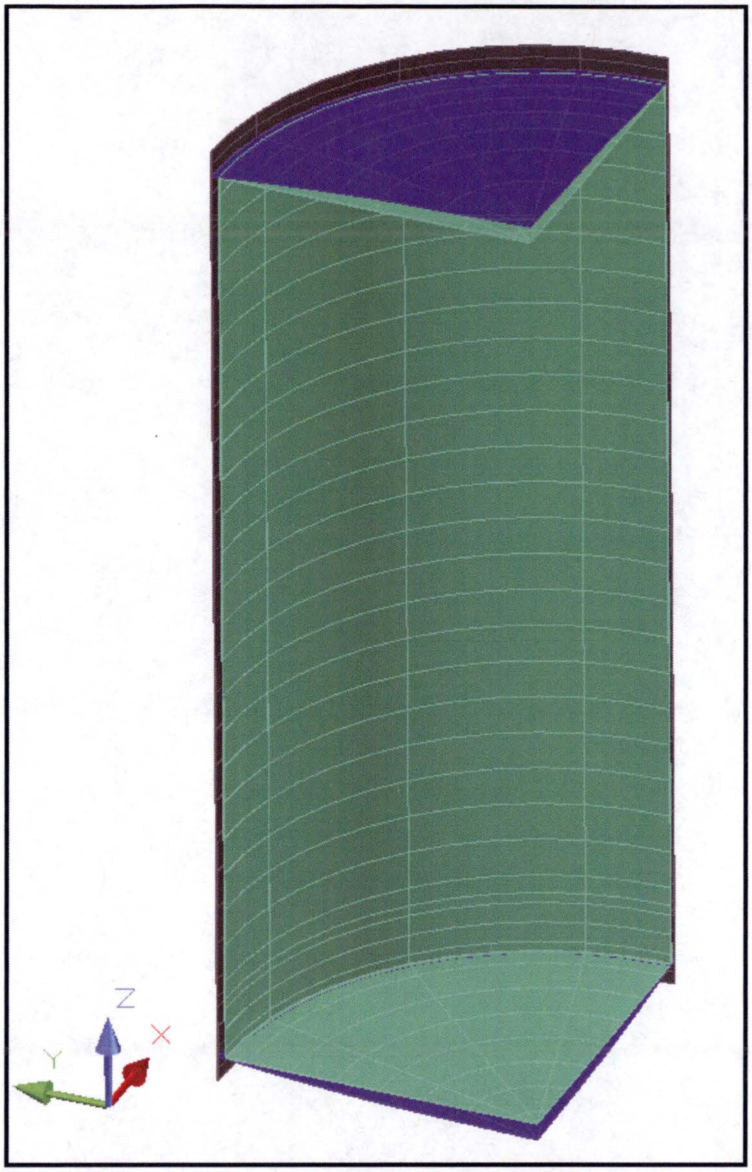


Figure 3.5-2 – View of Planar Elements for 55-Gallon Drum and Liner

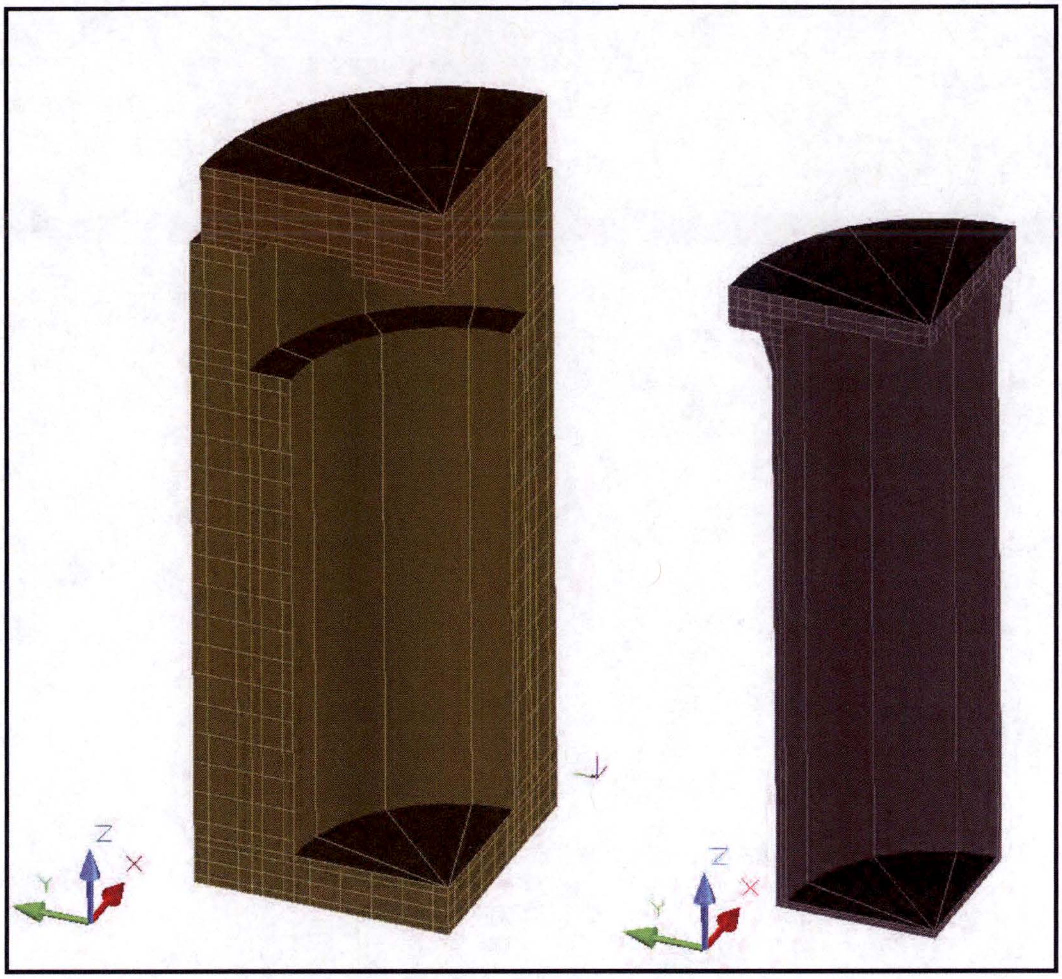


Figure 3.5-3 – 'Solids' Model for Cane Fiberboard Dunnage and Pipe Component

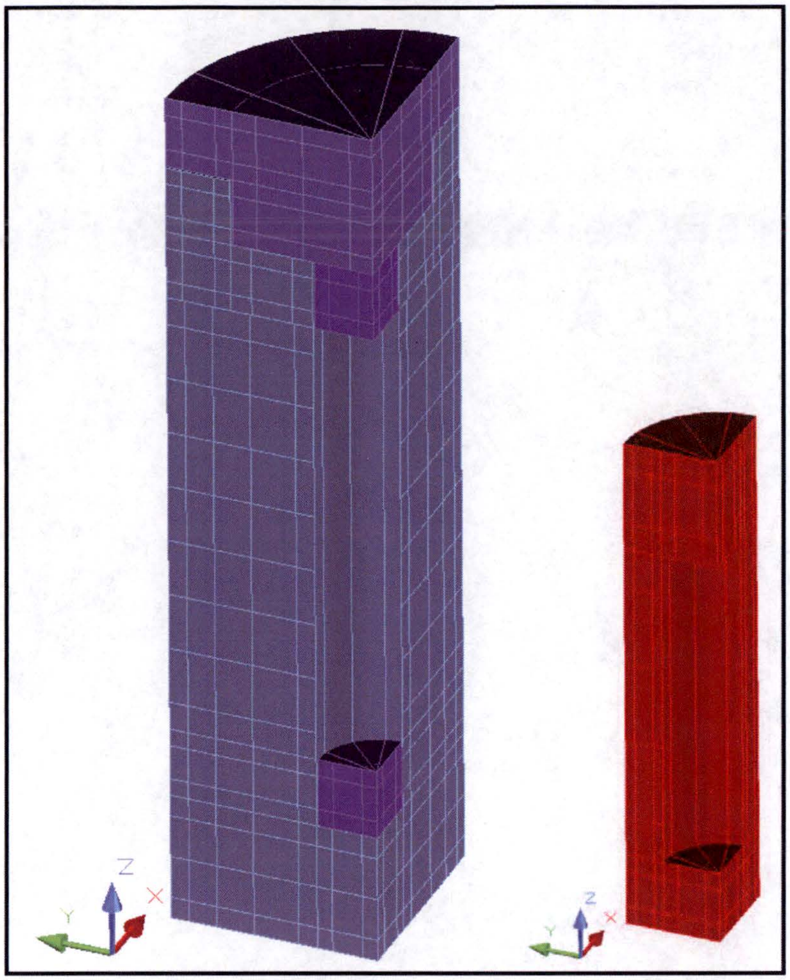


Figure 3.5-4 – 'Solids' Model for HDPE Shielding and SFC

4. CONTAINMENT

Containment of radioactive materials is provided by the SFC. See Section 2.10, *Special Form*, for more details on the SFC. Since the S300 package does not provide containment, this section does not apply.

5. SHIELDING EVALUATION

This chapter documents the shielding analysis for the S300 transportation package with a plutonium neutron source. Plutonium generates neutrons via an (α,n) reaction with a target nucleus. The S300 may be used to ship plutonium neutron sources with any target nucleus, although beryllium is the most common target nucleus and generates the largest number of neutrons. Such plutonium/beryllium sources are known as PuBe sources. Plutonium foils and alpha reference standards are also an allowed content, although these items lack a target nucleus and generate a negligible dose rate compared to PuBe sources. Hence, this chapter does not explicitly address shielding of the plutonium foils and alpha reference standards. The plutonium mass of the foils and alpha reference standards is bounded by the plutonium mass of the PuBe sources.

Both non-exclusive use and exclusive use conditions are considered. For non-exclusive use and air transport conditions, dose rates on the surface and 1 m are calculated for normal conditions of transport (NCT) and are shown to be less than the 10 CFR 71 limits of 200 mrem/hr and 10 mrem/hr, respectively. For exclusive use conditions applicable to a closed transport vehicle, dose rates on the package surface, vehicle surface, and 2 m from the vehicle surface are shown to be less than the 10 CFR 71 limits of 1000 mrem/hr, 200 mrem/hr, and 10 mrem/hr, respectively. For hypothetical accident conditions (HAC), the dose rates are less than 1000 mrem/hr at 1 m.

5.1 Description of Shielding Design

5.1.1 Design Features

The S300 packaging is a 55-gallon drum with polyethylene shielding inside of a 12-inch stainless steel pipe component (see Figure 1-1). The interior of the pipe contains radial and axial solid polyethylene shielding to provide an inner cavity with a diameter of 3.5 inches and a length of 17 inches. Solid disks of polyethylene, two inches thick, are also placed at the top and bottom of the cavity, reducing the usable cavity length to 13 inches. External to the steel pipe component is fiberboard dunnage. A polyethylene liner 0.11 inches thick is placed inside the drum. The outer dimension of the S300 drum is that of a standard 55-gallon drum, i.e., nominally 24 inches in diameter and 35 inches in height. Plywood and fiberboard dunnage are also present in the drum above, below, and around the pipe component. Dunnage is added to the top of the package as required so that the gap between the dunnage and top lid is less than 1/2 inch. The dimensions of the package are provided in Table 5-1.

The packaging includes polyethylene (shielding, $\rho = 0.92$ g/cm^3), stainless steel (pipe component, $\rho = 7.94$ g/cm^3), dunnage ($\rho = 0.224$ g/cm^3), and carbon steel (drum, $\rho = 7.8212$ g/cm^3). The material specifications are discussed further in Section 5.3.2, *Material Properties*.

Table 5-1 – S300 Packaging Dimensions

Component	Actual Dimension (inches)
Steel Pipe OD	12.8 (max)
Steel Pipe length	25.6
Steel pipe wall thickness	0.219 (min)
Steel pipe floor thickness	0.25 (min)
Steel Pipe lid thickness	0.9
Diameter of Polyethylene Plugs	3.5
Height of Polyethylene Plugs	2.0
ID of Polyethylene Sleeve	3.5
OD of Polyethylene Sleeve	11.8
Inner cavity height poly sleeve	17.0
Thickness poly sleeve lid	4.0
Thickness poly sleeve bottom	22.7-17.0-2.0 = 3.7
Outside drum height	34-13/16
Thickness of bottom dunnage	2.1
Height of pipe dunnage	21.4
Height of flange dunnage	4.8 + 0.5 = 5.3
Thickness of top dunnage (thickest location)	2.6
OD of dunnage	21.5 (slightly smaller for top dunnage)
ID of pipe dunnage	13.1
ID of flange dunnage	16.6
Drum liner thickness	0.11

5.1.2 Summary Table of Maximum Radiation Levels

The source may be contained within one of two special form capsules, the Model II and Model III. The Model II is larger than the Model III and therefore may hold a larger mass of source material. Maximum dose rates are provided for the following three scenarios:

- Table 5-2: Model II Capsule containing 206 g Pu, Non-Exclusive Use
- Table 5-3: Model II Capsule containing 350 g Pu, Exclusive Use (closed vehicle)
- Table 5-4: Model III Capsule containing 160 g Pu, Non-Exclusive Use

The transport index (TI) is the maximum dose rate at 1 m from the surface of the package. For non-exclusive use, the TI = 7.5. The TI for the Model II Capsule bounds the TI for the Model III Capsule.

The HAC dose rates are computed only for the maximum Pu loading of 350 g and are provided in Table 5-5.

Table 5-2 – Model II Capsule NCT Dose Rates (Non-exclusive use)

206 g Pu	**Package Surface (mrem/hr)**			**1 m from Package Surface (mrem/hr)**		
TI = 7.5	**Top**	**Side**	**Bottom**	**Top**	**Side**	**Bottom**
Gamma	<11.3	12.4	11.3	<0.4	0.5	0.4
Neutron	<114.3	187.0	114.3	<3.8	7.0	3.8
Total	<125.6	**199.4**	125.6	<4.1	7.5	4.1
Limit		200			10	

Note: All reported dose rates are rounded to the nearest one-tenth, although the total dose rate values are based on the sum of unrounded values. Therefore, the sum of the rounded gamma and neutron dose rates will not necessarily equal the total rounded dose rate value.

Table 5-3 – Model II Capsule NCT Dose Rates (Exclusive use)

350 g Pu	**Package Surface (mrem/hr)**			**Vehicle Surface (mrem/hr)**		
TI = NA	**Top**	**Side**	**Bottom**	**Top**	**Side**	**Bottom**
Gamma	<19.2	21.0	19.2	<9.0	0.9	9.0
Neutron	<194.2	317.7	194.2	<91.2	11.8	91.2
Total	<213.5	**338.7**	213.5	<100.2	12.7	100.2
Limit		1000			200	
	2m from Vehicle Surface (mrem/hr)			**Occupied Location (mrem/hr)**		
	Top	**Side**	**Bottom**	**Top**	**Side**	**Bottom**
Gamma	NA	0.1	NA	NA	<0.1	NA
Neutron	NA	1.6	NA	NA	<1.6	NA
Total	NA	1.7	NA	NA	<1.7	NA
Limit		10			2	

Note: All reported dose rates are rounded to the nearest one-tenth, although the total dose rate values are based on the sum of unrounded values. Therefore, the sum of the rounded gamma and neutron dose rates will not necessarily equal the total rounded dose rate value.

Table 5-4 – Model III Capsule NCT Dose Rates (Non-exclusive use)

160 g Pu	**Package Surface (mrem/hr)**			**1 m from Package Surface (mrem/hr)**		
TI = 5.8	**Top**	**Side**	**Bottom**	**Top**	**Side**	**Bottom**
Gamma	<8.8	9.6	8.8	<0.3	0.4	0.3
Neutron	<88.8	145.2	88.8	<2.9	5.4	2.9
Total	<97.6	154.8	97.6	<3.2	5.8	3.2
Limit		200			10	

Note: All reported dose rates are rounded to the nearest one-tenth, although the total dose rate values are based on the sum of unrounded values. Therefore, the sum of the rounded gamma and neutron dose rates will not necessarily equal the total rounded dose rate value.

Table 5-5 – Bounding HAC Dose Rates

350 g Pu	**1 m from Package Surface (mrem/hr)**		
	Top	**Side**	**Bottom**
Gamma	2.7	2.7	2.7
Neutron	58.3	58.3	58.3
Total	61.0	61.0	61.0
Limit		1000	

5.2 Source Specification

The source is modeled as a solid $PuBe_{13}$ neutron source, which bounds all other plutonium neutron sources and non-neutron sources. As the mass of the source may vary between packages, the source is computed for 1 g of plutonium.

5.2.1 Gamma Source

As the source is primarily a neutron emitter, the dose rate resulting from primary gamma radiation is a small fraction of the total dose rate. The gamma source is computed using the ORIGEN-S module of the SCALE6 code package[1] and is extracted from the same output file used to compute the neutron source. A detailed discussion of the data and assumptions used to develop the ORIGEN-S input file is included in Section 5.2.2, *Neutron Source*. The gamma source for 1 g of plutonium is listed in Table 5-6.

5.2.2 Neutron Source

The neutrons are generated by both (α,n) reactions and spontaneous fission, although the spontaneous fission component is negligible compared to the (α,n) component. Plutonium used in neutron sources is comprised of the following six isotopes: Pu-238, Pu-239, Pu-240, Pu-241, Pu-242, and Am-241. Of these six isotopes, all are alpha emitters with the exception of Pu-241, which is a beta emitter. Therefore, Pu-241 decay does not directly generate neutrons, although Pu-241 decays to Am-241, which is an alpha emitter and does generate neutrons.

The average plutonium isotopics used to generate the neutron source are obtained from LA-UR-09-06701[2] and are provided in Table 5-7. This report is included in Section 5.5.1, *Radionuclide Distribution Document LA-UR-09-06701*. Note that alpha emitters with a shorter half-life contribute more to the neutron source than an equivalent mass of a longer half-life alpha emitter because the alpha activity is greater for shorter half-lives. Therefore, the magnitude of the neutron source is directly related to the isotopics of the mixture.

Because Pu-241 has a half-life of 14.35 years, and since these sources may be 40 to 50 years old, it is conservatively assumed that all Pu-241 has completely decayed to Am-241. The "decay" is performed by simply treating the mass of Pu-241 as Am-241 and calculating the source at time zero; a formal decay calculation is not performed. Therefore, decay of the other plutonium isotopes is conservatively neglected. Note that the initial concentration of Am-241 is in addition to the mass of plutonium (see Table 5-7), so for 1 g of plutonium, the total mass of Pu+Am is 1.00025 g.

These isotopics are representative of the vast majority of plutonium neutron sources that have been generated. While the isotopics utilized do not necessarily bound all conceivable plutonium isotopics in regards to neutron source production, all packages will undergo dose rate

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[1] *SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluations*, ORNL/TM-2005/39, Version 6, Vols. I-III, January 2009.

[2] LA-UR-09-06701, *Radionuclide Distribution in Plutonium-239 Material Used for Sealed Source Production*, Los Alamos National Laboratory.

measurements at time of shipment, and the regulatory dose rate limits will not be exceeded if a PuBe source outlier is encountered.

The neutron source is calculated using the ORIGEN-S module of the SCALE6 code package. PuBe has the chemical formula $PuBe_{13}$.[3] Therefore, 1 g of plutonium has 0.49 g beryllium to maintain a Pu:Be atom ratio of 1:13. The actinide masses input to ORIGEN-S are included in Table 5-7. ORIGEN-S computes the neutron source assuming that the plutonium and beryllium are homogeneously mixed. The resultant neutron source per gram of plutonium is summarized in Table 5-8 and has a total magnitude of 1.519E+05 n/s. This source includes both spontaneous fission and (α,n) neutrons.

All MCNP dose rate calculations are performed for a source strength corresponding to 1 g of plutonium. These dose rates may then be scaled upward based on the initial plutonium mass of the source.

Although the vast majority of plutonium neutron sources would be PuBe, due to the many historical research programs conducted by the Department of Energy, non-PuBe plutonium neutron sources may exist. Therefore, it is desired to demonstrate that the PuBe neutron source in Table 5-8 bounds all other potential target isotopes. ORIGEN-S can compute (α,n) neutron sources for 19 different target isotopes, so these 19 isotopes are investigated. The 19 available target isotopes are listed in Table 5-9.

Detailed information on most of the non-PuBe sources is either unknown or non-existent. Therefore, developing a physically accurate representation for each of the 19 target isotopes is not possible. The approach is to develop models assuming an infinitely dilute mixture of plutonium and target isotope simply for comparison purposes. This will result in a bounding source magnitude because the neutron source increases as the mass of target isotope increases. The infinitely dilute source is a theoretical maximum that bounds the true source from a physically accurate source description. For the infinitely dilute mixture, an arbitrarily large target mass of 1000 g is selected per 1 g of plutonium.

The neutron source result for each of the target nuclides is summarized in Table 5-9. The target isotopes are listed in descending order of (α,n) neutron source strength. The PuBe source has the largest (α,n) neutron source strength and is therefore the bounding source type. The "Ratio to PuBe" column of the table is the ratio of the source strength for each target compared to the PuBe target.

Of the non-PuBe sources, the only practical target materials with a non-negligible source strength are B-11 and F-19. The source ratio for B-11 and F-19 are 0.309 and 0.120, respectively, indicating that these sources, as well as other targets, are well-bounded by the PuBe source.

The decay heat of the mixture is also computed by ORIGEN-S. The decay heat for 1 g of plutonium is 3.087E-03 W, or 1.1 W for a 350 g Pu source. This value is conservative because all of the Pu-241 is treated as Am-241.

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[3] RE Tate and AS Coffinberry, *Plutonium-Beryllium Neutron Sources, Their Fabrication and Neutron Yield*, 2nd UN Geneva Conference, 1958. This reference is provided in Section 6.9.1, *PuBe Neutron Source Paper.*

Table 5-6 – PuBe Gamma Source

Upper Energy (MeV)	Gamma source for 1 g Pu (γ/s)
0.05	2.831E+08
0.10	2.343E+08
0.20	3.924E+05
0.30	2.119E+04
0.40	1.050E+05
0.60	3.355E+04
0.80	8.015E+03
1.00	8.517E+01
1.33	7.952E+01
1.66	0.000E+00
2.00	3.302E+01
2.50	1.975E+01
3.00	1.131E+01
4.00	1.002E+01
5.00	3.330E+00
6.50	1.318E+00
8.00	2.554E-01
10.00	5.375E-02
Total	5.180E+08

Table 5-7 – Plutonium Isotopics

Isotope	Half-life (years)	Composition (Wt. %)	ORIGEN-S Input Mass for 1g Pu (g)
Pu-238	87.74	0.015	0.00015
Pu-239	24,119	92.6	0.9260
Pu-240	6,563	6.75	0.0675
Pu-241①	14.35	0.62	0.0
Pu-242	3.733E+05	0.033	0.00033
Am-241②	432.7	0.025	0.00645

①Modeled as Am-241 in ORIGEN-S.

②Am-241 is not included in the plutonium isotopics (i.e., the Pu isotopes alone sum to 100%). Therefore, 1 g Pu will have 0.00025 g Am-241 prior to decay, or a Pu+Am mass of 1.00025 g.

Table 5-8 – PuBe Neutron Source

Upper Energy (MeV)	Neutron source for 1 g Pu (n/s)
0	0.000E+00
0.01	1.158E-01
0.02	3.400E-01
0.05	2.034E+00
0.1	6.163E+00
0.2	1.855E+01
0.4	3.126E+02
0.6	1.293E+03
0.8	1.965E+03
1.0	2.196E+03
1.3	3.262E+03
1.7	3.331E+03
2.1	3.991E+03
2.4	3.938E+03
2.7	4.745E+03
3.0	7.544E+03
3.3	9.792E+03
3.6	9.489E+03
4.0	1.172E+04
4.4	1.071E+04
5.0	1.448E+04
6.0	1.518E+04
7.0	1.349E+04
8.0	1.496E+04
9.0	1.139E+04
10.0	7.087E+03
12.0	1.050E+03
15.0	5.177E-03
20.0	2.945E-04
Total	1.519E+05

Table 5-9 – Source Comparison of Available (α,n) Targets, Infinitely Dilute Mixture

Target isotope	(α,n) Neutron Source for 1 g Pu(n/s)	Ratio to PuBe
Be-9	2.422E+05	1.000
O-18	9.959E+04	0.411
Ne-22	9.547E+04	0.394
Ne-21	7.519E+04	0.310
B-11	7.485E+04	0.309
O-17	4.483E+04	0.185
F-19	2.898E+04	0.120
C-13	2.690E+04	0.111
Mg-26	1.772E+04	0.073
B-10	1.634E+04	0.067
Mg-25	1.391E+04	0.057
Li-7	7.141E+03	0.029
Si-29	5.771E+03	0.024
Na-23	4.814E+03	0.020
Si-30	4.118E+03	0.017
Al-27	1.633E+03	0.007
Cl-37	1.474E+03	0.006
N-14	0.000E+00	0.000
P-31	0.000E+00	0.000

5.3 Shielding Model

5.3.1 Configuration of Source and Shielding

NCT shielding models consider damage from 4-ft drop tests, which is negligible as discussed in Section 2.6.7, *Free Drop*. Damage is primarily confined to the rim of the package. The minor bending in the package rim is below the level of detail in the MCNP models because the protruding rims and locking mechanism are not modeled for simplicity. The MCNP model geometry is shown in Figure 5-1. Note that the model is simplified in the region of the pipe flange, although this simplification has negligible impact on the results.

Subsequent to a drop, it is assumed that the source will be shifted to a position that would generate the highest dose rates, i.e., at the bottom center of the package for the bottom dose rate calculation, or to the side of the package for the side dose rate calculation, as shown in Figure 5-2. It is conservatively assumed that the inner packaging would cease to be concentric if the S300 were lying on its side, closing the air gaps between the source and the dose rate locations. For simplicity, these air gaps are eliminated in the MCNP models in the side and bottom directions, although the thickness of each region is maintained. The net effect is to reduce the overall dimensions of the package, which conservatively brings the source closer to the dose rate locations.

It is not necessary to calculate dose rates on the top of the S300 because dose rates on the bottom will bound dose rates on the top for the following reasons: 1) there is a steel plug within the capsule above the source, but none below the source, 2) the top lid of the pipe component is thicker than the bottom (0.9 inches vs. 0.25 inches), 3) the top dunnage is thicker than the bottom dunnage (2.6 inches vs. 2.1 inches), placing the package surface farther from the source, and 4) the polyethylene shielding is thicker on the top than at the bottom (4.0 inches vs. 3.7 inches). Because the bottom dose rates bound the top dose rates, models with the S300 in an upside-down orientation with all air gaps closed between the source and the S300 lid are not developed.

The sealed source is modeled as Pu-Be_{13}, and any cladding material that encapsulates the source is conservatively neglected. The geometry of the source is consistent with 160 g Pu in a PuBe source, but this is not intended to limit the physical dimensions of the actual content to this exact configuration. The diameter of the source is 1.3 inches, and the height is 2.95 inches, consistent with the inner dimensions of the tantalum inner container manufactured by the Monsanto Research Corporation. A density of 3.7 g/cm^3 is computed based on the Pu mass and dimensional information.

Each sealed source is also enclosed in a stainless steel special form capsule. Two special form capsule designs are available, designated as the Model II and Model III capsules. Dimensions of these capsules are provided on Figure 1-3 and Figure 1-4 for the Model II and III capsule, respectively. As the source is a neutron source only, the capsule provides little shielding (capture gammas are generated outside the capsule). As the capsule has little effect on the dose rates, rather than develop separate models for each capsule type, a "hybrid" capsule is developed to bound both capsule designs. The hybrid capsule combines the minimum thicknesses from the two capsule types, see Table 5-11. Note that the overall length, ID, and OD of the capsules has been adjusted so that no air gap is present between the capsule and the inner polyethylene sleeve.

This simplification has been made for modeling convenience and has no impact on the calculation.

In the HAC configuration, the source is modeled as a point source. As the S300 lid may not remain on the package in an accident, it is assumed for the HAC models that the special form capsule has been ejected from the packaging. The source capsule itself is modeled in a simplified manner as a spherical shell of stainless steel with the same inner and outer radius of the hybrid capsule. The tally is calculated 1 m from the source over a spherical surface, which results in quick model convergence. Because the model is spherical, the top, bottom, and side dose rate values are the same.

Table 5-10 – S300 Overpack As-Modeled Dimensions

Component	Actual Dimension (inches)	As-Modeled Dimension (inches)
Steel Pipe OD	12.8 (max)	12.188
Steel Pipe length	25.6	25.7
Steel pipe wall thickness	0.219 (min)	0.219
Steel pipe floor thickness	0.25 (min)	0.25
Steel Pipe lid thickness	0.9	0.9
Diameter of Polyethylene Plugs	3.5	3.5
Height of Polyethylene Plugs	2.0	2.0
ID of Polyethylene Sleeve	3.5	3.5
OD of Polyethylene Sleeve	11.8	11.75
Inner cavity height poly sleeve	17.0	17.0
Thickness poly sleeve lid	4.0	4.0
Thickness poly sleeve bottom	22.7-17.0-2.0 = 3.7	3.7
Outside drum height	34-13/16	35
Thickness of bottom dunnage	2.1	2.1
Height of pipe dunnage	21.4	26.6 (combined pipe and flange dunnage)
Height of flange dunnage	4.8 + 0.5 = 5.3	26.6 (combined pipe and flange dunnage)
Thickness of top dunnage (thickest location)	2.6	3.1 (additional 0.5" assumed[4])
OD of dunnage	21.5 (slightly smaller for top dunnage)	20.588
ID of pipe dunnage	13.1	12.188
ID of flange dunnage	16.6	12.188
Drum liner thickness	0.11	0.11

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[4] In actual practice, dunnage will be added to the top of the package so that the gap between the top dunnage and the lid is less than 1/2 inch thick.

Table 5-11 – Hybrid Capsule Dimensions

Component	Model II Capsule Actual Dimension (inches)	Model III Capsule Actual Dimension (inches)	Hybrid Dimension used in MCNP (inches)
Overall length (not including shearable cap)	11.75	7.00	13.0
Thickness of cap	0.75	0.75	0.75
Thickness of sealing plug	0.78	0.77	0.77
Diameter and length of hole in sealing plug	0.25/0.38	NA	0.25/0.38
ID	2.062	1.50	2.562
OD	3.00	2.50	3.5
Side Thickness	0.469	0.5	0.469
Bottom Thickness	<1.0 when drill point included	<1.0 when drill point included	0.5

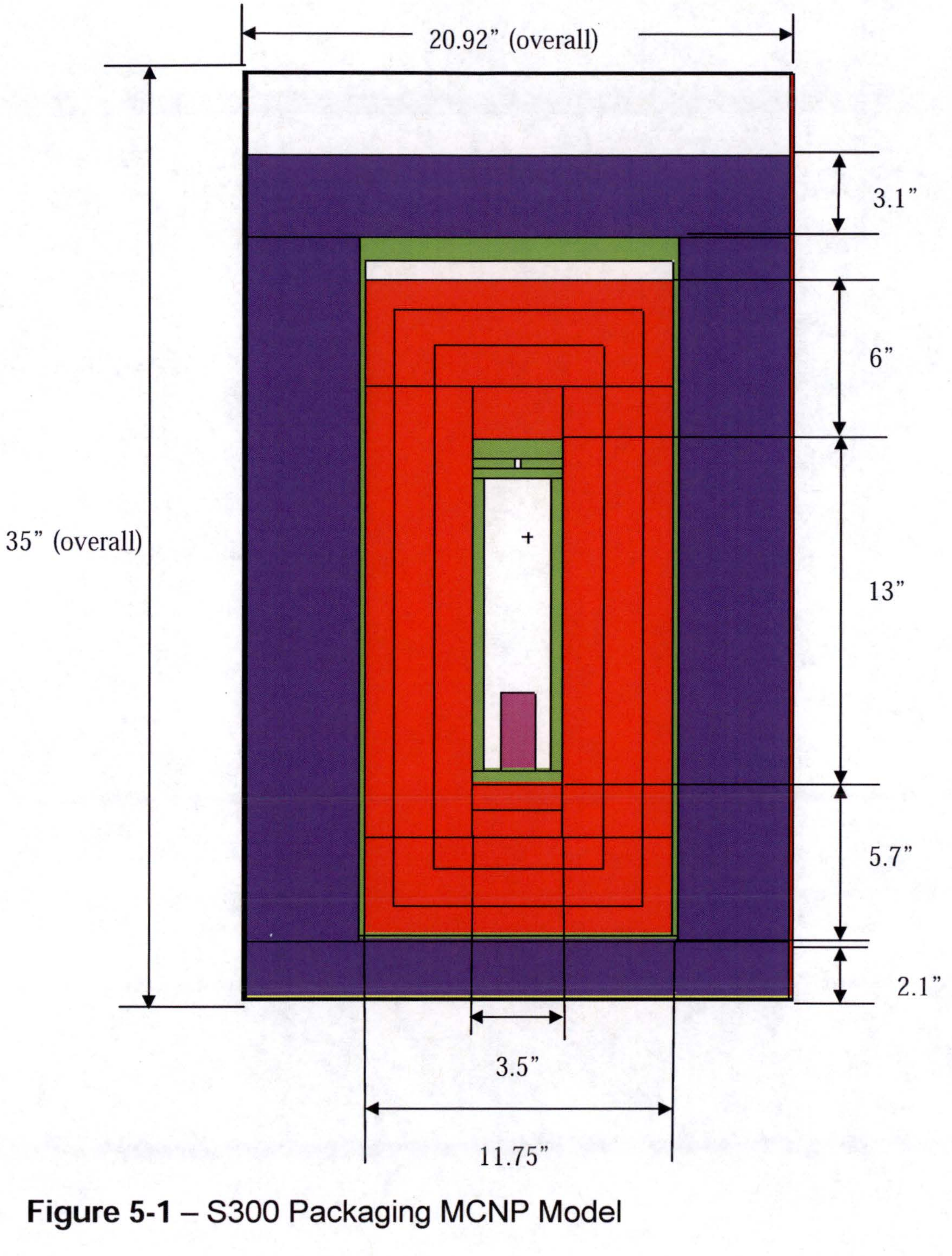
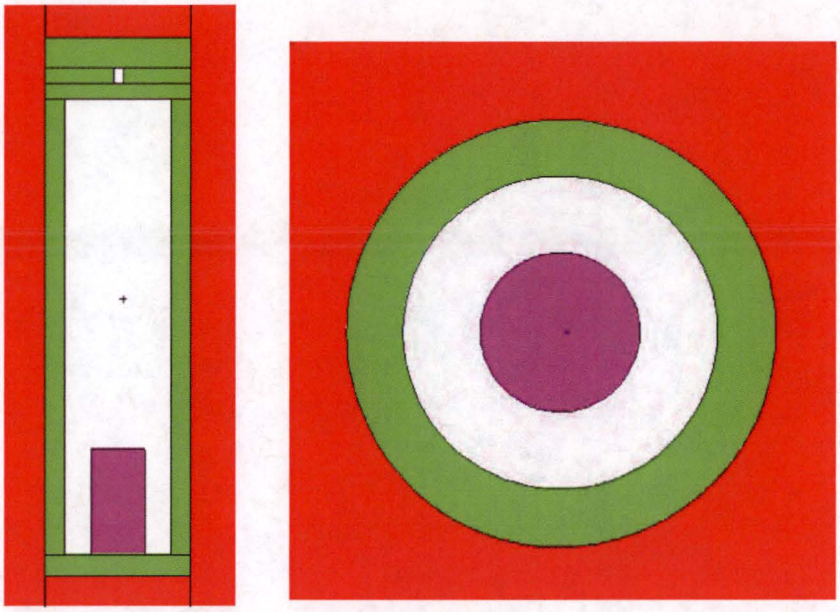
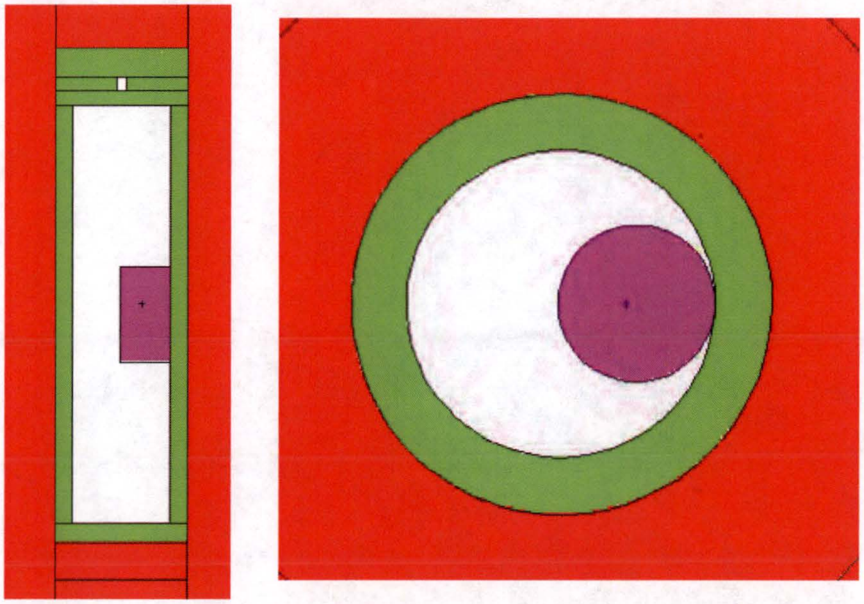


Figure 5-1 – S300 Packaging MCNP Model



Source in bottom position



Source in side position

Figure 5-2 – Source Positions for Bottom and Side Models

5.3.2 Material Properties

The material properties are provided in Table 5-12. The composition and density of common materials are taken from the SCALE Standard Composition Library[5]. Compositions are input as either atoms per molecule or weight percent (wt. %), depending on how the composition is listed in the reference. The dunnage is assumed to have the same composition as redwood but with a density of 14 lb/ft^3 (0.224 g/cm^3), as shown on the SAR drawing. The PuBe density is computed, as discussed in Section 5.3.1, *Configuration of Source and Shielding*.

Table 5-12 – Material Properties

<table>
<tr><th colspan="6">Polyethylene, CH_2 (density = 0.92 g/cm^3) (from SCALE)</th></tr>
<tr><td>Element</td><td>Library ID</td><td>Atoms</td><td>Element</td><td>Library ID</td><td>Atoms</td></tr>
<tr><td>Hydrogen</td><td>1001</td><td>2</td><td>Carbon</td><td>6000</td><td>1</td></tr>
<tr><th colspan="6">304SS (density = 7.94 g/cm^3) (from SCALE)</th></tr>
<tr><td>Element</td><td>Library ID</td><td>Wt. %</td><td>Element</td><td>Library ID</td><td>Wt. %</td></tr>
<tr><td>Carbon</td><td>6000</td><td>0.08</td><td>Manganese</td><td>25055</td><td>2.0</td></tr>
<tr><td>Silicon</td><td>14000</td><td>1.0</td><td>Iron</td><td>26000</td><td>68.375</td></tr>
<tr><td>Phosphorus</td><td>15031</td><td>0.045</td><td>Nickel</td><td>28000</td><td>9.5</td></tr>
<tr><td>Chromium</td><td>24000</td><td>19.0</td><td>-</td><td>-</td><td>-</td></tr>
<tr><th colspan="6">Dunnage – Composition: Redwood, $C_6H_{10}O_5$ (density 0.224 g/cm^3)
(composition from SCALE, density from SAR drawing)</th></tr>
<tr><td>Element</td><td>Library ID</td><td>Atoms</td><td>Element</td><td>Library ID</td><td>Atoms</td></tr>
<tr><td>Carbon</td><td>6000</td><td>6</td><td>Oxygen</td><td>8016</td><td>5</td></tr>
<tr><td>Hydrogen</td><td>1001</td><td>10</td><td>-</td><td>-</td><td>-</td></tr>
<tr><th colspan="6">Carbon steel (density = 7.8212 g/cm^3) (from SCALE)</th></tr>
<tr><td>Element</td><td>Library ID</td><td>Wt. %</td><td>Element</td><td>Library ID</td><td>Wt. %</td></tr>
<tr><td>Carbon</td><td>6000</td><td>1.0</td><td>Iron</td><td>26000</td><td>99.0</td></tr>
<tr><th colspan="6">$PuBe_{13}$ Source (density = 3.7 g/cm^3)</th></tr>
<tr><td>Element</td><td>Library ID</td><td>Atoms</td><td>Element</td><td>Library ID</td><td>Atoms</td></tr>
<tr><td>Plutonium</td><td>94239</td><td>1</td><td>Beryllium</td><td>4009</td><td>13</td></tr>
</table>

5.4 Shielding Evaluation

5.4.1 Methods

MCNP5 v1.40 is used for the shielding analysis[6]. MCNP5 is a standard, well-accepted shielding program utilized to compute dose rates for shielding licenses. A three-dimensional model is developed that captures all of the relevant design parameters of the S300 package. Dose rates

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[5] Standard Composition Library, ORNL/TM-2005/39, Version 6, Vol. III, Sec. M8, January 2009.

[6] MCNP – A General Monte Carlo N-Particle Transport Code, Version 5, LA-CP-03-0245, April 2003.

are calculated by tallying the neutron and gamma fluxes over surfaces (or volumes) of interest and converting these fluxes to dose rates.

The models are run in coupled neutron/photon mode to accurately tally gammas generated by the interaction of neutrons with the shielding material. Models are also developed for the primary gamma source, although the dose rate from the primary gamma source is negligible.

5.4.2 Input and Output Data

Six input/output cases are used to generate the results, as listed below.

- S300BOTTOM2N: NCT neutron and (n,γ) dose rates at the bottom of the package
- S300BOTTOM2G: NCT gamma dose rates at the bottom of the package
- S300OFFCENTER2N: NCT neutron and (n,γ) dose rates at the side of the package
- S300OFFCENTER2G: NCT gamma dose rates at the side of the package
- S300HAC2N: HAC neutron dose rates (no secondary gammas are tallied because there is no hydrogenous shielding material in this model)
- S300HAC2G: HAC gamma dose rates

A sample input file (S300OFFCENTER2N) is provided in Section 5.5.2, *Sample Input File*. All cases are run with 1 g of Pu in a PuBe source and the results are scaled to the desired source activity.

Russian roulette is utilized to accelerate program convergence. Convergence for this geometry is relatively quick, as the model geometry is not complex. The 10 MCNP statistical checks are met for all reported results, with the exception of the primary gamma dose rate 2 m from the transport vehicle. This dose rate is essentially zero and is acceptable. The 10 MCNP statistical checks are not provided for the mesh tallies, although the statistical uncertainty is low and the results are well behaved.

5.4.3 Flux-to-Dose Conversion

ANSI/ANS-6.1.1-1977 flux-to-dose-rate conversion factors are utilized for both neutron and gamma radiation. These factors are obtained from the MCNP user's manual and are provided in Table 5-13.

Table 5-13 – ANSI/ANS 1977 Flux-to-Dose-Rate Conversion Factors

Neutron		Gamma	
E (MeV)	(mrem/hr)/(n/cm^2/s)	E (MeV)	(mrem/hr)/(γ/cm^2/s)
2.50E-08	3.67E-03	0.01	3.96E-03
1.00E-07	3.67E-03	0.03	5.82E-04
1.00E-06	4.46E-03	0.05	2.90E-04
1.00E-05	4.54E-03	0.07	2.58E-04
1.00E-04	4.18E-03	0.1	2.83E-04
0.001	3.76E-03	0.15	3.79E-04
0.01	3.56E-03	0.2	5.01E-04
0.1	2.17E-02	0.25	6.31E-04
0.5	9.26E-02	0.3	7.59E-04
1	1.32E-01	0.35	8.78E-04
2.5	1.25E-01	0.4	9.85E-04
5	1.56E-01	0.45	1.08E-03
7	1.47E-01	0.5	1.17E-03
10	1.47E-01	0.55	1.27E-03
14	2.08E-01	0.6	1.36E-03
20	2.27E-01	0.65	1.44E-03
		0.7	1.52E-03
		0.8	1.68E-03
		1	1.98E-03
		1.4	2.51E-03
		1.8	2.99E-03
		2.2	3.42E-03
		2.6	3.82E-03
		2.8	4.01E-03
		3.25	4.41E-03
		3.75	4.83E-03
		4.25	5.23E-03
		4.75	5.60E-03
		5	5.80E-03
		5.25	6.01E-03
		5.75	6.37E-03
		6.25	6.74E-03
		6.75	7.11E-03
		7.5	7.66E-03
		9	8.77E-03
		11	1.03E-02
		13	1.18E-02
		15	1.33E-02

5.4.4 External Radiation Levels

For non-exclusive use, dose rates are computed at the package surface (r = 26.5662 cm) and 1 m (r = 126.5662 cm) from the package surface. For exclusive use, dose rates are computed at the package surface, the vehicle surface, and 2 m from the vehicle surface. Dose rates in an occupied location are not computed explicitly because the dose rate 2 m from the transportation vehicle is less than the occupied location dose rate limit of 2 mrem/hr, and the occupied location would be at a greater distance from the source. For the exclusive use calculations, it is assumed that the vehicle is a trailer with a width of 102 inches and that the package is on a pallet four inches high in the center of the vehicle. Because the trailer width results in a dose rate location of r = 129.54 cm at the vehicle side surface, this tally is essentially equivalent to the 1 m surface tally (r = 126.5662 cm) and the 1m surface tally is conservatively used for both tallies. The bottom of the vehicle is assumed to be at the bottom of the four-inch pallet, and no credit is taken for shielding by the pallet or bed of the trailer. The tally 2 m from the side of the vehicle is located at r = 329.54 cm.

The bottom tallies are computed with the source at the bottom center of the package (case name S300BOTTOM2N/G). Therefore, dose rates on the bottom surfaces are circumferentially symmetric about the centerline of the package, allowing concentric tallies that converge quickly. Segmenting surfaces are utilized to calculate the bottom dose rates in annular regions.

The side tallies are computed with the source off-center within the capsule (case name S300OFFCENTER2N/G). Calculation of the side dose rates is more complex because the side dose rates are not circumferentially symmetric. Because the source is assumed to shift to the inner wall of the package, the side surface dose rate near the source will be higher than the dose rate on the opposite side of the source. To capture this non-symmetric effect, a cylindrical mesh tally is utilized. For the side tallies of interest that utilize mesh tallies (surface and 1 m), the mesh tally has a height of 2.95 inches (to coincide with the source height) and a thickness of 1 cm. Circumferentially, the mesh is divided into 36 segments of equal width, or a segment width of 10°. Zero degrees corresponds to the positive x-axis (the location of the source) and the tally is indexed in the counterclockwise direction. A standard circumferentially symmetric tally is utilized for the 2 m side dose rate tally because the effect of radially shifting the source would not be detectable at this distance.

Dose rates computed for 1 g of Pu in a PuBe source are provided in Table 5-14 through Table 5-17. As expected, the maximum bottom dose rates at all locations occur at the center of the package, as shown in Table 5-14. The bottom dose rates bound the top dose rates; therefore, the top dose rates are not computed.

The dose rates 2 m from the side of the vehicle are provided in Table 5-15. Dose rates are calculated in three axial bands (beside, above, and below the source). The height of the center band is equal to the height of the source. The dose rates are essentially the same (within statistical fluctuation) for the three axial tally locations.

The dose rates at the package side surface and 1m from the package side surface are provided in Table 5-16 and Table 5-17, respectively. Note that the same tally is used for dose rates 1 m from the package side surface and at the vehicle side surface. Dose rates are computed in 10° circumferential increments. The variation in dose rate with circumferential location is apparent on the package surface, although the effect is much reduced at 1m. In both cases, the dose rates are a maximum near θ = 0° and a minimum near θ = 180°, as expected. Comparison with the bottom dose rates indicates that the side dose rates bound the bottom dose rates. The side dose rates are bounding because the side has less shielding than the bottom.

As the dose rates provided in Table 5-14 through Table 5-17 are for 1 g Pu in a PuBe source, these dose rates must be scaled to the actual source strength for the various scenarios. The dose rates for any arbitrary source may be computed by multiplying these dose rates by the actual Pu mass. In this manner, the dose rates for the various source strengths of interest may be computed.

NCT dose rates are computed for the following three scenarios:

- The largest source allowable within the Model II Capsule that does not exceed the non-exclusive use dose rate limits (206 g),
- 350 g source in the Model II Capsule (350 g is the largest source allowed for the Model II Capsule) for exclusive use shipments, and
- 160 g source in the Model III Capsule (160 g is the largest source that can geometrically fit in the Model III Capsule) for non-exclusive use shipments.

The Model II Capsule NCT dose rates for non-exclusive use are provided in Table 5-18. For 206 g of Pu, the limiting dose rate of 199.4 mrem/hr (limit = 200 mrem/hr) occurs at the side surface of the package, and the TI = 7.5. The limiting dose rate is intentionally chosen to be close to the limit to maximize the allowable source. The actual dose rate will be confirmed by measurement prior to shipment.

The Model II Capsule NCT dose rates for exclusive use are provided in Table 5-19. For 350 g of Pu, the maximum dose rate of 338.7 mrem/hr (limit = 1000 mrem/hr) occurs on the side of the package.

The Model III Capsule NCT dose rates for non-exclusive use are provided in Table 5-20. It is assumed that 160 g is the maximum size of the source that may geometrically fit within the Model III Capsule, and the maximum surface dose rate of 154.8 mrem/hr does not approach the limit of 200 mrem/hr. The S300 containing a Model III Capsule has a maximum TI = 5.8, which is bounded by the TI of the Model II Capsule.

The HAC dose rates are summarized in Table 5-21. The total dose rate for 350 g Pu is 61.0 mrem/hr (limit = 1000 mrem/hr).

Table 5-14 – NCT Bottom Dose Rates (mrem/hr), 1 g Pu in PuBe

Radial Location (cm)	Neutron	σ	(n,γ)	σ	Gamma	σ	Total	σ
Bottom Surface of Package								
0 to 2.5	0.55	1.5%	0.05	1.5%	1.43E-03	6.4%	0.61	1.4%
2.5 to 7.5	0.52	0.7%	0.05	0.6%	1.30E-03	3.2%	0.57	0.7%
7.5 to 12.5	0.42	0.6%	0.04	0.5%	1.08E-03	2.4%	0.46	0.6%
12.5 to 17.5	0.29	0.6%	0.03	0.5%	7.90E-04	2.3%	0.33	0.5%
17.5 to 26.5	0.22	0.4%	0.02	0.4%	5.70E-04	1.8%	0.24	0.4%
Bottom Surface of Vehicle								
Radial Location (cm)	**Neutron**	**σ**	**(n,γ)**	**σ**	**Gamma**	**σ**	**Total**	**σ**
0 to 2.5	0.26	1.8%	0.025	2.0%	6.29E-04	7.1%	0.29	1.7%
2.5 to 7.5	0.25	0.8%	0.024	0.8%	6.47E-04	3.6%	0.27	0.7%
7.5 to 12.5	0.22	0.7%	0.023	0.6%	5.75E-04	2.7%	0.24	0.6%
12.5 to 17.5	0.19	0.6%	0.020	0.6%	5.14E-04	2.4%	0.21	0.5%
17.5 to 26.5	0.05	0.2%	0.005	0.2%	1.48E-04	0.9%	0.06	0.2%
1 m from Bottom Surface of Package								
Radial Location (cm)	**Neutron**	**σ**	**(n,γ)**	**σ**	**Gamma**	**σ**	**Total**	**σ**
0 to 7.5	0.02	2.3%	0.002	2.5%	4.18E-05	8.5%	0.02	2.1%
7.5 to 12.5	0.02	1.8%	0.002	2.0%	4.61E-05	7.8%	0.02	1.6%
12.5 to 17.5	0.02	1.5%	0.002	1.6%	5.55E-05	6.9%	0.02	1.4%
17.5 to 126.6	0.01	0.3%	0.001	0.3%	2.91E-05	1.3%	0.01	0.3%

Table 5-15 – NCT Side 2m Dose Rates (mrem/hr), 1 g Pu in PuBe

Axial Location (cm)	Neutron	σ	(n,γ)	σ	Gamma	σ	Total	σ
Above Source	0.005	0.4%	0.0003	0.4%	1.29E-05	1.6%	0.005	0.3%
Beside Source	0.005	0.3%	0.0003	0.4%	1.32E-05	1.5%	0.005	0.3%
Below Source	0.005	0.4%	0.0003	0.4%	1.29E-05	1.6%	0.005	0.3%

Table 5-16 – NCT Side Surface Dose Rates (mrem/hr), 1 g Pu in PuBe

Circumferential Location (degrees)	Neutron	σ	(n,γ)	σ	Gamma	σ	Total	σ
0 to 10	0.91	0.5%	0.06	0.6%	0.003	2.3%	0.97	0.5%
10 to 20	0.91	0.5%	0.06	0.6%	0.003	2.3%	0.97	0.5%
20 to 30	0.89	0.5%	0.06	0.6%	0.003	2.3%	0.95	0.5%
30 to 40	0.87	0.5%	0.06	0.6%	0.002	2.3%	0.92	0.5%
40 to 50	0.85	0.6%	0.06	0.6%	0.002	2.4%	0.90	0.5%
50 to 60	0.83	0.6%	0.05	0.6%	0.002	2.5%	0.88	0.5%
60 to 70	0.81	0.6%	0.05	0.6%	0.002	2.5%	0.86	0.5%
70 to 80	0.79	0.6%	0.05	0.6%	0.002	2.5%	0.84	0.5%
80 to 90	0.77	0.6%	0.05	0.6%	0.002	2.6%	0.82	0.5%
90 to 100	0.75	0.6%	0.05	0.6%	0.002	2.9%	0.80	0.5%
100 to 110	0.74	0.6%	0.05	0.6%	0.002	2.6%	0.79	0.5%
110 to 120	0.73	0.6%	0.05	0.6%	0.002	2.7%	0.78	0.6%
120 to 130	0.72	0.6%	0.05	0.6%	0.002	2.7%	0.77	0.6%
130 to 140	0.71	0.6%	0.05	0.6%	0.002	2.6%	0.76	0.6%
140 to 150	0.71	0.6%	0.05	0.6%	0.002	2.7%	0.76	0.6%
150 to 160	0.71	0.6%	0.05	0.6%	0.002	2.8%	0.76	0.6%
160 to 170	0.70	0.6%	0.05	0.6%	0.002	2.7%	0.75	0.6%
170 to 180	0.70	0.6%	0.05	0.6%	0.002	2.6%	0.75	0.6%
180 to 190	0.71	0.6%	0.05	0.6%	0.002	2.7%	0.76	0.6%
190 to 200	0.70	0.6%	0.05	0.6%	0.002	2.7%	0.75	0.6%
200 to 210	0.70	0.6%	0.05	0.6%	0.002	2.7%	0.75	0.6%
210 to 220	0.71	0.6%	0.05	0.6%	0.002	2.7%	0.76	0.6%
220 to 230	0.70	0.6%	0.05	0.6%	0.002	2.6%	0.75	0.6%
230 to 240	0.71	0.6%	0.05	0.6%	0.002	2.7%	0.76	0.6%
240 to 250	0.72	0.6%	0.05	0.6%	0.002	2.7%	0.77	0.6%
250 to 260	0.74	0.6%	0.05	0.6%	0.002	2.9%	0.79	0.6%
260 to 270	0.75	0.6%	0.05	0.6%	0.002	2.8%	0.80	0.5%
270 to 280	0.76	0.6%	0.05	0.6%	0.002	2.6%	0.81	0.5%
280 to 290	0.78	0.6%	0.05	0.6%	0.002	2.6%	0.84	0.5%
290 to 300	0.80	0.6%	0.05	0.6%	0.002	2.4%	0.86	0.5%
300 to 310	0.83	0.6%	0.05	0.6%	0.002	2.5%	0.88	0.5%
310 to 320	0.85	0.5%	0.06	0.6%	0.002	2.6%	0.91	0.5%
320 to 330	0.87	0.5%	0.06	0.6%	0.003	2.4%	0.93	0.5%
330 to 340	0.89	0.5%	0.06	0.6%	0.003	2.3%	0.95	0.5%
340 to 350	0.89	0.5%	0.06	0.6%	0.003	2.4%	0.95	0.5%
350 to 360	0.90	0.5%	0.06	0.6%	0.003	2.4%	0.96	0.5%

Table 5-17 – NCT Side 1m/Vehicle Surface Dose Rates (mrem/hr), 1 g Pu in PuBe

Circumferential Location (degrees)	Neutron	σ	(n,γ)	σ	Gamma	σ	Total	σ
0 to 10	0.033	1.1%	0.002	1.2%	0.0001	5.0%	0.036	1.1%
10 to 20	0.033	1.1%	0.002	1.2%	0.0001	5.0%	0.035	1.1%
20 to 30	0.033	1.1%	0.002	1.2%	0.0001	5.2%	0.035	1.1%
30 to 40	0.033	1.1%	0.002	1.2%	0.0001	4.7%	0.035	1.1%
40 to 50	0.032	1.2%	0.002	1.3%	0.0001	5.1%	0.035	1.1%
50 to 60	0.032	1.2%	0.002	1.3%	0.0001	6.1%	0.034	1.1%
60 to 70	0.032	1.2%	0.002	1.3%	0.0001	4.9%	0.034	1.1%
70 to 80	0.032	1.2%	0.002	1.2%	0.0001	5.9%	0.034	1.1%
80 to 90	0.031	1.2%	0.002	1.3%	0.0001	5.0%	0.033	1.1%
90 to 100	0.030	1.2%	0.002	1.3%	0.0001	5.7%	0.032	1.1%
100 to 110	0.030	1.2%	0.002	1.3%	0.0001	5.1%	0.032	1.1%
110 to 120	0.030	1.2%	0.002	1.3%	0.0001	5.6%	0.033	1.1%
120 to 130	0.030	1.2%	0.002	1.3%	0.0001	5.2%	0.032	1.1%
130 to 140	0.030	1.2%	0.002	1.3%	0.0001	5.5%	0.032	1.1%
140 to 150	0.030	1.2%	0.002	1.3%	0.0001	5.3%	0.032	1.1%
150 to 160	0.029	1.2%	0.002	1.3%	0.0001	7.0%	0.031	1.1%
160 to 170	0.030	1.2%	0.002	1.3%	0.0001	5.6%	0.033	1.1%
170 to 180	0.030	1.2%	0.002	1.3%	0.0001	5.6%	0.032	1.1%
180 to 190	0.030	1.2%	0.002	1.3%	0.0001	5.2%	0.032	1.1%
190 to 200	0.030	1.2%	0.002	1.3%	0.0001	5.3%	0.032	1.1%
200 to 210	0.029	1.2%	0.002	1.3%	0.0001	6.3%	0.031	1.1%
210 to 220	0.030	1.2%	0.002	1.3%	0.0001	5.8%	0.033	1.1%
220 to 230	0.030	1.2%	0.002	1.3%	0.0001	5.3%	0.032	1.1%
230 to 240	0.030	1.2%	0.002	1.3%	0.0001	5.4%	0.032	1.1%
240 to 250	0.030	1.2%	0.002	1.3%	0.0001	6.0%	0.032	1.1%
250 to 260	0.030	1.2%	0.002	1.3%	0.0001	5.5%	0.032	1.1%
260 to 270	0.029	1.2%	0.002	1.3%	0.0001	5.9%	0.032	1.1%
270 to 280	0.030	1.2%	0.002	1.3%	0.0001	5.6%	0.033	1.1%
280 to 290	0.030	1.2%	0.002	1.3%	0.0001	6.2%	0.033	1.1%
290 to 300	0.032	1.2%	0.002	1.3%	0.0001	5.5%	0.034	1.1%
300 to 310	0.031	1.2%	0.002	1.3%	0.0001	5.1%	0.033	1.1%
310 to 320	0.033	1.1%	0.002	1.2%	0.0001	5.4%	0.035	1.0%
320 to 330	0.032	1.1%	0.002	1.2%	0.0001	4.9%	0.035	1.1%
330 to 340	0.033	1.1%	0.002	1.2%	0.0001	5.1%	0.036	1.0%
340 to 350	0.033	1.1%	0.002	1.2%	0.0001	5.0%	0.035	1.1%
350 to 360	0.034	1.1%	0.002	1.3%	0.0001	5.3%	0.036	1.1%

Table 5-18 – Model II Capsule NCT Dose Rates (Non-exclusive use)

206 g Pu	**Package Surface (mrem/hr)**			**1 m from Package Surface (mrem/hr)**		
TI = 7.5	**Top**	**Side**	**Bottom**	**Top**	**Side**	**Bottom**
Gamma	<11.3	12.4	11.3	<0.4	0.5	0.4
Neutron	<114.3	187.0	114.3	<3.8	7.0	3.8
Total	<125.6	**199.4**	125.6	<4.1	7.5	4.1
Limit		200			10	

Note: All reported dose rates are rounded to the nearest one-tenth, although the total dose rate values are based on the sum of unrounded values. Therefore, the sum of the rounded gamma and neutron dose rates will not necessarily equal the total rounded dose rate value.

Table 5-19 – Model II Capsule NCT Dose Rates (Exclusive use)

350 g Pu	**Package Surface (mrem/hr)**			**Vehicle Surface (mrem/hr)**		
TI = NA	**Top**	**Side**	**Bottom**	**Top**	**Side**	**Bottom**
Gamma	<19.2	21.0	19.2	<9.0	0.9	9.0
Neutron	<194.2	317.7	194.2	<91.2	11.8	91.2
Total	<213.5	**338.7**	213.5	<100.2	12.7	100.2
Limit		1000			200	
	2m from Vehicle Surface (mrem/hr)			**Occupied Location (mrem/hr)**		
	Top	**Side**	**Bottom**	**Top**	**Side**	**Bottom**
Gamma	NA	0.1	NA	NA	<0.1	NA
Neutron	NA	1.6	NA	NA	<1.6	NA
Total	NA	1.7	NA	NA	<1.7	NA
Limit		10			2	

Note: All reported dose rates are rounded to the nearest one-tenth, although the total dose rate values are based on the sum of unrounded values. Therefore, the sum of the rounded gamma and neutron dose rates will not necessarily equal the total rounded dose rate value.

Table 5-20 – Model III Capsule NCT Dose Rates (Non-exclusive use)

160 g Pu	**Package Surface (mrem/hr)**			**1 m from Package Surface (mrem/hr)**		
TI = 5.8	**Top**	**Side**	**Bottom**	**Top**	**Side**	**Bottom**
Gamma	<8.8	9.6	8.8	<0.3	0.4	0.3
Neutron	<88.8	145.2	88.8	<2.9	5.4	2.9
Total	<97.6	154.8	97.6	<3.2	5.8	3.2
Limit		200			10	

Note: All reported dose rates are rounded to the nearest one-tenth, although the total dose rate values are based on the sum of unrounded values. Therefore, the sum of the rounded gamma and neutron dose rates will not necessarily equal the total rounded dose rate value.

Table 5-21 – Bounding HAC Dose Rates

350 g Pu	**1 m from Package Surface (mrem/hr)**		
	Top	**Side**	**Bottom**
Gamma	2.7	2.7	2.7
Neutron	58.3	58.3	58.3
Total	61.0	61.0	61.0
Limit		1000	

5.5 Appendices

5.5.1 Radionuclide Distribution Document LA-UR-09-06701

Radionuclide Distribution in Plutonium-239 Material Used for Sealed Source Production

Justin M. Griffin P.E.
Off-Site Source Recovery Project
Los Alamos National Laboratory

Introduction

As early as the 1950's, the U.S. government realized the need to allow distribution of radioactive materials for use in research, industrial, and medical applications. As a result, in 1954, the U.S. Atomic Energy Act of 1946 was amended to provide civilian access to radioactive material for peaceful uses; and to allow the U.S. to assist other countries in developing their peaceful nuclear programs.[1] These efforts resulted in distribution of government-reactor-produced batches of radioactive material to selected source manufacturers for production and distribution of sealed sources all over the world.

These batches of radioactive material included plutonium-239 (^{239}Pu), and tended to vary in the actual distribution of related nuclides. Several batches of ^{239}Pu material were sold for source production, but since ^{239}Pu created by neutron capture in uranium-238 never occurs in an isotopically pure form, the exact radionuclide distribution in a ^{239}Pu sealed source cannot be predicted without knowledge of the characteristics of materials used in production of the source – this level of documentation is not available. The isotopic distribution of plutonium nuclides in a ^{239}Pu source includes mass numbers 238 to 242 as well as various levels of daughter products from these initial isotopes (due to natural decay).[2] The short half-life of ^{243}Pu essentially terminates the plutonium isotope products at ^{242}Pu.[3]

Background

^{239}Pu sealed sources were manufactured for a variety of essential uses; however, over the years a significant number of them have been declared unwanted and are no longer used by their owner. In Public Law 99-240, titled "Low-Level Waste Policy Amendments Act of 1985," Congress assigned the Department of Energy (DOE) the responsibility for the management and disposal of "Greater-than-Class C" radioactive material as defined in 10 CFR 61. This includes sealed sources containing 239Pu. In response to Public Law 99-240, DOE established the Off-Site Source Recovery Project (OSRP) for the specific purposes of recovering, managing, and disposing of excess or unwanted sealed sources, such as those which contain U.S.-origin plutonium.

After the terrorist events of September 11, 2001, ^{239}Pu and other sealed sources were identified as a major vulnerability to U.S. security and deemed to have a high attractiveness profile from a homeland security perspective. This resulted in a ramp-up of OSRP recovery activities and highlighted the need for a final disposition option for disused ^{239}Pu sealed sources.

The Waste Isolation Pilot Plant (WIPP) was the only disposal pathway available and remains the only safe and secure permanent disposal facility for ^{236}Pu sources in the U.S. As such, the ^{239}Pu sources recovered by OSRP must meet WIPP Waste Acceptance Criteria (WAC) prior to

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[1] U.S. Congress, "The Atomic Energy Act of 1954," Public Law 83-703, 83rd Congress.

[2] G. M. Matlack, "A Plutonium Primer: An Introduction to Plutonium Chemistry and its Radioactivity," Los Alamos National Laboratory report LA-UR-02-6594 (January 2003), pp. 19-20.

[3] "Properties of Plutonium Isotopes," in *Plutonium Handbook: A Guide to the Technology*, O.J. Wick, editor (The American Nuclear Society, La Grange Park, Illinois, 1980), Vol. I, Chap. 1, p. 3.

disposition. These WIPP criteria include requirements for specific radiological characterization of packages to identify the quantities and types of each radionuclide present in the package prior to disposal.[4]

Such an exacting requirement by WIPP for radiological characterization presented a challenge to OSRP in identification of the isotopic distribution of radionuclides in ^{239}Pu sealed sources. The exact composition of sources made from unknown batches (or even mixtures of different ^{239}Pu batch-material) provided by the government to source manufacturers is difficult to determine for each individual sealed source. To alleviate this challenge, an alternate method was developed to demonstrate that these sources meet the waste acceptance criteria at WIPP.

WIPP and EPA Acceptance

Los Alamos National Laboratory (LANL) report titled, "Transuranic Waste Acceptance Criteria for the Waste Isolation Pilot Plant," was developed to provide the necessary technical basis for overall radiological characterization of ^{239}Pu (and other actinide) sealed source packages for compliance with the WIPP WAC. The radiological characterization discussed therein is based on information and data designated as Acceptable Knowledge (AK) under U.S. Environmental Protection Agency (EPA) guidance.

OSRP elected to qualify this AK information by Peer Review in accordance with 40 CFR 194.22(b) in order to use the report's findings as the foundation for radiological characterization of sealed sources containing ^{239}Pu. The basis for selecting this method was due to the fact that confirmatory testing, such as non-destructive assay (NDA), is not possible or reliable for many of the sources packaged by OSRP, and because of the valid documentation that already exists regarding sealed source manufacture.[5]

Documentation exists because sealed sources were manufactured to fulfill a specific requirement or for use in a particular device. This is in contrast to other common types of waste, like residual debris material (i.e., contaminated gloves, paper, etc.) generated from some other activity involving transuranic radioactive material. An NDA measurement is typically the only way to identify and quantify the radionuclide content of a package containing residual debris waste material, but this method does not work for the ^{239}Pu sealed sources packaged by OSRP.

A Peer Review Panel was convened in accordance with the guidance in NUREG-1297, titled "Peer Review for High-Level Nuclear Waste Repositories." The panel evaluated the AK information to determine if the information proposed for use in the characterization process presented by LANL was acceptable for the radiological characterization of sealed source waste in compliance with the WIPP WAC. The final Peer Review Panel Report concluded that the specific documentation and information identified by LANL was acceptable.[6]

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[4] D. Moody, D. Gadbury, et. al., "Transuranic Waste Acceptance Criteria for the Waste Isolation Pilot Plant," U.S. Department of Energy Carlsbad Field Office report DOE/WIPP-02-3122, Revision 6.3 (February 5, 2009), pp. 3-7 to 3-9.

[5] M.W. Pearson, G. Vance, "Radiological Characterization of Actinide Sealed Source Waste for Disposal at WIPP," Los Alamos National Laboratory report LA-CP-04-0116 (January 2004), p. 3.

[6] J. Booth, H. Ryans, J. Harvill, T. Snowden, "Sealed Sources Peer Review Report," Washington Group International (December 2003), pp. 17-18.

LANL Report Conclusions

According to LANL Report "Transuranic Waste Acceptance Criteria for the Waste Isolation Pilot Plant," ^{239}Pu sources were made for a variety of purposes from weapons grade material.[7] These plutonium materials were provided for source manufacture in accordance with the Material Control and Accountability requirements existing at that time. This information was collected by the Nuclear Materials Management and Safeguards System (NMMSS) in a database format. NMMSS database[8] lists over 2,000 known U.S.-origin sources containing plutonium furnished by the government and includes sufficient information on the radionuclide distribution and assay dates to allow the determination of a representative distribution of radionuclides expected to be present in ^{239}Pu sources at any given time.

Using the information in the NMMSS database, an average plutonium radionuclide distribution was calculated for the known inventory of ^{239}Pu sources. Individual sealed sources containing ^{239}Pu may vary in the isotopic distribution of plutonium nuclides (due to production batch differences, source manufacturer blending of different batches prior to source encapsulation, and natural decay). Nevertheless, an acceptable representative radionuclide distribution for ^{239}Pu sealed sources was developed and approved by Peer Review. The values in Table 1 were determined to be acceptable by WIPP and EPA as the representative radionuclide distribution to use for ^{239}Pu sources destined for disposition at WIPP.

Nuclide	Grams of Nuclide per Gram of Plutonium	Mass Percent (approx)
^{238}Pu	1.479E-04	<0.05%
^{239}Pu	9.321E-01	>93.0%
^{240}Pu	6.503E-02	<7.0%
^{241}Pu	2.435E-03	<1.0%
^{242}Pu	3.269E-04	<0.05%
^{241}Am	2.500E-04	<0.05%

Table 1: Representative Radionuclide Distribution Average from LA-CP-04-0116, Table 10 [p. 22]

Source Manufacturer Information

In the U.S., plutonium sealed sources were manufactured/distributed by four entities; Los Alamos Scientific Laboratory, Mound Laboratory (Mound), Monsanto Research Corp. (MRC), and Nuclear Materials & Equip. Co. (NUMEC). The plutonium sources were manufactured at various intervals from the 1950s to the early 1980s. Only Mound, MRC, and NUMEC distributed the plutonium sources commercially, with approval from the Atomic Energy Commission.

In their 1962 Catalog and Price List, MRC states that the plutonium used in both their ^{239}Pu alpha sources and ^{239}Pu/Be neutron sources "varies in composition, but is generally about 92 per cent Pu 239, 7 per cent Pu 240 and 1 per cent Pu 241 plus Am 241."[9] This document is provided, in part, as Attachment A. Mound Laboratory was operated by Monsanto Research Corporation under contract

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[7] Weapons grade material includes plutonium where the ^{240}Pu content is generally ≤6%. (R.H. Condit, "Plutonium: An Introduction," Plutonium Primer Workshop, DOE Office of Arms Control & Proliferation, Washington, D.C., September 29, 1993, Lawrence Livermore National Laboratory document UCRL-JC115357, p. 23.)

[8] Martin Marietta Energy Systems, Inc., "Nuclear Materials Management and Safeguards System," U.S. Dept. of Energy NMMSS report SS-1, Listing of Sealed Sources by Manufacturer as of 12-31-85.

[9] Monsanto Research Corporation, "Catalog and Price List," (March 1962), pp. 19 and 22.

with the Atomic Energy Commission.[10] Therefore, the percentages appearing in the MRC catalog (Attachment A) are assumed to represent the sources made under the 'Mound Laboratory' name as well.

Similarly, a 1965 letter from NUMEC, in response to an inquiry from a customer, regarding the isotopic content of NUMEC plutonium sources states that the isotopic assay of plutonium in NUMEC sources is 92% Pu-239, 7% Pu-240 and 1% Pu-241.[11] This document is provided herein as Attachment B.

Manufacturer Assay Dates

As already noted, plutonium sources were fabricated from the 1950s to the early 1980s. Fortunately, the NMMSS records include the original assay date for over 2,000 sealed sources containing ^{239}Pu. Therefore, the values for initial, average, and the latest known dates of source production can be used for decay calculations. Depending on the aspects of the study, one or more of the following assay date values for ^{239}Pu sealed source production could be used for generalized decay calculations:

- The earliest assay date stated in NMMSS is January 1, 1950.
- The latest assay date from NMMSS is June 30, 1981.
- Analysis of the 2,214 entries for ^{239}Pu sealed source in NMMSS yields an average assay date equivalent to October 16, 1963.

These can be used in lieu of known, source-specific assay dates.

Identification of Natural Decay Products

All radioactive material decays over time into daughter products, and ^{239}Pu created by neutron capture is no different. In addition to the initial plutonium nuclides (^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, and ^{242}Pu), Americium-241, a natural decay product of ^{241}Pu, is also present.[12] As the ^{241}Pu decays (the mass percent of it decreases) in a sample, the amount of ^{241}Am subsequently increases. The presence of ^{241}Am in a source becomes important after several years of decay, and will contribute to dose rates measured from older ^{239}Pu sealed sources. ^{241}Am is not a fissile material and is not detrimental to the criticality safety of plutonium sealed sources.

Other daughter products will also arise as the result of the natural decay of nuclides in the plutonium source. However, these are not relevant for the purposes of this discussion and are not presented here (with the exception of ^{241}Am). Furthermore, according to the U.S. Department of Transportation, competent authority approvals do not have to identify daughter products in sealed sources that occur as part of the natural decay chain of the contents.[13]

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[10] U.S. Atomic Energy Commission, "AEC Withdraws as a Supplier of Plutonium-Beryllium Neutron Sources," AEC Press Release D-288, November 1, 1961.

[11] K.E. Ball, Nuclear Materials & Equip. Co., response letter to the Rhode Island Nuclear Science Center, January 1965.

[12] T.E. Sampson, "Plutonium Isotopic Composition by Gamma-Ray Spectroscopy: A Review," Los Alamos National Laboratory report LA-10750-MS UC-10 (September 1986), p. 2.

[13] C. Betts, Chief of Standards Development, Office of Hazardous Material Standards, U.S. Dept. of Transportation, official letter to the Department of Energy Office of Environmental Management, November 2008.

Summary and Conclusion

The detailed analysis and calculations presented in Los Alamos National Laboratory report LA-CP-04-0116 concluded that plutonium sources have a representative radionuclide distribution which includes 93.2% ^{239}Pu, 6.5% ^{240}Pu, and <1% ^{241}Pu plus all other nuclides. The method used to determine these percentages was acceptable to WIPP and EPA as a representative radionuclide distribution for ^{239}Pu sources destined for disposition at WIPP.

Additional research into plutonium source manufacturing records, catalogs, and other related documentation shows that the three commercial U.S. suppliers (Mound, MRC, and NUMEC) marketed their plutonium sources as having a radionuclide distribution which included 92% ^{239}Pu, 7% ^{240}Pu, and 1% ^{241}Pu. Since it is not specifically stated, we assume these values are based on some initial manufacturer assay date, which could range from the 1950s to the early 1980s.

It is understood that the original nuclide activities will change over time while daughter products, such as ^{241}Am, appear due to natural radioactive decay. Although it is not required to identify these subsequent nuclides on competent authority approvals, the effects of such daughter nuclides may contribute to source dose rates upon packaging. Dose rate measurements are required at the package surface and at one meter for transportation compliance verification prior to shipment.[14]

Based on previous research and analysis, and the assumptions discussed above, development of a representative radionuclide distribution in ^{239}Pu material used for sealed source production is justifiable when more specific data is not known. However, since the results presented in LANL Report, "Transuranic Waste Acceptance Criteria for the Waste Isolation Pilot Plant"; and the values stated by sources manufacturers differ slightly, reconciliation between the two is necessary.

For the purposes of this report, the two sets of values are reconciled as shown in Table 2.

Nuclide	LA-CP-04-0116 Values Expressed as Grams of Nuclide per Gram of Plutonium (and approx. Mass-%)	Manufacturers' Documented Values Expressed As Mass-%	Reconciled Values Expressed As Approx. Mass-%[15]
^{238}Pu	1.479E-04 (0.015)	Not Stated	0.015
^{239}Pu	9.321E-01 (93.21)	92	92.6
^{240}Pu	6.503E-02 (6.50)	7	6.75
^{241}Pu	2.435E-03 (0.24)	1	0.62
^{242}Pu	3.269E-04 (0.033)	Not Stated	0.033
^{241}Am[16]	2.500E-04 (0.025)	Not Explicit	0.025

Table 2: Representative Radionuclide Distributions in ^{239}Pu Material used for Initial Sealed Source Production

The exact radionuclide distribution for an individual sealed source containing ^{239}Pu will vary depending on a number of factors, as previously stated. However, generally speaking, a

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[14] 49 CFR 173.441, "Radiation level limitations and exclusive use provisions." [Code of Federal Regulations]

[15] Plutonium values do not add up to exactly 100% due to rounding in LA-CP-04-0116, and the lack of significant digits in the manufacturers' documented values.

[16] Americium is in addition to the mass of plutonium present and is not included in the plutonium isotopes.

representative radionuclide distribution in ^{239}Pu material used for initial sealed source production is expected to include approximately 92.6% ^{239}Pu, 6.75% ^{240}Pu, 0.62% ^{241}Pu, and <1% of the other nuclides as shown in the last column of Table 2 above.

This representative radionuclide distribution for ^{239}Pu used in sealed source production can be used in conjunction with the earliest known, latest, or average assay date recorded in NMMSS as a basis to perform various analysis and calculations for plutonium sources when the specific isotopic breakdown data, and the corresponding assay date, is not otherwise available.

Attachment A

Revised. 3-1-6

CATALOG AND PRICE LIST

ALPHA, BETA, HEAT AND NEUTRON SOURCES, AND THRESHOLD DETECTORS

From

POLONIUM 210
PLUTONIUM 239
NEPTUNIUM 237
and
OTHER AVAILABLE ISOTOPES

MONSANTO RESEARCH CORPORATION
Dayton Laboratory
1515 Nicholas Road
Dayton 7, Ohio

A subsidiary of Monsanto Chemical Company

TABLE OF CONTENTS

INTRODUCTION

This catalog describes alpha, beta, heat and neutron sources and threshold detectors available from Monsanto Research Corporation, a wholly owned subsidiary of Monsanto Chemical Company.

Polonium 210 and plutonium 239 are used for alpha and neutron sources. When other alpha-emitting isotopes become available, they will also be used for source fabrication.

The number of beta emitters is so large that no attempt will be made to list them. Any that can be released will be used as specified in requests, within the limitations of our facilities.

Heat sources from polonium 210 in units of about 1000 curies each are prepared, and several such capsules can be combined into one source.

Threshold detectors are made from plutonium 239, uranium 238, uranium 235 and neptunium 237. Non-radioactive elements will also be packaged as detectors when requested.

Monsanto Research Corporation invites your inquiries concerning special sources of any type, as well as development projects. For additional information, please write or call

Manager, Nuclear Sources Department
Dayton Laboratory
Monsanto Research Corporation
Station B, Box 8
Dayton 7, Ohio

Telephone 268-5481 (Area Code 513)

POLICY

Monsanto Research Corporation will prepare radioactive sources and guarantee them to meet the standards of the Atomic Energy Commission. For this purpose, a staff of highly trained scientists with broad experience in the technology of radioactive materials and devices is maintained.

Every effort will be made to see that radioactive materials go only to those trained to use them and information on proper techniques will be readily available.

> "Monsanto Research Corporation assumes no liability for damage to sources after shipment. Any items shown defective at the time of shipment will be replaced free of charge."

This policy supersedes all others, and orders will be accepted only on the above basis. The terms and conditions of customer purchase orders are so varied and multitudinous that they cannot be accepted.

ORDERING RADIOISOTOPES

The procedures for obtaining approvals for possession and use of radioisotopes and for placing orders for them are varied and subject to change as the Atomic Energy Act is amended. A license from the Atomic Energy Commission is required by all who receive radioisotopes, except those who operate facilities owned by the Commission. Monsanto Research Corporation must have a copy of the license before shipment can be made.

Monsanto Research Corporation will be glad to assist all who wish to apply for a license or place an order. Application for a license is made to:

Licensing Branch
Division of Licensing and Regulation
U.S. Atomic Energy Commission
Washington 25, D. C.

Non-fissionable isotopes, such as polonium and beta emitters, require only a license and purchase order.

Fissionable materials, such as Pu 239 and U 235, require (1) a license, (2) purchase order on Form OR-640, and (3) lease agreement. Form OR-640 and the lease agreement are obtained from:

AEC Materials Leasing Officer
Production Division
U.S. Atomic Energy Commission
Post Office Box E
Oak Ridge, Tennessee

The purchase order on Form OR-640 is sent to Monsanto Research Corporation by the customer when the lease agreement has been completed.

ORDERING RADIOISOTOPES (Cont'd)

When the license is granted, the Licensing Branch will supply the allocation for the fissionable material to the fabricator of the source.

The Atomic Energy Commission has a Program of Assistance to Educational Institutions when radioisotopes are used for educational and training purposes. Under this program the institution pays only the shipping charges. Inquiries concerning the program are to be directed to:

Coordinator
Nuclear Education and Training
U.S. Atomic Energy Commission
Washington 25, D. C.

Foreign countries that have a cooperative agreement with the United States with provision for transfer of research materials may obtain fissionable radioisotopes. Non-fissionable isotopes are obtainable without the cooperative agreement, but approval of the AEC Division of Licensing and Regulation is required. Application for any radioactive material is made to:

Director
Division of International Affairs
U.S. Atomic Energy Commission
Washington 25, D. C.

Questions concerning orders for any radioactive materials should be directed to:

Manager, Nuclear Sources Department
Dayton Laboratory
Monsanto Research Corporation
Station B, Box 8
Dayton 7, Ohio
Telephone 268-5481 (Area Code 513)

DELIVERY AND SHIPPING

DELIVERY

Standard sources will usually be shipped within two to four weeks after receipt of the order, license and AEC approvals. More definite schedules can be given when the order is placed.

Special sources, for which materials must be ordered, can be shipped within two to four weeks after the materials are received.

SHIPPING

The purchaser should designate his preference of Motor Freight, Railway Express, Air Freight or Air Express. "Protective Signature" is obtainable for Railway or Air Express. All shipments are F.O.B. Dayton, Ohio.

PLUTONIUM ALPHA SOURCES

The plutonium used in alpha sources varies in composition, but is generally about 92 per cent Pu 239, 7 per cent Pu 240 and 1 per cent Pu 241 plus Am 241. The alpha increase will approximate two per cent per year due to Pu 241.

Plutonium used in alpha sources is leased from the Atomic Energy Commission. Because of the small amounts used, the lease charge is negligible.

The sources are quite stable at concentrations of 10^5 cpm/cm^2. As much as 10^7 cpm/cm^2 can be deposited, but sources of this strength will show a slight alpha wipe and must be carefully handled. Heating the sources several hours at 450°C gives better adherence, but broadens the energy distribution.

Because of the long half-life of plutonium (24,600 years), thick deposits will show some self-absorption of alphas. However, even were a concentration of 10^8 cpm/cm^2 (1.44 mg/cm^2) attainable, the self-absorption would be only about 4 per cent.

For calibration of instruments, large area sources hold no great advantage over small area sources, unless phosphors of non-uniform response are used in the alpha meter. The expense of preparing large area sources which are uniform is not justified.

ITEM VI

PLUTONIUM ALPHA SOURCE

Plutonium alpha sources are electrolytically or electrochemically deposited on metal plates, per Drawing NS-9 in Appendix. A smooth hard surface is preferable, stainless steel being quite satisfactory. Sometimes it is desirable to flash-coat gold over plutonium to reduce the possibility of contamination. A very thin copper coating before deposition of the gold leads to better adherence and does not greatly affect the energy curve of the alphas.

At present, large area sources will be more satisfactory if made up from small units no more than one inch square. Inquiries concerning customer's requirements are invited.

Quantity of Plutonium

Maximum of 10^7 cpm/cm^2; lower concentrations give better deposits

Container

Stainless steel, copper or nickel, 0.01 to 0.062 inch thick and 0.25 to 1.0 inch round or square

Cover

Gold will be plated over the plutonium if requested (Item VI-A). The thickness of gold may vary from 0.00003 to 0.00015 inch, with respective energy absorptions of 10 and 50 per cent.

Uniformity of Deposit

The uniformity of the deposit will be determined and held to ±10 per cent on request (Items VI-B and VI-C).

PRICE LIST

PLUTONIUM ALPHA SOURCES

Item Number	Plutonium, counts/min	Price/Item
VI - open	to $10^7/\text{cm}^2$	$ 50
VI-A - gold plated	to $10^7/\text{cm}^2$	70
VI-B - open - uniformity determined	to $10^7/\text{cm}^2$	85
VI-C - gold plated - uniformity determined	to $10^7/\text{cm}^2$	100

Prices are for one to ten items and are for fabrication only. Reductions will be made on larger quantities, and quotations will be made on request. The shipping container for amounts over one millicurie is the same as for polonium alpha sources, Drawing NS-5 in Appendix.

Terms: Net 30 days

All prices are F.O.B. Dayton and are subject to change without notice. Prices on non-standard items or sources not listed will be quoted when details of the requested source are furnished.

The above prices do not include the cost of the returnable shipping container listed on page 29, but they do include a non-returnable container.

PLUTONIUM-BERYLLIUM NEUTRON SOURCES

The plutonium used in neutron sources varies in composition, but is generally about 92 per cent Pu 239, 7 per cent Pu 240 and 1 per cent Pu 241 plus Am 241. The neutron increase will approximate two per cent per year due to Pu 241.

Plutonium sources have the advantage of a long half-life (24,600 years) and nearly constant neutron emission. They have the disadvantage of large physical size and non-uniform neutron distribution.

Plutonium is not sold in the United States but is on loan from the Atomic Energy Commission. The rental fee, $22.80 per curie per year, is collected by the AEC. Monsanto Research Corporation charges only for fabrication of plutonium sources.

The amount of plutonium per curie is about 16 grams of Pu 239. This amount is referred to as one curie in this catalog.

Since plutonium is a fissionable material, no more than 25 curies will be shipped in one container, though it has been demonstrated that 100 curies as a plutonium-beryllium source is safe. No more than 10 curies will be put in one source container.

ITEM VII

PLUTONIUM-BERYLLIUM NEUTRON SOURCE

The method of fabricating plutonium-beryllium sources requires a high melting metal for the inner container. Tantalum is used for the inner and stainless steel for the outer container. About one-fourth of the internal volume is void.

The sources are made per Drawing NS-8 in Appendix. Other sizes will be made to fit special needs.

Neutron Emission

One curie (16 grams) of plutonium when reacted to form $PuBe_{13}$ emits approximately 1.7×10^6 n/sec. Hence, the emission from the largest source prepared (10 curies) is 1.7×10^7 n/sec.

Neutron Energy

The configuration of a plutonium-beryllium source has some effect on the spectrum. A typical spectrum of a 5-curie source was determined by M. E. Anderson at Mound Laboratory (unpublished data).

Gamma Emission

The 4.45 mev gamma from the alpha-neutron reaction on beryllium is the principal gamma. The soft gammas from plutonium are absorbed in the source container.

Operating Temperature

Plutonium-beryllium sources are prepared at 1500-2000°C but should not be used for long periods above 700°C, as the compound will react slowly with the container at higher temperatures.

PRICE LIST

PLUTONIUM-BERYLLIUM NEUTRON SOURCES

Prices are for fabrication plus the shipping container. The lease charge for the plutonium is currently 4-3/4 per cent per annum on a value of $30 per gram in the United States ($22.80 per curie per year). Foreign countries will negotiate sale contracts with the AEC Division of International Affairs.

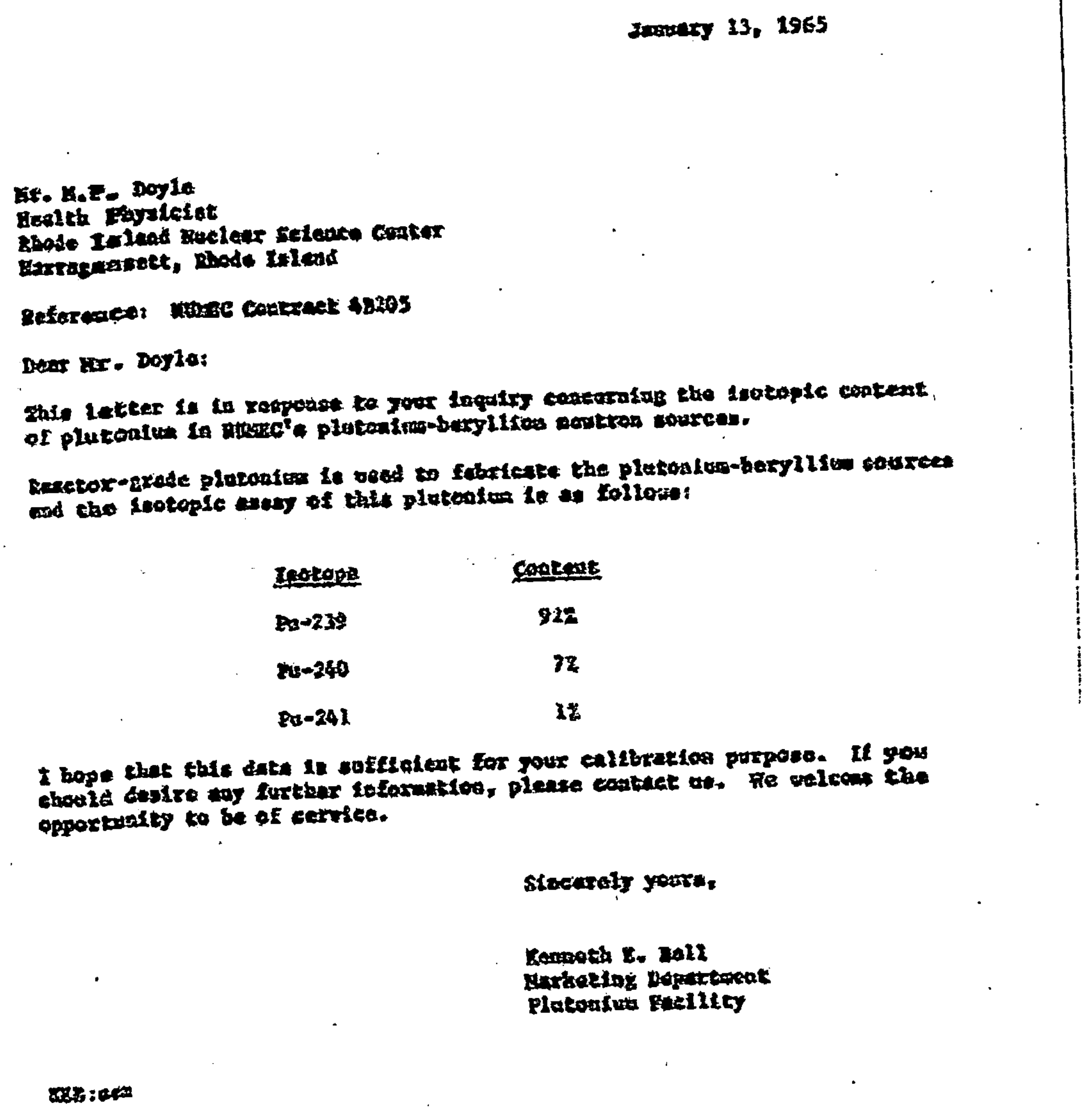
Grams of Plutonium	Item VII-PuBe	Grams of Plutonium	Item VII-PuBe
0 - 1	$550	80	$1,000
1 - 8	625	96	1,075
8 -16	700	112	1,150
32	775	128	1,225
48	850	144	1,300
64	925	160	1,375

All prices are F.O.B. Dayton and are subject to change without notice. Prices for non-standard items or sources not listed will be quoted when details of the requested source are furnished.

Terms: Net 30 days

The above prices include the cost of the shipping containers which are returnable for reuse or refund. Sizes and prices of the containers are listed on page 29.

Attachment B



January 13, 1965

Mr. M.F. Doyle
Health Physicist
Rhode Island Nuclear Science Center
Narragansett, Rhode Island

Reference: NUMEC Contract 4B205

Dear Mr. Doyle:

This letter is in response to your inquiry concerning the isotopic content of plutonium in NUMEC's plutonium-beryllium neutron sources.

Reactor-grade plutonium is used to fabricate the plutonium-beryllium sources and the isotopic assay of this plutonium is as follows:

Isotope	Content
Pu-239	91%
Pu-240	7%
Pu-241	1%

I hope that this data is sufficient for your calibration purpose. If you should desire any further information, please contact us. We welcome the opportunity to be of service.

Sincerely yours,

Kenneth E. Ball
Marketing Department
Plutonium Facility

KEB:[illegible]

5.5.2 Sample Input File

Sample case S300OFFCENTER2N:

```
Neut&(n,gam) dose rates, S300
10   0          -505 500 -501  #11        imp:n=1   imp:p=1  $source reg
11   4  -3.7     302 -303 -510            imp:n=1   imp:p=1  $source
20   1  -0.92  -63    2   -3  62  -158    imp:n=1   imp:p=1  $poly sleve
30   1  -0.92  -63    2   -3  -159 158    imp:n=4   imp:p=4  $poly sleve
40   1  -0.92  -63    2   -3  159         imp:n=16 imp:p=16  $poly sleve
50   0         -63    5   -87             imp:n=16 imp:p=16  $void around
sleeve
60   1  -0.92  -63    4   -2 -158         imp:n=4   imp:p=4  $bottom poly
70   1  -0.92  -63    4   -2 -159 158     imp:n=16 imp:p=16  $bottom poly
80   1  -0.92  -63    4   -2  159         imp:n=64 imp:p=64  $bottom poly
90   1  -0.92  -63    3   -5 -158         imp:n=1   imp:p=1  $top poly
100  1  -0.92  -63    3   -5 -159 158     imp:n=4   imp:p=4  $top poly
110  1  -0.92  -63    3   -5  159         imp:n=16 imp:p=16  $top poly
120  2  -7.94   6 -4 -8                   imp:n=64 imp:p=64  $steel cont
bottom
130  2  -7.94   -8    4   -7 (63: -4: 87) imp:n=16 imp:p=16  $steel cont
140  3  -0.224  -550 -60    7               imp:n=16 imp:p=16  $dunnage
150  3  -0.224  -550  8   -7   6            imp:n=16 imp:p=16  $side fiber
board
151  1  -0.92   12 -10 550 -59              imp:n=16 imp:p=16
160  3  -0.224  -550  12   -6               imp:n=64 imp:p=64  $bottom dun
170  0         -550  -10   60               imp:n=16 imp:p=16  $sp top barl
180  5  -7.8212  -13  -14   12 (59:-12:10) imp:n=16 imp:p=16  $barrel
190  5  -7.8212   15 -12 -13                 imp:n=64 imp:p=64  $barrel bottom
200     0    (13: 14: -15) -100 -102 103 imp:n=64 imp:p=64  $ 1m/vehicle
surface
201     0    101 -103 -100                imp:n=64 imp:p=64  $ bottom vehicle
210     0    (100: 102: -101) 600 -601 -602 imp:n=16 imp:p=16  $ 2m vehicle
surface
500     2  -7.94   507 -500     -62    imp:n=1  imp:p=1  $ hybrid capsule
501     2  -7.94   500 -501 505 -62    imp:n=1  imp:p=1  $ hybrid capsule
502     2  -7.94   501 -502     -62    imp:n=1  imp:p=1  $ hybrid capsule
503     2  -7.94   502 -503 504 -62    imp:n=1  imp:p=1  $ hybrid capsule
504     2  -7.94   503 -506     -62    imp:n=1  imp:p=1  $ hybrid capsule
505     0          502 -503 -504       imp:n=1  imp:p=1  $ hybrid capsule
506     1  -0.92   506 -3 -62          imp:n=1  imp:p=1  $ 2" plug top
507     1  -0.92   508 -507 -62        imp:n=1  imp:p=1  $ 2" plug bottom
508     1  -0.92   2 -508 -62          imp:n=2  imp:p=2  $ 2" plug bottom
999     0          -600:601:602        imp:n=0  imp:p=0  $ outside interest

62       cz     4.445  $inner radius of poly sleve 3.5"id
63       cz    14.9225 $outer radius of poly sleve
2        pz    15.5067 $bottom of source (empty part) cylinder
3        pz    58.6867 $top of source (empty part) cylinder +17"
4        pz     6.1087 $bottom of bottom poly
5        pz    68.8467 $top of top poly
6        pz     5.4737 $bottom of steel container
7        pz    73.0377 $top of steel container
87       pz    70.7517 $top of steel container interior
8        cz    15.4788 $outer radius of steel container
60       pz    80.9117 $top of top dunnage
```

```
10        pz     88.7603 $top inside barrel
59        cz     26.4262 $outside radius fiberboard
12        pz      0.1397 $bottom inside barrel
13        cz     26.5662 $outside radius barrel $ 0.14 cm thick
14        pz        88.9 $top outside barrel
15        pz           0 $bottom outside barrel
100       cz    126.5662 $ 1 meter surface
101       pz    -100.0   $ 1 meter surface
102       pz     188.9   $ 1 meter surface
103       pz    -10.16   $ bottom of vehicle (4")
158       rcc          0          0     12.4587        0   $splitting surface
                       0      50.165      8.255
159       rcc          0          0      8.9662        0   $splitting surface
                       0       57.15     12.065
301       pz       26.2255  $ Tally Plane
302       pz       32.1183  $ Tally Plane/bottom of source
303       pz       39.6113  $ Tally Plane/top of source
304       pz       45.5041  $ Tally Plane
401       cz       2.5     $
402       cz       7.5
403       cz       12.5
404       cz       17.5
c    RJM
500      pz 21.8567
501      pz 49.8729
502      pz 50.8635
503      pz 51.8287
504      cz 0.3175
505      cz 3.2537
506      pz 53.7337
507      pz 20.5867
508      pz 18.0467
510      c/z 1.6 0 1.651
c 511      pz 32.6517
c 512      pz 39.0779
550      cz    26.1468
600      pz -200
601      pz  300
602      cz 329.54

mode   n p
c
c
c pure polyethylene (density = 0.92 g/cc)
m1     1001       2 $MAT
       6000       1
mt1    poly.60t
c
c 304SS (density = 7.94 g/cc)
m2     6000   -0.08
       14000  -1.0
       15031  -0.045
       24000  -19.0
       25055  -2.0
       26000  -68.375
       28000  -9.5
c
```

```
c dunnage - redwood comp (from scale), 0.224g/cm3 from SAR drawings
m3     6000  6
       1001  10
       8016  5
c
c   source material Pu-Be13
m4     94239  1
       4009   13
mt4    be.60t
c
c  carbon steel (density = 7.8212 g/cc)
m5     26000  -99.0
        6012  -1.0
cut:n              $Implicit capture for neutrons
c phys:p     4j 1   $Detailed photon physics over whole energy range
cut:p  j .01  0    $Analog capture for photons
c
sdef         pos=1.6 0.0 35.8648 erg=d1   par=1 wgt=1.519E+05
             ext=d2 rad=d3 axs=0 0 1
si2          3.7465
si3          1.651
c Neutron energy spectrum for 1g Pu
#       si1   sp1
         h    d
         0.00 0.000E+00
         0.01 1.158E-01
         0.02 3.400E-01
         0.05 2.034E+00
         0.1 6.163E+00
         0.2 1.855E+01
         0.4 3.126E+02
         0.6 1.293E+03
         0.8 1.965E+03
         1.0 2.196E+03
         1.3 3.262E+03
         1.7 3.331E+03
         2.1 3.991E+03
         2.4 3.938E+03
         2.7 4.745E+03
         3.0 7.544E+03
         3.3 9.792E+03
         3.6 9.489E+03
         4.0 1.172E+04
         4.4 1.071E+04
         5.0 1.448E+04
         6.0 1.518E+04
         7.0 1.349E+04
         8.0 1.496E+04
         9.0 1.139E+04
         10.0 7.087E+03
         12.0 1.050E+03
         15.0 5.177E-03
         20.0 2.945E-04
c     totals 1.519E+05
c
c Tallies
c
```

```
c     ANSI/ANS-6.1.1-1977 Neutron Flux to Dose Factors (mrem/hr)
de0     2.5e-08    1.0e-07    1.0e-06    1.0e-05    1.0e-04
        1.0e-03    1.0e-02    1.0e-01    5.0e-01    1.0
        2.5        5.0        7.0        10.0       14.0
        20.0
df0     3.67e-03   3.67e-03   4.46e-03   4.54e-03   4.18e-03
        3.76e-03   3.56e-03   2.17e-02   9.26e-02   1.32e-01
        1.25e-01   1.56e-01   1.47e-01   1.47e-01   2.08e-01
        2.27e-01
fc2 Neutron dose rates on surface side (mrem/h)
f2:n  13
fs2  -301 -302 -303 -304
c
fc12 Neutron dose rates at 1 m side/vehicle surface (mrem/h)
f12:n  100
fs12 -301 -302 -303 -304
c
fc22 Neutron dose rates on surface top (mrem/h)
f22:n  14
fs22  -401 -402 -403 -404
c
fc32 Neutron dose rates at 1 meter top (mrem/h)
f32:n  102
fs32  -402 -403 -404
c
fc42 Neutron dose rates on surface bottom (mrem/h)
f42:n  15
fs42  -401 -402 -403 -404
c
fc52 Neutron dose rates at 1 meter bottom (mrem/h)
f52:n  101
fs52   -402 -403 -404
c
fc62 Neutron dose rates on vehicle bottom (mrem/hr)
f62:n  103
fs62   -402 -403 -404
c
fc72 Neutron dose rates at 2 m from vehicle surface (mrem/h)
f72:n  602
fs72 -301 -302 -303 -304
c
fc102 Gamma dose rates on surface side (mrem/h)
f102:p  13
fs102  -301 -302 -303 -304
c      ansi/ans-6.1.1-1977 fluence-to-dose, photons(mrem/hr)/(p/cm**2/s)
de102      0.01   0.03   0.05   0.07   0.10   0.15   0.20   0.25   0.30
           0.35   0.40   0.45   0.50   0.55   0.60   0.65   0.70   0.80
           1.00   1.40   1.80   2.20   2.60   2.80   3.25   3.75   4.25
           4.75   5.00   5.25   5.75   6.25   6.75   7.50   9.00   11.0
           13.0   15.0
df102      3.96-3 5.82-4 2.90-4 2.58-4 2.83-4 3.79-4 5.01-4 6.31-4 7.59-4
           8.78-4 9.85-4 1.08-3 1.17-3 1.27-3 1.36-3 1.44-3 1.52-3 1.68-3
           1.98-3 2.51-3 2.99-3 3.42-3 3.82-3 4.01-3 4.41-3 4.83-3 5.23-3
           5.60-3 5.80-3 6.01-3 6.37-3 6.74-3 7.11-3 7.66-3 8.77-3 1.03-2
           1.18-2 1.33-2
c
fc112 Gamma dose rates at 1 m side/vehicle surface (mrem/h)
```

```
f112:p  100
fs112 -301 -302 -303 -304
c      ansi/ans-6.1.1-1977 fluence-to-dose, photons(mrem/hr)/(p/cm**2/s)
de112        0.01    0.03    0.05    0.07    0.10    0.15    0.20    0.25    0.30
             0.35    0.40    0.45    0.50    0.55    0.60    0.65    0.70    0.80
             1.00    1.40    1.80    2.20    2.60    2.80    3.25    3.75    4.25
             4.75    5.00    5.25    5.75    6.25    6.75    7.50    9.00    11.0
             13.0    15.0
df112        3.96-3 5.82-4 2.90-4 2.58-4 2.83-4 3.79-4 5.01-4 6.31-4 7.59-4
             8.78-4 9.85-4 1.08-3 1.17-3 1.27-3 1.36-3 1.44-3 1.52-3 1.68-3
             1.98-3 2.51-3 2.99-3 3.42-3 3.82-3 4.01-3 4.41-3 4.83-3 5.23-3
             5.60-3 5.80-3 6.01-3 6.37-3 6.74-3 7.11-3 7.66-3 8.77-3 1.03-2
             1.18-2 1.33-2
c
fc122 Gamma dose rates on surface top (mrem/h)
f122:p  14
fs122  -401 -402 -403 -404
c      ansi/ans-6.1.1-1977 fluence-to-dose, photons(mrem/hr)/(p/cm**2/s)
de122        0.01    0.03    0.05    0.07    0.10    0.15    0.20    0.25    0.30
             0.35    0.40    0.45    0.50    0.55    0.60    0.65    0.70    0.80
             1.00    1.40    1.80    2.20    2.60    2.80    3.25    3.75    4.25
             4.75    5.00    5.25    5.75    6.25    6.75    7.50    9.00    11.0
             13.0    15.0
df122        3.96-3 5.82-4 2.90-4 2.58-4 2.83-4 3.79-4 5.01-4 6.31-4 7.59-4
             8.78-4 9.85-4 1.08-3 1.17-3 1.27-3 1.36-3 1.44-3 1.52-3 1.68-3
             1.98-3 2.51-3 2.99-3 3.42-3 3.82-3 4.01-3 4.41-3 4.83-3 5.23-3
             5.60-3 5.80-3 6.01-3 6.37-3 6.74-3 7.11-3 7.66-3 8.77-3 1.03-2
             1.18-2 1.33-2
c
fc132 Gamma dose rates at 1 meter top (mrem/h)
f132:p  102
fs132  -402 -403 -404
c      ansi/ans-6.1.1-1977 fluence-to-dose, photons(mrem/hr)/(p/cm**2/s)
de132        0.01    0.03    0.05    0.07    0.10    0.15    0.20    0.25    0.30
             0.35    0.40    0.45    0.50    0.55    0.60    0.65    0.70    0.80
             1.00    1.40    1.80    2.20    2.60    2.80    3.25    3.75    4.25
             4.75    5.00    5.25    5.75    6.25    6.75    7.50    9.00    11.0
             13.0    15.0
df132        3.96-3 5.82-4 2.90-4 2.58-4 2.83-4 3.79-4 5.01-4 6.31-4 7.59-4
             8.78-4 9.85-4 1.08-3 1.17-3 1.27-3 1.36-3 1.44-3 1.52-3 1.68-3
             1.98-3 2.51-3 2.99-3 3.42-3 3.82-3 4.01-3 4.41-3 4.83-3 5.23-3
             5.60-3 5.80-3 6.01-3 6.37-3 6.74-3 7.11-3 7.66-3 8.77-3 1.03-2
             1.18-2 1.33-2
c
fc142 Gamma dose rates on surface bottom (mrem/h)
f142:p  15
fs142  -401 -402 -403 -404
c      ansi/ans-6.1.1-1977 fluence-to-dose, photons(mrem/hr)/(p/cm**2/s)
de142        0.01    0.03    0.05    0.07    0.10    0.15    0.20    0.25    0.30
             0.35    0.40    0.45    0.50    0.55    0.60    0.65    0.70    0.80
             1.00    1.40    1.80    2.20    2.60    2.80    3.25    3.75    4.25
             4.75    5.00    5.25    5.75    6.25    6.75    7.50    9.00    11.0
             13.0    15.0
df142        3.96-3 5.82-4 2.90-4 2.58-4 2.83-4 3.79-4 5.01-4 6.31-4 7.59-4
             8.78-4 9.85-4 1.08-3 1.17-3 1.27-3 1.36-3 1.44-3 1.52-3 1.68-3
             1.98-3 2.51-3 2.99-3 3.42-3 3.82-3 4.01-3 4.41-3 4.83-3 5.23-3
             5.60-3 5.80-3 6.01-3 6.37-3 6.74-3 7.11-3 7.66-3 8.77-3 1.03-2
```

```
           1.18-2 1.33-2
c
fc152 Gamma dose rates at 1 meter bottom (mrem/h)
f152:p  101
fs152   -402 -403 -404
c      ansi/ans-6.1.1-1977 fluence-to-dose, photons(mrem/hr)/(p/cm**2/s)
de152      0.01   0.03   0.05   0.07   0.10   0.15   0.20   0.25   0.30
           0.35   0.40   0.45   0.50   0.55   0.60   0.65   0.70   0.80
           1.00   1.40   1.80   2.20   2.60   2.80   3.25   3.75   4.25
           4.75   5.00   5.25   5.75   6.25   6.75   7.50   9.00   11.0
           13.0   15.0
df152      3.96-3 5.82-4 2.90-4 2.58-4 2.83-4 3.79-4 5.01-4 6.31-4 7.59-4
           8.78-4 9.85-4 1.08-3 1.17-3 1.27-3 1.36-3 1.44-3 1.52-3 1.68-3
           1.98-3 2.51-3 2.99-3 3.42-3 3.82-3 4.01-3 4.41-3 4.83-3 5.23-3
           5.60-3 5.80-3 6.01-3 6.37-3 6.74-3 7.11-3 7.66-3 8.77-3 1.03-2
           1.18-2 1.33-2
c
fc162 Gamma dose rates at vehicle bottom (mrem/h)
f162:p  103
fs162   -402 -403 -404
c      ansi/ans-6.1.1-1977 fluence-to-dose, photons(mrem/hr)/(p/cm**2/s)
de162      0.01   0.03   0.05   0.07   0.10   0.15   0.20   0.25   0.30
           0.35   0.40   0.45   0.50   0.55   0.60   0.65   0.70   0.80
           1.00   1.40   1.80   2.20   2.60   2.80   3.25   3.75   4.25
           4.75   5.00   5.25   5.75   6.25   6.75   7.50   9.00   11.0
           13.0   15.0
df162      3.96-3 5.82-4 2.90-4 2.58-4 2.83-4 3.79-4 5.01-4 6.31-4 7.59-4
           8.78-4 9.85-4 1.08-3 1.17-3 1.27-3 1.36-3 1.44-3 1.52-3 1.68-3
           1.98-3 2.51-3 2.99-3 3.42-3 3.82-3 4.01-3 4.41-3 4.83-3 5.23-3
           5.60-3 5.80-3 6.01-3 6.37-3 6.74-3 7.11-3 7.66-3 8.77-3 1.03-2
           1.18-2 1.33-2
c
fc172 Gamma dose rates at 2 m from vehicle side surface (mrem/h)
f172:p  602
fs172 -301 -302 -303 -304
c      ansi/ans-6.1.1-1977 fluence-to-dose, photons(mrem/hr)/(p/cm**2/s)
de172      0.01   0.03   0.05   0.07   0.10   0.15   0.20   0.25   0.30
           0.35   0.40   0.45   0.50   0.55   0.60   0.65   0.70   0.80
           1.00   1.40   1.80   2.20   2.60   2.80   3.25   3.75   4.25
           4.75   5.00   5.25   5.75   6.25   6.75   7.50   9.00   11.0
           13.0   15.0
df172      3.96-3 5.82-4 2.90-4 2.58-4 2.83-4 3.79-4 5.01-4 6.31-4 7.59-4
           8.78-4 9.85-4 1.08-3 1.17-3 1.27-3 1.36-3 1.44-3 1.52-3 1.68-3
           1.98-3 2.51-3 2.99-3 3.42-3 3.82-3 4.01-3 4.41-3 4.83-3 5.23-3
           5.60-3 5.80-3 6.01-3 6.37-3 6.74-3 7.11-3 7.66-3 8.77-3 1.03-2
           1.18-2 1.33-2
c
c
c          Mesh tallies
c          A cylindrical mesh tally is placed around the package.
c          The radial regions of interest are from 26.57 to 27.57 (surface)
c          and 126.57 to 127.57 (1m).  Circumferentially there are 36
segments,
c          each 10 degrees wide.  Theta=0 corresponds to the positive x-axis.
c          radius=i
c          axial=j
c          circumferential=k
```

```
c
fmesh14:n    geom=cyl origin=0  0  0 axs=0  0  1 vec=1  0  0
             imesh=26.57 27.57 126.57 127.57
             iints=1 1 1 1
             jmesh=32.12 39.61
             jints=1 1
             kmesh=1
             kints=36
             out=ik
fmesh24:p    geom=cyl origin=0  0  0 axs=0  0  1 vec=1  0  0
             imesh=26.57 27.57 126.57 127.57
             iints=1 1 1 1
             jmesh=32.12 39.61
             jints=1 1
             kmesh=1
             kints=36
             out=ik
c       ansi/ans-6.1.1-1977 fluence-to-dose, photons(mrem/hr)/(p/cm**2/s)
de24         0.01    0.03    0.05    0.07    0.10    0.15    0.20    0.25    0.30
             0.35    0.40    0.45    0.50    0.55    0.60    0.65    0.70    0.80
             1.00    1.40    1.80    2.20    2.60    2.80    3.25    3.75    4.25
             4.75    5.00    5.25    5.75    6.25    6.75    7.50    9.00    11.0
             13.0    15.0
df24         3.96-3 5.82-4 2.90-4 2.58-4 2.83-4 3.79-4 5.01-4 6.31-4 7.59-4
             8.78-4 9.85-4 1.08-3 1.17-3 1.27-3 1.36-3 1.44-3 1.52-3 1.68-3
             1.98-3 2.51-3 2.99-3 3.42-3 3.82-3 4.01-3 4.41-3 4.83-3 5.23-3
             5.60-3 5.80-3 6.01-3 6.37-3 6.74-3 7.11-3 7.66-3 8.77-3 1.03-2
             1.18-2 1.33-2
prdmp   j j 1 2
ctme    300
```

6. CRITICALITY EVALUATION

The S300 is used to transport sealed neutron sources, alpha reference standards, foils (e.g., threshold detectors), and other similar source configurations containing plutonium. The contents are transported in one of two special form capsules, the Model II and Model III. Different mass limits are utilized for the two capsule designs, as the Model II is larger than the Model III. The following analyses demonstrate that the S300 package complies with the requirements of 10 CFR 71.55 and 71.59. The criticality safety index varies based on the payload under consideration.

6.1 Description of Criticality Design

6.1.1 Design Features

The Model II or Model III special form capsule (SFC) is the only design feature credited for criticality control in the HAC array analysis. The HAC array is the only condition in which the reactivity approaches the upper subcritical limit. The pipe component is credited in the NCT analysis because it is undamaged under NCT. The presence of the polyethylene shielding allows for low reactivites in the NCT array condition because it isolates the fissile mass in each package.

6.1.2 Summary Table of Criticality Evaluation

The upper subcritical limit (USL) for ensuring that the package is acceptably subcritical, as determined in Section 6.8, *Benchmark Evaluations*, is:

$$\text{USL} = 0.9257$$

The package is considered to be acceptably subcritical if the computed k_{safe} (k_s), which is defined as $k_{effective}$ (k_{eff}) plus twice the statistical uncertainty (σ), is less than or equal to the USL, or:

$$k_s = k_{eff} + 2\sigma \leq \text{USL}$$

The USL is determined on the basis of a benchmark analysis and incorporates the combined effects of code computational bias, the uncertainty in the bias based on both benchmark-model and computational uncertainties, and an administrative margin. The results of the benchmark analysis indicate that the USL is adequate to ensure subcriticality of the package.

The packaging design is shown to meet the requirements of 10 CFR 71.55(b). In the single package normal conditions of transport (NCT) models, credit is taken for the pipe component and polyethylene, although the dunnage and overpack is conservatively neglected for simplicity. In the single package hypothetical accident condition (HAC) models, optimum water moderation is modeled within the SFC and pipe overpack. In all single package models, 12inches of water reflection is utilized.

Infinite reflection is utilized in all NCT array models because the polyethylene shielding material effectively isolates each package. In the HAC array cases, it is assumed that the SFCs are ejected from the pipe component and form a close-packed hexagonal array. Because no credit is taken for the pipe component, finite arrays are modeled for HAC.

The contents are divided into two categories: (1) neutron source, and (2) general payload. The neutron source content consists of plutonium bonded to an (α,n) target nucleus, typically (but not limited to) beryllium. The general payload typically consists of plutonium alpha reference standards and plutonium foils. Other items containing plutonium within the general payload mass limits would also be acceptable for transport as a general payload, as no geometrical information is utilized in the general payload analysis.

Analyses for the two contents are performed separately for the Model II and Model III SFCs. The maximum results of the criticality calculations for each combination of SFC and content are summarized in Table 6-1.

In addition, the air transport requirements for fissile material from 10 CFR 71.55(f) are also met. The air transport results are summarized in Table 6-2. Note that the USL for air transport is different than the USL for the primary analysis because a different computer program (and hence different benchmark cases) is utilized. Compliance with the requirements of 10 CFR 71.64, *Special Requirements for Plutonium Air Shipments*, has not been demonstrated, and therefore authorization is not being sought for air transport in any airspace subject to the laws and regulations of the United States.

Table 6-1 – Summary of Criticality Evaluation

SFC	**Model II**	**Model III**	**Model II**	**Model III**
Payload type	Neutron Source		General Payload	
Pu mass limit (g)	350	160	300	160
CSI	0.3		4.0	
Normal Conditions of Transport (NCT)				
Case	k_s	k_s	k_s	k_s
Single Unit Maximum	0.1675	0.1381	0.3647	0.2979
Infinite Array Maximum	0.1690	0.1386	0.3657	0.2982
Hypothetical Accident Conditions (HAC)				
Case	k_s	k_s	k_s	k_s
Single Unit Maximum	0.1994	0.1440	0.3910	0.3131
Finite Array Maximum	0.9045	0.6772	0.9239	0.6138
USL = 0.9257				

Table 6-2 – Summary of Criticality Evaluation, Air Transport

SFC	Model II	Model III
Pu mass limit (g)	210 (1)	160
k_s	0.8930	
USL = 0.9377		

(1) Note that 210 g of plutonium is conservatively used in the criticality analysis. However, as seen in Table 1-2, the maximum allowable content for air transport is 206 g of plutonium.

6.1.3 Criticality Safety Index

An infinite number of packages is used in all NCT array calculations. Therefore, the CSI for each scenario is determined based upon the size of the HAC array. For the neutron source contents, an HAC array of approximately 350 packages is utilized (2N = 350) so that the CSI = 50/N = 0.3. For the general payload, an HAC array of 25 packages is utilized (2N = 25) so that the CSI = 50/N = 4.0.

6.2 Fissile Material Contents

The fissile material contains plutonium and is divided into two categories, (1) plutonium neutron sources, and (2) general plutonium material, including but not limited to threshold foils and alpha reference standards.

The plutonium isotopics may vary between the various items, although the composition will always be composed of the following six isotopes: Pu-238, Pu-239, Pu-240, Pu-241, Pu-242, and Am-241. It is conservatively assumed that Pu-239 is the only plutonium isotope in the mixture. Including all the plutonium isotopes would lower the reactivity, both by reducing the mass of Pu-239 and increasing the mass of Pu-240, which acts as a poison. Pu-241 is more reactive than Pu-239, but because Pu-240 is always present in significantly larger quantities than Pu-241, it is conservative to simply model all plutonium as Pu-239. Therefore, the actual isotopic distribution is not needed to ensure criticality control.

6.2.1 Plutonium Neutron Sources

Plutonium neutron sources consist of plutonium mixed with an (α,n) target isotope, most commonly beryllium. Other targets isotopes, such as boron or fluorine, are possible, although are quite rare. Currently, there are several thousand known PuBe sources located around the world, while only several (<10) non-PuBe sources are known. For this reason, the criticality models address only PuBe sources.

PuBe sources have been manufactured by several companies. PuBe sources manufactured by Monsanto Research Corporation consist of PuBe source material packed into a tantalum inner container, which is then clad in stainless steel (see Section 6.9.2, *PuBe Source Dimensions*). The density of the PuBe source material is approximately 3.7 g/cm^3 (see Section 6.9.1, *PuBe Neutron Source Paper*). PuBe sources were manufactured in a variety of sizes, with the largest source having a mass of 160 g Pu. Rather than model a PuBe neutron source explicitly with the tantalum and steel cladding, the PuBe is modeled without any cladding. Tantalum is a strong neutron absorber, and it cannot be show that all PuBe neutron sources generated by all manufacturers contain tantalum inner cladding. Therefore, tantalum cladding is conservatively neglected. While all PuBe sources are clad in steel to provide confinement as a sealed source, the steel is also conservatively neglected in the criticality models, since it also acts as a neutron poison. Although the cladding is not modeled, water cannot mix with the PuBe material because the stainless steel cladding is always present.

The bare PuBe slug is modeled with a diameter of 1.3 inches, consistent with a 160 g PuBe source (10 Ci) per the Monsanto drawing (see Section 6.9.2, *PuBe Source Dimensions*). The height of the PuBe slug is selected to give the desired mass, 6.48 inches for 350 g Pu (for the Model II analysis), or 2.96 inches for 160 g Pu (for the Model III analysis). These dimensions are used for modeling purposes only, and are not intended to limit the actual sealed source content to these exact dimensions. PuBe exists as a compound with the chemical formula $PuBe_{13}$. Therefore, it is modeled in MCNP with 1 plutonium atom and 13 beryllium atoms at a density of 3.7 g/cm^3.

6.2.2 General Plutonium Materials

The general plutonium material may be threshold foils, alpha reference standards, or other source, solid-form quantities of plutonium small enough to fit within the two SFC types available. Threshold foils are thin foils of plutonium that may be clad in copper, nickel, aluminum, or other materials. Each foil typically contains between 1 mg to 5 g of plutonium. Alpha reference standards (alpha source) typically consist of plutonium electrolytically or electrochemically deposited on a thin metallic surface, typically stainless steel. Because alpha particles have a short range through solid matter, the mass of plutonium used in an alpha source is necessarily quite small (on the order of milligram quantities).

Because the geometry of the general plutonium contents varies widely, no attempt has been made to model the actual geometry of these items. Rather, the plutonium is modeled both as a discrete lump, and as a homogenous mixture of plutonium and water, neglecting all cladding materials. These modeling extremes represent a more reactive condition than would be achieved by modeling the contents explicitly. For this reason, the general plutonium content has a much higher CSI than the plutonium neutron sources content.

When modeling the general contents as a discrete lump, a cylindrical geometry is assumed in which the diameter is the same as the height. For 300 g plutonium, this lump has a diameter and height of 1.06 inches, while for 160 g of plutonium the diameter and height is 0.86 inches. A plutonium density of 19.84 g/cm^3 is utilized. When modeling the general contents as homogenized over the SFC volume, full-density water is utilized. A variety of homogenized number densities are developed for different fissile heights and masses. As an example, the homogenized number densities for the maximum mass in the Model II and Model III SFC are summarized in Table 6-3. These number densities represent the mass homogenized over the entire SFC volume, which is the most reactive condition. The ratio of the hydrogen to plutonium number density (H/Pu) is also listed in the table below. This ratio is useful to assess the degree of moderation of the system.

Table 6-3 – General Payload, Homogenized Number Densities

	Model II SFC	**Model III SFC**
Pu Mass (g)	300	160
SFC Maximum Volume (cm^3)	532.2	143.9
H/Pu	45.7	22.5
Isotope	**Number Density (atoms/b-cm)**	**Number Density (atoms/b-cm)**
Pu-239	1.4201E-03	2.8012E-03
H	6.4955E-02	6.3107E-02
O	3.2477E-02	3.1554E-02
Total	9.8852E-02	9.7462E-02

6.3 General Considerations

6.3.1 Model Configuration

The MCNP model used for NCT cases is a simplified version of the actual geometry. The entire 55 gallon drum and dunnage are neglected for simplicity. This simplification is conservative, as it brings the water reflector closer to the fissile material in the single package cases, and greatly reduces the package to package spacing in the NCT array cases. The MCNP model geometry for the Model II SFC in a pipe component is shown in Figure 6-1.

The actual dimensions and as-modeled dimensions of the pipe component and SFCs are shown in Table 6-4 and Table 6-5, respectively. The OD of the steel pipe is modeled at 12.8 inches, and the side, bottom, and lid of the pipe component is modeled with a thickness of 0.219 inches. The entire region between the SFC and pipe is completely filled with polyethylene, without modeling minor gaps. Six inches of polyethylene are modeled at the axial ends of the SFC, and the stainless steel pipe component bottom and lid are modeled in contact with the polyethylene. Therefore, for both SFC models, the axial length of the pipe component is shorter than the actual pipe component length, which is conservative for the NCT array.

The modeling details for the NCT models are inconsequential because the payload is not moderated for NCT, and there are essentially no package to package interactions because of the large amount of neutron shielding. For this reason, all NCT array cases are performed with an infinite hexagonal array.

No HAC testing was performed on the S300 package to conclusively demonstrate the post-accident condition of the overpack and pipe component. For the HAC single package cases, it is conservative for the SFC to remain inside the pipe component because the polyethylene shielding is a better reflector than water. However, for the HAC array cases, it is conservatively assumed that the SFC is ejected from the pipe component. This is conservative in the array case because it results in a tightly packed hexagonal array of SFCs with no polyethylene to isolate the packages. In addition, it is assumed in HAC that optimum moderation may occur within the

SFC, although testing has shown that the SFCs remain watertight when submerged in water and both SFCs are certified by the U.S. Department of Transportation as IAEA Special Form.

More details of the model configurations are provided in Section 6.4, *Single Package Evaluation*, Section 6.5, *Evaluation of Package Arrays under Normal Conditions of Transport*, and Section 6.6, *Package Arrays under Hypothetical Accident Conditions*.

6.3.2 Material Properties

The material properties of the fissile material are discussed in Section 6.2, *Fissile Material Contents*. The material properties of the packaging materials are provided in Table 6-6. The composition and density of common materials are taken from the SCALE Standard Composition Library. Compositions are input as either atoms per molecule or weight percent (wt. %), depending on how the composition is listed in the reference. Water is modeled simply as 1 oxygen atom for every 2 hydrogen atoms over a range of different densities.

6.3.3 Computer Codes and Cross-Section Libraries

MCNP5 v1.40 is used for the criticality analysis. All cross sections utilized are at room temperature (293.6 K). Pu-239 utilizes preliminary ENDF/B-VII cross section data that are considered by Los Alamos National Laboratory to be more accurate than ENDF/B-VI cross sections. ENDF/B-V cross sections are utilized for chromium, nickel, and iron because natural composition ENDF/B-VI cross sections are not available for these elements. The remaining isotopes utilize ENDF/B-VI cross sections. Titles of the cross sections utilized in the models have been extracted from the MCNP output (when available) and provided in Table 6-7. The $S(\alpha,\beta)$ card LWTR.60T is used to simulate hydrogen bound to oxygen in water, and the $S(\alpha,\beta)$ card POLY.60T is used to simulate hydrogen bound to carbon in polyethylene.

All cases are run with 2500 neutrons per generation for 250 generations, skipping the first 50. The 1 sigma uncertainty is approximately 0.001 for all cases.

6.3.4 Demonstration of Maximum Reactivity

The reactivities of the NCT cases, both single package and array, and HAC single package cases, are negligible. The maximum reactivity is obtained for the HAC array cases. For the HAC arrays with PuBe material, approximately 350 packages are modeled, which is in excess of the minimum number required to justify a CSI = 0.3. For the HAC arrays with the general payload, 25 packages are modeled to justify a CSI = 4.0. All plutonium is conservatively modeled as Pu-239 because it is the most reactive.

In the HAC array cases, it is conservatively assumed that the SFC is completely ejected from the package. Therefore, the SFCs are modeled in a close-packed hexagonal array with optimum moderation both within and between the SFCs. Ejecting the SFCs from every package is a highly conservative assumption, because a close-packed array formed of only SFCs is not credible.

For the PuBe source payload, the fissile material is modeled as a single discrete lump of PuBe without tantalum, steel, or any other cladding, which could act as a poison. Water is assumed to enter the SFC, although it was demonstrated during the SFC certification testing that the SFCs remain watertight subsequent to an accident. For the general payload, the source is homogenized with water, which is more reactive than if the payload were modeled explicitly. Homogenizing the payload increases the moderation and neglects any cladding materials that may act as a poison. Homogenizing the payload also increases the reactivity compared to explicitly modeling thin foils of plutonium clad in structural materials.

Optimum moderation is sought in all models. In the PuBe models, the water density is allowed to vary in three regions: (1) beside the PuBe inside the SFC, (2) above the PuBe within the SFC, and (3) between the SFCs. In the general payload models, various moderation conditions are examined by changing the fissile solution height, and fissile mass. The water density between the SFCs is also examined.

Calculations are peformed both for the Model II and Model III SFC because the mass limit is different for the two SFCs. The Model II bounds the Model III because the mass limit for the Model II is significantly higher. The most reactive HAC array scenarios are as follows:

- Case D32: Model II SFC, 350 g Pu in PuBe, 1.0 g/cm^3 water beside PuBe, 0 g/cm^3 water above PuBe, 0 g/cm^3 water between SFCs, $k_s = 0.9045$
- Case E24: Model III SFC, 160 g Pu in PuBe, 1.0 g/cm^3 water beside PuBe, 0.3 g/cm^3 water above PuBe, 0.3 g/cm^3 water between SFCs, $k_s = 0.6772$
- Case G2: Model II SFC, 300 g Pu homogenized with water over the entire SFC volume, 1.0 g/cm^3 water between SFCs, $k_s = 0.9239$
- Case H5: Model III SFC, 160 g Pu homogenized with water over the entire SFC volume, 1.0 g/cm^3 water between SFCs, $k_s = 0.6138$

Table 6-4 – S300 Pipe Component As-Modeled Dimensions

Component	Actual Dimension (in)	As-Modeled Dimension (in)
Steel Pipe OD	12.8	12.8
Steel pipe wall thickness	0.219	0.219
Steel Pipe lid thickness	0.9	0.219
Steel pipe floor thickness	0.25	0.219
Steel pipe length (flange to bottom)	25.6	23.97 (Model II) 19.21 (Model III)
Poly side thickness	4.15 = (11.8-3.5)/2	4.68
Poly top thickness	6.0 = 2.0+4.0	6.0
Poly bottom thickness	5.7 = 22.7-2.0-17.0+2.0	6.0

Table 6-5 – Special Form Capsule As-Modeled Dimensions

Component	Model II Capsule Actual Dimension (in)	As-Modeled Dimension (in)
Overall length (not including shearable cap)	11.75	11.75
Thickness of cap+sealing plug	1.53 = 0.75+0.78	1.53
ID	2.062	2.062
OD	3.00	3.00
Bottom Thickness	<1.0 when drill point included	0.5
Component	**Model III Capsule Actual Dimension (in)**	**As-Modeled Dimension (in)**
Overall length (not including shearable cap)	7.00	7.00
Thickness of cap+sealing plug	1.53 = 7.0-1.0-4.47	1.53
ID	1.50	1.50
OD	2.50	2.50
Bottom Thickness	<1.0 when drill point included	0.5

Table 6-6 – Material Properties

Polyethylene, CH_2 (density = 0.92 g/cm^3)					
Element	Library ID	Atoms	Element	Library ID	Atoms
Hydrogen	1001	2	Carbon	6000	1
304SS (density = 7.94 g/cm^3)					
Element	Library ID	Wt. %	Element	Library ID	Wt. %
Carbon	6000	0.08	Manganese	25055	2.0
Silicon	14000	1.0	Iron	26000	68.375
Phosphorus	15031	0.045	Nickel	28000	9.5
Chromium	24000	19.0	-	-	-

Table 6-7 – Cross Section Libraries Utilized

Isotope/Element	Cross Section Label (from MCNP output)
1001.62c	1-h-1 at 293.6K from endf-vi.8 njoy99.50
4009.62c	4-be-9 at 293.6K from endf/b-vi.8 njoy99.50
6000.66c	6-c-0 at 293.6K from endf-vi.6 njoy99.50
8016.62c	8-o-16 at 293.6K from endf-vi.8 njoy99.50
14000.60c	14-si-nat from endf/b-vi
15031.66c	15-p-31 at 293.6K from endf-vi.6 njoy99.50
24000.50c	njoy
25055.62c	25-mn-55 at 293.6K from endf/b-vi.8 njoy99.50
26000.55c	njoy
28000.50c	njoy
94239.69c	94-pu-239 at 293.6K from t16 pu239la7d njoy99.50

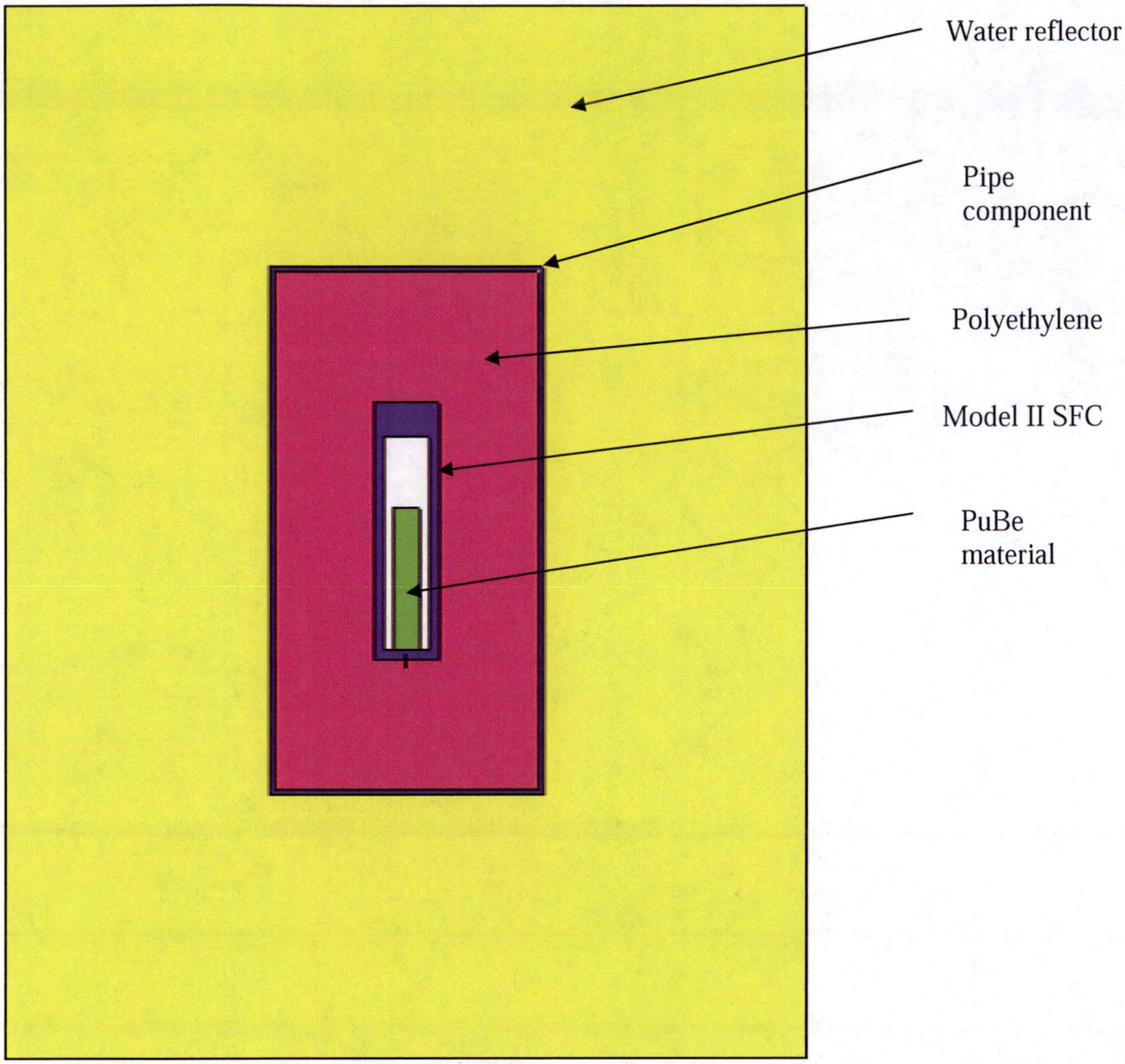


Figure 6-1 – NCT Single Package Model

6.4 Single Package Evaluation

6.4.1 Configuration

NCT

The NCT single package configuration is described in Section 6.3.1, *Model Configuration.* The NCT single package configuration is basically a pipe component without the overpack. The pipe component is reflected with 12 inches of water.

NCT single package calculations are performed for the following 4 scenarios:

- Case A1: 350 g Pu in PuBe, Model II SFC (neutron source payload)
- Case A2: 160 g Pu in PuBe, Model III SFC (neutron source payload)
- Case A3: 300 g Pu, Model II SFC (general payload)
- Case A4: 160 g Pu, Model III SFC (general payload)

In the general payload models, the plutonium is modeled simply as a discrete lump with a diameter equal to the height. The NCT single package results are summarized in Table 6-8. The reactivity values are very low for all four scenarios, although the reactivity is higher when the plutonium is compacted into a slug without beryllium. Case A3 is the most reactive, with k_s = 0.3647. This k_s value is far below the USL of 0.9257.

HAC

In the HAC single package evaluation, the SFC may be either inside or outside the pipe component, whichever scenario is most reactive. In the HAC single package cases, water is assumed to flood the SFC. For the PuBe neutron source payload, water is simply modeled in the void space inside the SFC. Water cannot mix with the PuBe material because it is sealed in a cladding of stainless steel, although the cladding is not modeled. For the general payload case, it is assumed that the plutonium may be either a discrete lump (same as the NCT fissile geometry) or homogeneously mixed with water.

The HAC single package results are listed in Table 6-9. Cases B1 and B2 are for 350 g Pu (as PuBe) in a Model II SFC inside and outside the pipe component. Cases B11 and B12 are for 160 g Pu (as PuBe) in a Model III SFC inside and outside the pipe component. In both cases, the system is slightly more reactive with the SFC inside the pipe component because polyethylene is a more effective reflector than water.

Cases B21 through B31 are for 300 g plutonium (max) in a Model II SFC for the general payload. In Case B21, the plutonium is modeled as a single cylindrical lump with a flooded SFC inside the pipe component. Case B22 is the same as Case B21 except the SFC is outside the pipe component. Consistent with the results for the PuBe material, the reactivity decreases when the SFC is removed from the pipe component. Therefore, the pipe component is modeled in the remaining cases. In Cases B23 through B31, the plutonium is homogeneously mixed with water across the diameter of the Model II SFC for a range of different fissile heights and masses. As the height of the fissile mixture varies from 3 cm to 24.7 cm (maximum), the degree of moderation changes. Of these homogenized cases, the reactivity is maximized at the maximum mixture height. Because reactivity is maximized at the maximum height, to further increase moderation, the mass of plutonium must be reduced. In Cases B29 through B31, a reduced plutonium mass is modeled as homogenized over the entire height. Reducing the mass increases the moderation but decreases the reactivity. Case B21 is the most reactive, with the fissile material modeled as a single lump. Typically, a homogenized representation would be more reactive than a single lump, but because the available volume within the SFC is small and the height is much greater than the diameter, the homogenized geometry is less favorable than a single lump for a single package configuration.

Cases B41 through B49 follow the same methodology described in the previous paragraph for 160 g plutonium (max) in a Model III SFC with a general payload. The results trend in the same manner, and the most reactive case (Case B41) is modeled as a single lump with a fully flooded SFC within the pipe component.

Comparing all HAC single package models, the most reactive is Case B21, with $k_s = 0.3910$. This case features a Model II SFC with 300 g of plutonium as single discrete lump and a fully flooded SFC inside the pipe component. This k_s value is far below the USL of 0.9257.

6.4.2 Results

The NCT single package results are listed in Table 6-8, and the HAC single package results are listed in Table 6-9.

Table 6-8 – NCT Single Package Results

Case ID	Filename	k_{eff}	σ	k_s $(k+2\sigma)$
A1	NS_II	0.1664	0.0005	0.1675
A2	NS_III	0.1373	0.0004	0.1381
A3	NSF_II	0.3637	0.0005	0.3647
A4	NSF_III	0.2971	0.0004	0.2979

Table 6-9 – HAC Single Package Results

Case ID	Filename	Height (cm)	Pu Mass (g)	k_{eff}	σ	k_s $(k+2\sigma)$
PuBe Source, 350 g Pu, Model II SFC						
B1	**HS_II**	**lump**	**350**	**0.1981**	**0.0007**	**0.1994**
B2	HS_II_EX	lump	350	0.1915	0.0006	0.1927
PuBe Source, 160 g Pu, Model III SFC						
B11	**HS_III**	**lump**	**160**	**0.1430**	**0.0005**	**0.1440**
B12	HS_III_EX	lump	160	0.1354	0.0005	0.1363
General Source, 300 g Pu Maximum, Model II SFC						
B21	**HSF_IIS**	**lump**	**300**	**0.3898**	**0.0006**	**0.3910**
B22	HSF_IIS_EX	lump	300	0.3883	0.0006	0.3896
B23	HSF_II_H03	3	300	0.2658	0.0006	0.2670
B24	HSF_II_H05	5	300	0.2743	0.0008	0.2758
B25	HSF_II_H10	10	300	0.3022	0.0008	0.3038
B26	HSF_II_H15	15	300	0.3166	0.0009	0.3183
B27	HSF_II_H20	20	300	0.3241	0.0009	0.3260
B28	HSF_II_H25	24.7	300	0.3275	0.0009	0.3294
B29	HSF_II_M200	24.7	200	0.3058	0.0009	0.3075
B30	HSF_II_M250	24.7	250	0.3175	0.0009	0.3192
B31	HSF_II_M275	24.7	275	0.3231	0.0009	0.3248
General Source, 160 g Pu Maximum, Model III SFC						
B41	**HSF_IIIS**	**lump**	**160**	**0.3122**	**0.0005**	**0.3131**
B42	HSF_IIIS_EX	lump	160	0.3103	0.0005	0.3113
B43	HSF_III_H03	3	160	0.1999	0.0006	0.2010
B44	HSF_III_H05	5	160	0.1979	0.0006	0.1992
B45	HSF_III_H10	10	160	0.2095	0.0007	0.2109
B46	HSF_III_H13	12.6	160	0.2166	0.0007	0.2180
B47	HSF_III_M100	12.6	100	0.1900	0.0007	0.1913
B48	HSF_III_M120	12.6	120	0.1980	0.0007	0.1995
B49	HSF_III_M140	12.6	140	0.2048	0.0007	0.2062

6.5 Evaluation of Package Arrays under Normal Conditions of Transport

6.5.1 Configuration

The NCT array configuration is almost identical to the NCT single package configuration utilized in Section 6.4, *Single Package Evaluation.* The only difference is that the water reflector has been removed and replaced with a reflective hexagonal surface. This results in an infinite array of packages. The geometry of the Model III SFC in the array condition is shown in Figure 6-2. Cases are run in which the water density between packages varies between 0 and 1.0 g/cm^3.

The results of the NCT array cases are listed in Table 6-10. The reactivity changes very little when the water density between packages is varied. This indicates that the packages are effectively isolated from one another and that these differences are simply statistical fluctuation. In fact, the NCT array reactivity values are identical to the NCT single package results within statistical fluctuation.

Case C22 is the most reactive, with $k_s = 0.3657$. This case is for the general payload, Model II SFC, with 300 g Pu, and 0.25 g/cm^3 water between packages. This k_s value is well below the USL of 0.9257.

6.5.2 Results

The NCT array results are listed in Table 6-10.

Table 6-10 – NCT Array Results

Case ID	Filename	Water Density between SFCs (g/cm^3)	k_{eff}	σ	k_s ($k+2\sigma$)
PuBe Source, 350 g Pu, Model II SFC					
C1	**NA_II_W000**	**0.00**	**0.1681**	**0.0004**	**0.1690**
C2	NA_II_W025	0.25	0.1663	0.0005	0.1673
C3	NA_II_W050	0.50	0.1657	0.0005	0.1667
C4	NA_II_W075	0.75	0.1671	0.0005	0.1682
C5	NA_II_W100	1.00	0.1669	0.0005	0.1679
PuBe Source, 160 g Pu, Model III SFC					
C11	NA_III_W000	0.00	0.1368	0.0004	0.1377
C12	NA_III_W025	0.25	0.1374	0.0004	0.1382
C13	NA_III_W050	0.50	0.1367	0.0004	0.1376
C14	**NA_III_W075**	**0.75**	**0.1376**	**0.0005**	**0.1386**
C15	NA_III_W100	1.00	0.1369	0.0005	0.1378
General Source, 300 g Pu, Model II SFC					
C21	NAF_II_W000	0.00	0.3640	0.0005	0.3649
C22	**NAF_II_W025**	**0.25**	**0.3647**	**0.0005**	**0.3657**
C23	NAF_II_W050	0.50	0.3638	0.0005	0.3648
C24	NAF_II_W075	0.75	0.3629	0.0005	0.3638
C25	NAF_II_W100	1.00	0.3634	0.0005	0.3644
General Source, 160 g Pu, Model III SFC					
C31	NAF_III_W000	0.00	0.2968	0.0004	0.2975
C32	NAF_III_W025	0.25	0.2972	0.0004	0.2981
C33	NAF_III_W050	0.50	0.2969	0.0005	0.2978
C34	**NAF_III_W075**	**0.75**	**0.2974**	**0.0004**	**0.2982**
C35	NAF_III_W100	1.00	0.2972	0.0004	0.2981

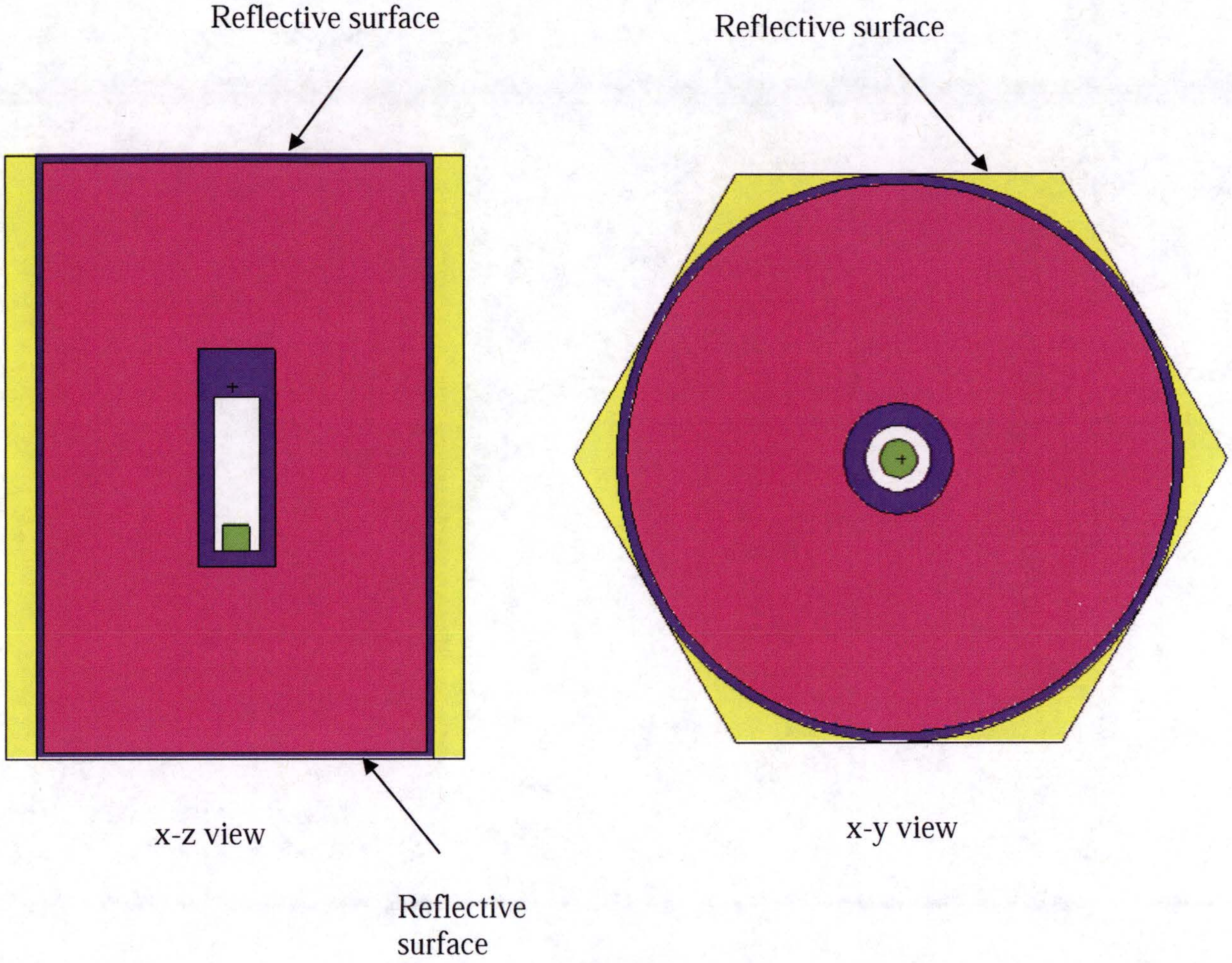


Figure 6-2 – NCT Array, Model III SFC, General Payload

6.6 Package Arrays under Hypothetical Accident Conditions

6.6.1 Configuration

For all HAC array models, it is conservatively assumed that the SFC is ejected from the overpack and forms a close-packed hexagonal array. Because this scenario does not take credit for the shielding provided by the polyethylene, it is necessary to model finite rather than infinite arrays. Optimum moderation is addressed, both within the SFC and between the SFCs. All models are reflected with 12 inches of water. The array assumptions, while conservative, are likely not credible, because every SFC is assumed to be ejected from every S300, and form a close-packed hexagonal array with optimum moderation.

6.6.1.1 Neutron Source Configuration

For any neutron source material, a CSI of 0.3 is justified. To justify a CSI of 0.3, at least 334 packages must be modeled (2N = 334, N = 167, and 50/N = 0.3). Because modeling a large number of discrete packages in a hexagonal array can be cumbersome, a simplified modeling approach is utilized. The array boundary is modeled as a cylinder, and an infinite universe of packages in a hexagonal array is inserted into the cylindrical bounds. The effect of this modeling approach “slices” SFCs on the model boundary, as shown in Figure 6-3.

To determine the dimension of the large outer cylinder, the unit cell area must be computed. The unit cell area of a hexagonal lattice with pitch P is:

$$A = \frac{\sqrt{3}}{2} P^2$$

For the Model II SFC, P = 7.622 cm, so that A = 50.3116 cm^2. The area of the cylinder is then the desired number of packages multiplied by area A. To add additional conservatism due to the package “slicing” at the boundaries, the total number of packages is increased by 5%, or 334*1.05 = 350.7. For an array in which there are two layers, the number of packages per layer is then 350.7/2 = 175.35, and the total area is 175.35*A = 8822.1 cm^2. This area corresponds to a circle of radius 52.9922 cm. The outer boundary radii for other scenarios may be computed in a similar manner.

For the neutron source, the water is divided into three regions: (1) water beside the slug within the SFC, (2) water above the slug within the SFC, and (3) water between the SFCs. The water density is varied in each of these three regions to find the most reactive condition.

<u>Model II SFC</u>

For the Model II SFC, both two and three layer arrays are considered, as shown in Figure 6-3 and Figure 6-4. Both configurations have approximately the same number of packages. Results are summarized in Table 6-11. Cases D1 through D15 are the two-layer results, while Cases D21 through D39 are the three-layer results. Initially, the water density is varied between 0 and 1.0 g/cm^3 inside the SFC, with void between the SFCs (Cases D1 through D11 for 2 layers and Cases D21 through D31 for 3 layers). Maximum reactivity is achieved with full density water. Next, the most reactive 2 and 3 layer cases are run with reduced water density above the PuBe

(Cases D12 through D15 for 2 layers, and Cases D32 through D35 for 3 layers). In both cases, maximum reactivity is achieved with void above the PuBe, although the 3 layer model is more reactive (compare Case D12 with Case D32). Additional permutations are performed with the most reactive 3 layer model as the base model. In Cases D36 and D37, the water density beside the PuBe is reduced, which reduces the reactivity. And in Cases D38 and D39, water is added between the SFCs. Adding water between the SFCs quickly causes a reduction in reactivity.

The most reactive case with 350 g Pu in PuBe, Model II SFC, is Case D32, with $k_s = 0.9045$. This configuration has 3 layers, 1.0 g/cm^3 water beside the PuBe, void above the PuBe, and void between the SFCs. This value is below the USL of 0.9257.

Model III SFC

The Model III SFC with 160 g Pu in PuBe analysis is performed in the same manner as the Model II SFC analysis. Because the Model III SFC is smaller than the Model II SFC, the outer array dimensions are smaller, and 3 and 4 layer models are developed to maintain approximate parity between the height and diameter of the array. The 3 layer Model III SFC array configuration is illustrated in Figure 6-5; the 4 layer model is similar.

Results for the Model III SFC analysis with PuBe are summarized in Table 6-12 and Table 6-13 for 3 and 4 layers, respectively. More cases are required to find the most reactive case compared to the Model II analysis because maximum reactivity is achieved with low-density water above the PuBe and between the SFCs rather than void. First, cases are run over a range of water densities inside the SFC (Cases E1 through E11 for 3 layers, and Cases F1 through F11 for 4 layers). In both scenarios, the most reactive condition is with full-density water. Next, cases are run with full-density water beside the PuBe, and a range of water densities above the PuBe (Cases E12 through E21 for 3 layers, and Cases F12 through F21 for 4 layers). In both scenarios, the most reactive condition is with 0.3 g/cm^3 water above the PuBe. Finally, cases are run with full-density water beside the PuBe, 0.3 g/cm^3 water above the PuBe, and a range of water densities between the SFCs (Cases E22 through E31 for 3 layers, and Cases F22 through F31 for 4 layers). The most reactive case for 3 and 4 layers have similar reactivities, although Case E24 is the most reactive, with $k_s = 0.6772$. Case E24 has 3 layers of SFCs, full-density water beside the PuBe, 0.3 g/cm^3 water above the PuBe, and 0.3 g/cm^3 water between the SFCs. This k_s value is far below the USL of 0.9257, which indicates that a smaller CSI could be justified for the Model III SFC, if desired.

6.6.1.2 General Payload Configuration

For the general source material, a CSI of 4.0 is justified. To justify a CSI of 4.0, 25 packages are modeled (2N = 25, N = 12.5, and 50/N = 4.0). Because the number of packages is much smaller than the PuBe analysis, an integer number of packages are modeled and no packages are "sliced" at the model boundaries.

Models are developed both with a discrete fissile material lump, and homogenized with water. This approach is taken because the exact payload geometry is not modeled. The homogenized modeling is performed first, followed by the discrete fissile material lump models.

Model II SFC

Results are summarized in Table 6-14 for the Model II SFC with a 300 g plutonium general payload. Cases G1 through G23 are the homogenized models. Initially, the models are homogenized with water throughout the entire SFC volume and full-density water between the SFCs. Three different single-layer arrangements of 25 packages are investigated in Cases G1 through G3. These three arrangements (Configurations 1 through 3) are shown on Figure 6-6. Case G4 is a 2 layer model, with 13 packages on the bottom layer and 12 packages on the top layer. Configuration 2 (Case G2) is the most reactive of the first four arrangements, and is used in the remainder of the models.

In Cases G5 through G14, the water density between SFCs is varied between 0 and 0.9 g/cm^3. Decreasing the water density between the SFCs decreases the reactivity. In Cases G15 through G17, the height of the homogenized cylinder is reduced, and full-density water is modeled at the top of the cavity. Reducing the fissile height decreases the reactivity. In Cases G18 through G22, the mass of plutonium is reduced to allow more moderation. Reducing the mass of plutonium reduces the reactivity. Because the most reactive case has full-density water between the SFCs and is at the maximum possible fissile height, an additional case is run to investigate the effect of increasing the moderation by increasing the SFC pitch. In Case G23, the pitch is increased slightly to 7.8 cm, and the reactivity drops compared to Case G2. Therefore, of the homogenized cases, Case G2 is the most reactive.

Cases G31 through G39 are the discrete models for the Model II. In these models, the fissile material is modeled as a discrete lump at the bottom of the SFC cavity. There are two regions in which the water density may vary; (1) beside the fissile material lump, and (2) between the SFCs. The water is always at full-density within the SFC above the fissile material lump to maximize reflection, as the array is only a single layer. In Cases G31 through G35, the water density beside the fissile material lump is varied from 0 to 1.0 g/cm^3 with full-density water between the SFCs. Case G35, with full-density water beside the fissile material lump, is the most reactive. In Cases G36 through G39, the water beside the fissile material lump is modeled at full-density, while the water density between the SFCs is varied between 0 and 1.0 g/cm^3. The reactivity changes between Cases G36 through G39 are within the statistical uncertainly of the method, although Case G39 is the most reactive discrete model, with $k_s = 0.5155$.

Comparing the most reactive homogenized model (Case G2) and discrete model (Case G39), the homogenized model is significantly more reactive than the discrete model. Therefore, the most reactive general payload model for the Model II SFC with 300 g plutonium is Case G2, with $k_s = 0.9239$. This value is below the USL of 0.9257. Although the most reactive case is approaching the USL, a number of very conservative assumptions are utilized to obtain this result.

Model III SFC

The Model III SFC analysis is performed in the same manner as the Model II SFC analysis described above. Because the reactivity of the Model III HAC array is significantly less than the Model II SFC array, a reduced number of cases is performed to simplify the analysis. It is inferred based on the Model II SFC analysis that Configuration 2 is bounding, reactivity is maximized using the maximum mass of plutonium homogenized over the full SFC cavity height, and minimum SFC pitch. Therefore, only five homogenized cases are run (Cases H1 through H5), in which the water density between the SFCs is varied. Results are provided in Table 6-15.

One discrete lump model is run (Case H6), with full-density water inside and between the SFCs, to demonstrate that the homogenized configuration is significantly more reactive than the discrete representation.

Case H5 is the most reactive, with $k_s = 0.6138$. This value is well below the USL of 0.9257. Because the most reactive case is far from the USL, a lower CSI could be justified, if desired.

6.6.2 Results

Results for the HAC array cases are summarized in the following tables. Model II SFC results for the neutron source material is in Table 6-11. Model III SFC results for the neutron source material are in Table 6-12 and Table 6-13 for 3 and 4 layers, respectively. Model II SFC results for the general payload is in Table 6-14, and Model III SFC results for the general payload is in Table 6-15.

Table 6-11 – HAC Array Results, PuBe, Model II SFC

Case ID	Filename	Water Beside PuBe (g/cm^3)	Water Above PuBe (g/cm^3)	Water Between SFCs (g/cm^3)	k_{eff}	σ	k_s ($k+2\sigma$)
2 Layers							
D1	HA_II_R2_WI000	0	0	0	0.5495	0.0009	0.5512
D2	HA_II_R2_WI010	0.1	0.1	0	0.6527	0.0010	0.6547
D3	HA_II_R2_WI020	0.2	0.2	0	0.7066	0.0010	0.7086
D4	HA_II_R2_WI030	0.3	0.3	0	0.7350	0.0010	0.7370
D5	HA_II_R2_WI040	0.4	0.4	0	0.7561	0.0011	0.7583
D6	HA_II_R2_WI050	0.5	0.5	0	0.7672	0.0010	0.7693
D7	HA_II_R2_WI060	0.6	0.6	0	0.7804	0.0011	0.7826
D8	HA_II_R2_WI070	0.7	0.7	0	0.7859	0.0012	0.7883
D9	HA_II_R2_WI080	0.8	0.8	0	0.7919	0.0011	0.7940
D10	HA_II_R2_WI090	0.9	0.9	0	0.7976	0.0011	0.7998
D11	HA_II_R2_WI100	1.0	1.0	0	0.8062	0.0011	0.8084
D12	HA_II_R2_WI100_WT000	1.0	0	0	0.8884	0.0011	0.8906
D13	HA_II_R2_WI100_WT010	1.0	0.1	0	0.8822	0.0012	0.8847
D14	HA_II_R2_WI100_WT020	1.0	0.2	0	0.8708	0.0012	0.8732
D15	HA_II_R2_WI100_WT030	1.0	0.3	0	0.8607	0.0012	0.8631
3 Layers							
D21	HA_II_R3_WI000	0	0	0	0.5709	0.0010	0.5729
D22	HA_II_R3_WI010	0.1	0.1	0	0.6757	0.0010	0.6778
D23	HA_II_R3_WI020	0.2	0.2	0	0.7269	0.0011	0.7290
D24	HA_II_R3_WI030	0.3	0.3	0	0.7518	0.0011	0.7540
D25	HA_II_R3_WI040	0.4	0.4	0	0.7630	0.0012	0.7653
D26	HA_II_R3_WI050	0.5	0.5	0	0.7784	0.0011	0.7807
D27	HA_II_R3_WI060	0.6	0.6	0	0.7869	0.0012	0.7892
D28	HA_II_R3_WI070	0.7	0.7	0	0.7927	0.0012	0.7951
D29	HA_II_R3_WI080	0.8	0.8	0	0.7989	0.0011	0.8010
D30	HA_II_R3_WI090	0.9	0.9	0	0.8002	0.0012	0.8025
D31	HA_II_R3_WI100	1.0	1.0	0	0.8022	0.0012	0.8046
D32	**HA_II_R3_WI100_WT000**	**1.0**	**0**	**0**	**0.9023**	**0.0011**	**0.9045**
D33	HA_II_R3_WI100_WT010	1.0	0.1	0	0.8948	0.0012	0.8973
D34	HA_II_R3_WI100_WT020	1.0	0.2	0	0.8854	0.0011	0.8877
D35	HA_II_R3_WI100_WT030	1.0	0.3	0	0.8750	0.0012	0.8775
D36	HA_II_R3_WI080_WT000	0.8	0	0	0.8837	0.0012	0.8862
D37	HA_II_R3_WI090_WT000	0.9	0	0	0.8957	0.0012	0.8981
D38	HA_II_R3_WI100_WT000_WX010	1.0	0	0.1	0.8960	0.0012	0.8984
D39	HA_II_R3_WI100_WT000_WX020	1.0	0	0.2	0.8896	0.0012	0.8921

Table 6-12 – HAC Array Results, PuBe, Model III SFC (3 layers)

Case ID	Filename	Water Beside PuBe (g/cm^3)	Water Above PuBe (g/cm^3)	Water Between SFCs (g/cm^3)	k_{eff}	σ	k_s ($k+2\sigma$)
E1	HA_III_R3_WI000	0	0	0	0.4792	0.0009	0.4810
E2	HA_III_R3_WI010	0.1	0.1	0	0.5240	0.0009	0.5257
E3	HA_III_R3_WI020	0.2	0.2	0	0.5567	0.0009	0.5586
E4	HA_III_R3_WI030	0.3	0.3	0	0.5800	0.0009	0.5818
E5	HA_III_R3_WI040	0.4	0.4	0	0.5950	0.0010	0.5971
E6	HA_III_R3_WI050	0.5	0.5	0	0.6059	0.0010	0.6079
E7	HA_III_R3_WI060	0.6	0.6	0	0.6102	0.0010	0.6122
E8	HA_III_R3_WI070	0.7	0.7	0	0.6136	0.0009	0.6154
E9	HA_III_R3_WI080	0.8	0.8	0	0.6175	0.0010	0.6195
E10	HA_III_R3_WI090	0.9	0.9	0	0.6185	0.0011	0.6208
E11	HA_III_R3_WI100	1.0	1.0	0	0.6204	0.0010	0.6224
E12	HA_III_R3_WI100_WT000	1.0	0	0	0.6257	0.0010	0.6278
E13	HA_III_R3_WI100_WT010	1.0	0.1	0	0.6437	0.0010	0.6457
E14	HA_III_R3_WI100_WT020	1.0	0.2	0	0.6488	0.0010	0.6508
E15	HA_III_R3_WI100_WT030	1.0	0.3	0	0.6556	0.0011	0.6579
E16	HA_III_R3_WI100_WT040	1.0	0.4	0	0.6536	0.0011	0.6558
E17	HA_III_R3_WI100_WT050	1.0	0.5	0	0.6508	0.0010	0.6529
E18	HA_III_R3_WI100_WT060	1.0	0.6	0	0.6442	0.0009	0.6460
E19	HA_III_R3_WI100_WT070	1.0	0.7	0	0.6379	0.0009	0.6396
E20	HA_III_R3_WI100_WT080	1.0	0.8	0	0.6343	0.0010	0.6363
E21	HA_III_R3_WI100_WT090	1.0	0.9	0	0.6254	0.0011	0.6276
E22	HA_III_R3_WI100_WT030_WX010	1.0	0.3	0.1	0.6628	0.0010	0.6647
E23	HA_III_R3_WI100_WT030_WX020	1.0	0.3	0.2	0.6686	0.0011	0.6707
E24	**HA_III_R3_WI100_WT030_WX030**	**1.0**	**0.3**	**0.3**	**0.6750**	**0.0011**	**0.6772**
E25	HA_III_R3_WI100_WT030_WX040	1.0	0.3	0.4	0.6748	0.0010	0.6769
E26	HA_III_R3_WI100_WT030_WX050	1.0	0.3	0.5	0.6733	0.0010	0.6753
E27	HA_III_R3_WI100_WT030_WX060	1.0	0.3	0.6	0.6734	0.0011	0.6756
E28	HA_III_R3_WI100_WT030_WX070	1.0	0.3	0.7	0.6700	0.0011	0.6722
E29	HA_III_R3_WI100_WT030_WX080	1.0	0.3	0.8	0.6697	0.0011	0.6719
E30	HA_III_R3_WI100_WT030_WX090	1.0	0.3	0.9	0.6653	0.0010	0.6672
E31	HA_III_R3_WI100_WT030_WX100	1.0	0.3	1.0	0.6620	0.0012	0.6643

Table 6-13 – HAC Array Results, PuBe, Model III SFC (4 layers)

Case ID	Filename	Water Beside PuBe (g/cm^3)	Water Above PuBe (g/cm^3)	Water Between SFCs (g/cm^3)	k_{eff}	σ	k_s ($k+2\sigma$)
F1	HA_III_R4_WI000	0	0	0	0.4739	0.0009	0.4756
F2	HA_III_R4_WI010	0.1	0.1	0	0.5205	0.0008	0.5222
F3	HA_III_R4_WI020	0.2	0.2	0	0.5528	0.0009	0.5546
F4	HA_III_R4_WI030	0.3	0.3	0	0.5740	0.0009	0.5758
F5	HA_III_R4_WI040	0.4	0.4	0	0.5908	0.0010	0.5927
F6	HA_III_R4_WI050	0.5	0.5	0	0.5971	0.0010	0.5991
F7	HA_III_R4_WI060	0.6	0.6	0	0.6053	0.0010	0.6073
F8	HA_III_R4_WI070	0.7	0.7	0	0.6096	0.0010	0.6115
F9	HA_III_R4_WI080	0.8	0.8	0	0.6132	0.0011	0.6155
F10	HA_III_R4_WI090	0.9	0.9	0	0.6142	0.0010	0.6161
F11	HA_III_R4_WI100	1.0	1.0	0	0.6168	0.0011	0.6191
F12	HA_III_R4_WI100_WT000	1.0	0	0	0.6227	0.0010	0.6247
F13	HA_III_R4_WI100_WT010	1.0	0.1	0	0.6399	0.0011	0.6420
F14	HA_III_R4_WI100_WT020	1.0	0.2	0	0.6493	0.0011	0.6515
F15	HA_III_R4_WI100_WT030	1.0	0.3	0	0.6499	0.0010	0.6520
F16	HA_III_R4_WI100_WT040	1.0	0.4	0	0.6493	0.0010	0.6514
F17	HA_III_R4_WI100_WT050	1.0	0.5	0	0.6472	0.0011	0.6495
F18	HA_III_R4_WI100_WT060	1.0	0.6	0	0.6416	0.0010	0.6437
F19	HA_III_R4_WI100_WT070	1.0	0.7	0	0.6350	0.0010	0.6370
F20	HA_III_R4_WI100_WT080	1.0	0.8	0	0.6297	0.0011	0.6318
F21	HA_III_R4_WI100_WT090	1.0	0.9	0	0.6220	0.0011	0.6241
F22	HA_III_R4_WI100_WT030_WX010	1.0	0.3	0.1	0.6600	0.0011	0.6622
F23	HA_III_R4_WI100_WT030_WX020	1.0	0.3	0.2	0.6653	0.0010	0.6673
F24	HA_III_R4_WI100_WT030_WX030	1.0	0.3	0.3	0.6678	0.0011	0.6701
F25	HA_III_R4_WI100_WT030_WX040	1.0	0.3	0.4	0.6717	0.0010	0.6736
F26	HA_III_R4_WI100_WT030_WX050	1.0	0.3	0.5	0.6705	0.0010	0.6725
F27	**HA_III_R4_WI100_WT030_WX060**	**1.0**	**0.3**	**0.6**	**0.6717**	**0.0011**	**0.6739**
F28	HA_III_R4_WI100_WT030_WX070	1.0	0.3	0.7	0.6673	0.0010	0.6693
F29	HA_III_R4_WI100_WT030_WX080	1.0	0.3	0.8	0.6646	0.0011	0.6668
F30	HA_III_R4_WI100_WT030_WX090	1.0	0.3	0.9	0.6638	0.0011	0.6660
F31	HA_III_R4_WI100_WT030_WX100	1.0	0.3	1.0	0.6605	0.0011	0.6626

Table 6-14 – HAC Array Results, General Payload, Model II SFC

Homogenized							
Case ID	**Filename**	**Pu Mass (g)**	**Height (cm)**	**Water Between SFCs (g/cm^3)**	**k_{eff}**	**σ**	**k_s ($k+2\sigma$)**
G1	HAF_II_C1	300	24.7	1.0	0.9186	0.0014	0.9213
G2	**HAF_II_C2**	**300**	**24.7**	**1.0**	**0.9216**	**0.0012**	**0.9239**
G3	HAF_II_C3	300	24.7	1.0	0.9067	0.0012	0.9092
G4	HAF_II_R2	300	24.7	1.0	0.8227	0.0012	0.8251
G5	HAF_II_C2_W000	300	24.7	0	0.8940	0.0013	0.8965
G6	HAF_II_C2_W010	300	24.7	0.1	0.8994	0.0014	0.9023
G7	HAF_II_C2_W020	300	24.7	0.2	0.9005	0.0013	0.9030
G8	HAF_II_C2_W030	300	24.7	0.3	0.9072	0.0013	0.9097
G9	HAF_II_C2_W040	300	24.7	0.4	0.9088	0.0014	0.9115
G10	HAF_II_C2_W050	300	24.7	0.5	0.9110	0.0013	0.9136
G11	HAF_II_C2_W060	300	24.7	0.6	0.9158	0.0012	0.9183
G12	HAF_II_C2_W070	300	24.7	0.7	0.9166	0.0014	0.9194
G13	HAF_II_C2_W080	300	24.7	0.8	0.9177	0.0012	0.9201
G14	HAF_II_C2_W090	300	24.7	0.9	0.9188	0.0013	0.9214
G15	HAF_II_C2_H10	300	10	1.0	0.7304	0.0013	0.7330
G16	HAF_II_C2_H15	300	15	1.0	0.8263	0.0012	0.8288
G17	HAF_II_C2_H20	300	20	1.0	0.8843	0.0012	0.8868
G18	HAF_II_C2_M200	200	24.7	1.0	0.8804	0.0012	0.8828
G19	HAF_II_C2_M225	225	24.7	1.0	0.8924	0.0012	0.8949
G20	HAF_II_C2_M250	250	24.7	1.0	0.9044	0.0013	0.9069
G21	HAF_II_C2_M275	275	24.7	1.0	0.9120	0.0013	0.9146
G22	HAF_II_C2_M295	295	24.7	1.0	0.9153	0.0013	0.9180
G23	HAF_II_C2_P2	300	24.7	1.0	0.9101	0.0014	0.9129

Discrete Lump							
Case ID	**Filename**	**Pu Mass (g)**	**Water Beside Lump (g/cm^3)**	**Water Between SFCs (g/cm^3)**	**k_{eff}**	**σ**	**k_s ($k+2\sigma$)**
G31	HAF_IIS_C2_WI000	300	0	1.0	0.4945	0.0008	0.4961
G32	HAF_IIS_C2_WI025	300	0.25	1.0	0.4988	0.0009	0.5005
G33	HAF_IIS_C2_WI050	300	0.5	1.0	0.5023	0.0008	0.5039
G34	HAF_IIS_C2_WI075	300	0.75	1.0	0.5086	0.0009	0.5103
G35	HAF_IIS_C2_WI100	300	1.0	1.0	0.5128	0.0008	0.5144
G36	HAF_IIS_C2_WI100_WX000	300	1.0	0	0.5120	0.0009	0.5137
G37	HAF_IIS_C2_WI100_WX025	300	1.0	0.25	0.5131	0.0009	0.5149
G38	HAF_IIS_C2_WI100_WX050	300	1.0	0.5	0.5127	0.0009	0.5145
G39	HAF_IIS_C2_WI100_WX075	300	1.0	0.75	0.5139	0.0008	0.5155

Table 6-15 – HAC Array Results, General Payload, Model III SFC

Homogenized							
Case ID	**Filename**	**Pu Mass (g)**	**Height (cm)**	**Water Between SFCs (g/cm^3)**	**k_{eff}**	**σ**	**k_s ($k+2\sigma$)**
H1	HAF_III_C2_W000	160	12.6	0	0.5698	0.0012	0.5721
H2	HAF_III_C2_W025	160	12.6	0.25	0.5818	0.0011	0.5841
H3	HAF_III_C2_W050	160	12.6	0.5	0.5916	0.0011	0.5938
H4	HAF_III_C2_W075	160	12.6	0.75	0.6045	0.0012	0.6068
H5	**HAF_III_C2_W100**	**160**	**12.6**	**1.0**	**0.6114**	**0.0012**	**0.6138**

Discrete Lump							
Case ID	**Filename**	**Pu Mass (g)**	**Water Beside Lump (g/cm^3)**	**Water Between SFCs (g/cm^3)**	**k_{eff}**	**σ**	**k_s ($k+2\sigma$)**
H11	HAF_III_C2_WI100_WX100	160	1.0	1.0	0.4227	0.0008	0.4243

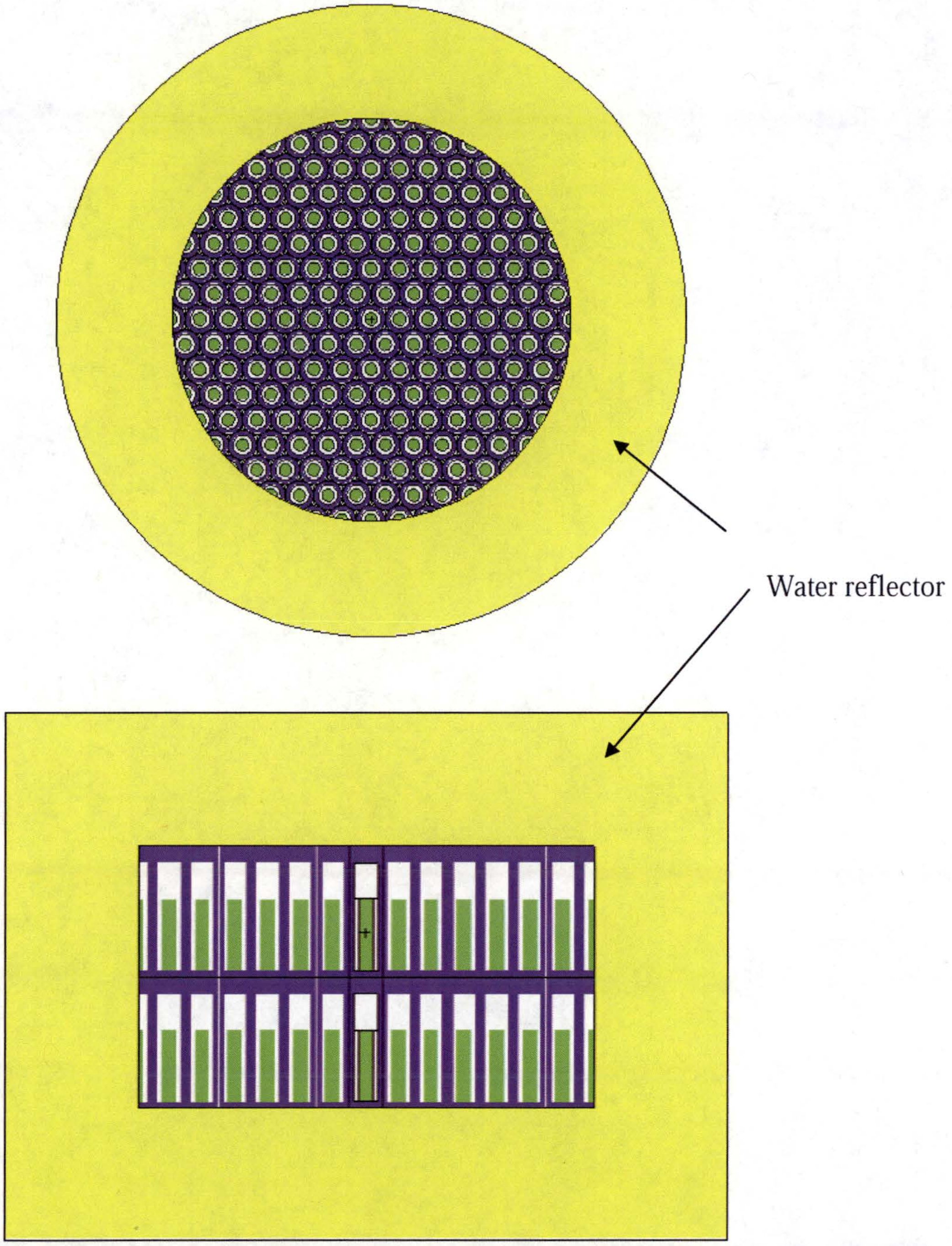


Figure 6-3 – HAC Array, Model II SFC, PuBe Payload (2 layers)

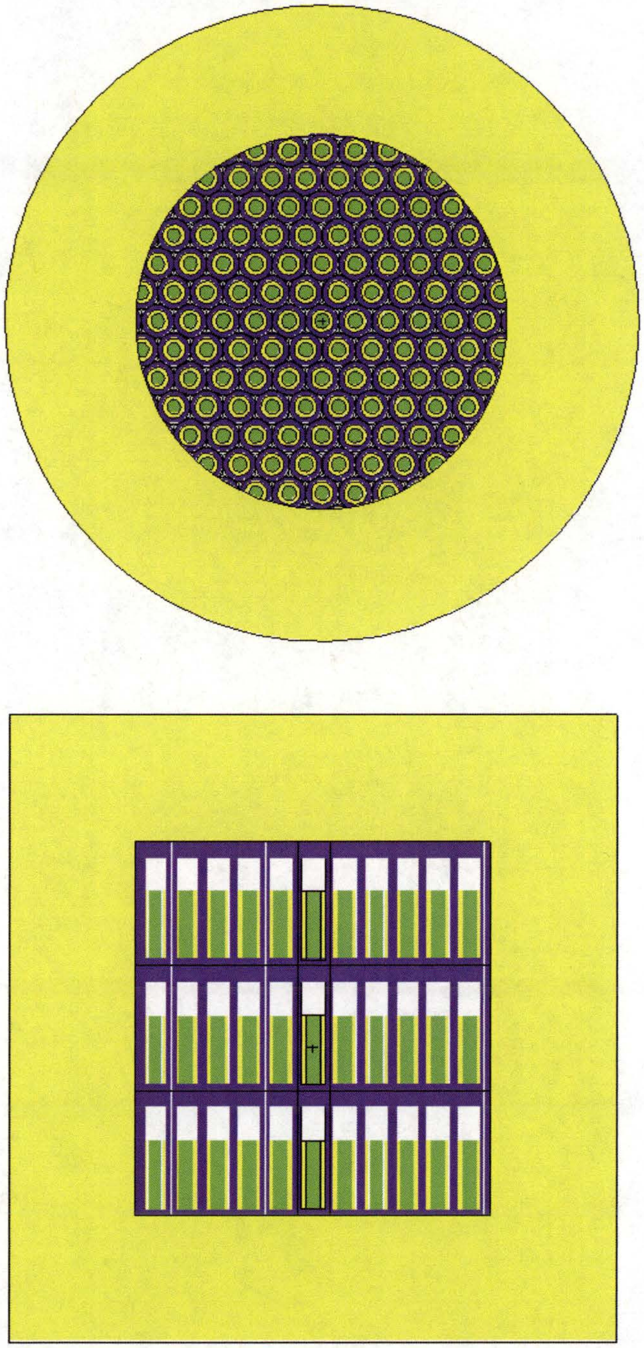


Figure 6-4 – HAC Array, Model II SFC, PuBe Payload (3 layers)

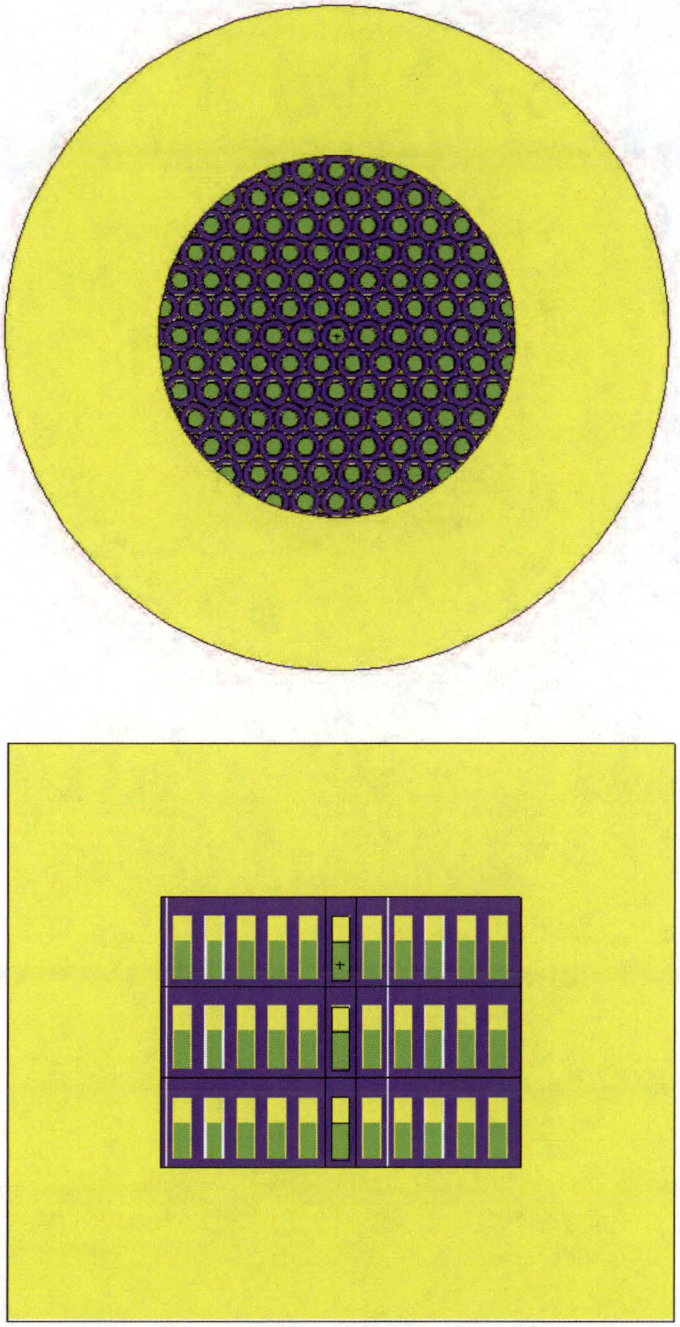
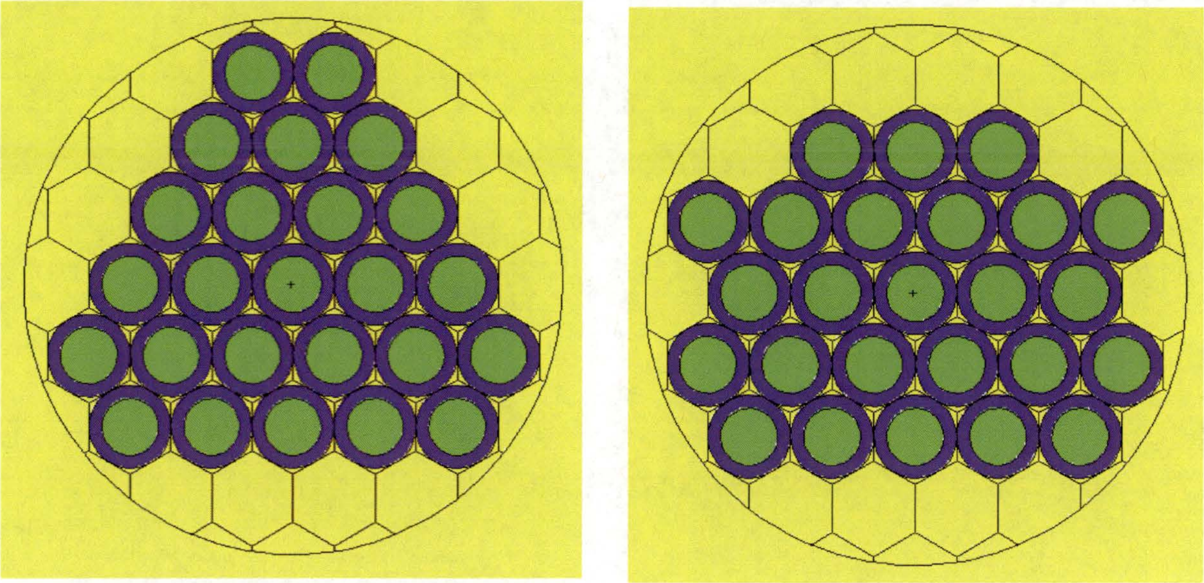
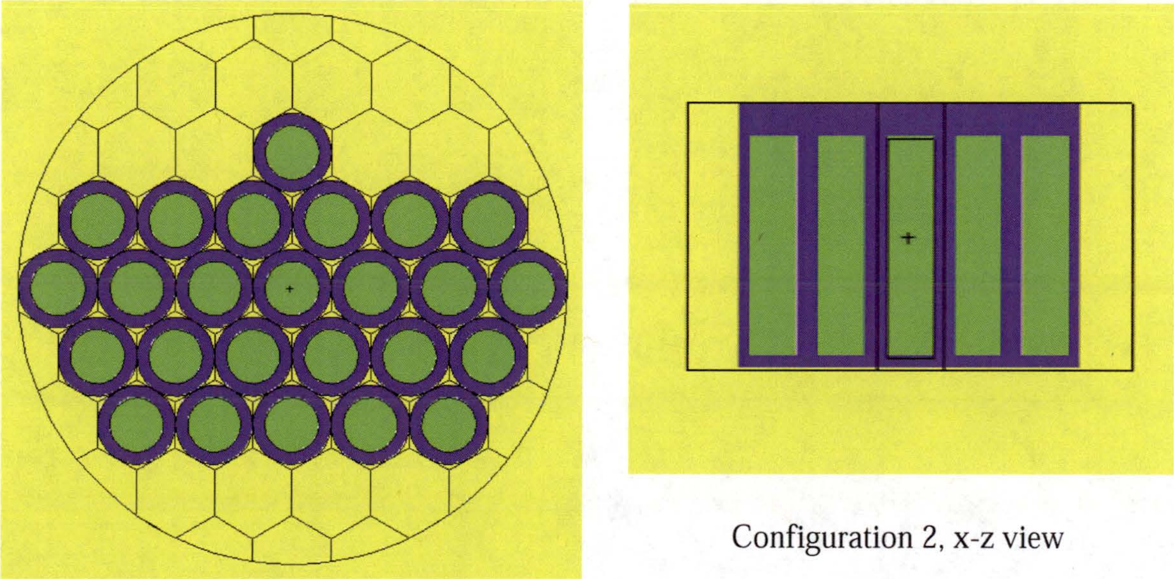


Figure 6-5 – HAC Array, Model III SFC, PuBe Payload (3 layers)



Configuration 1

Configuration 2



Configuration 2, x-z view

Configuration 3

Figure 6-6 – HAC Array, Model II SFC, Homogenized General Payload

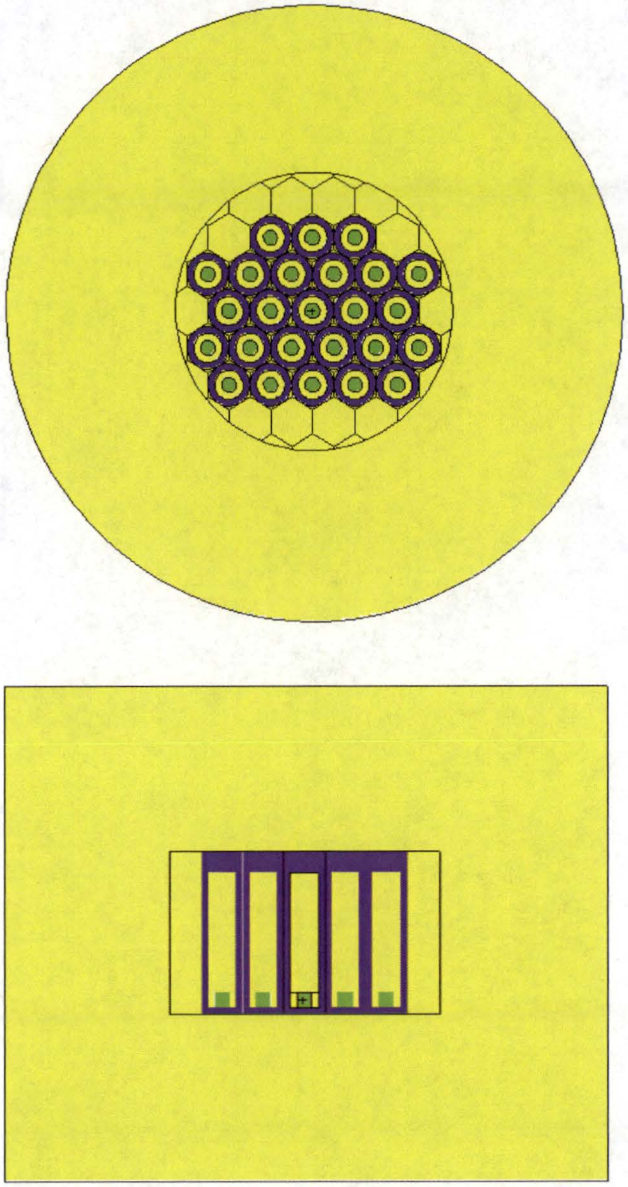


Figure 6-7 – HAC Array, Model II SFC, Discrete General Payload

6.7 Fissile Material Packages for Air Transport

The applicable licensing requirements for air transport of fissile material are contained in 10 CFR 71.55(f). These requirements are implemented by assuming that the S300 packaging materials and contents are reconfigured in the most reactive spherical geometry, reflected by 20 cm of water.

The analysis is performed for 210 g Pu-239, which bounds the non-exclusive use limiting value of 206 g Pu-239. The analysis demonstrates that the package is safely subcritical when reconfigured as described above.

The criticality analysis for air transport is performed using the KENO V.a module of the SCALE5 code package. Note that the criticality analysis in the earlier part of this chapter was performed using MCNP5 v1.40. KENO rather than MCNP is utilized for the air transport calculations, since, for the simple spheres used in this analysis, KENO simplifies input preparation compared to MCNP.

The approach is to assume that all of the contents and packaging material arrange in the most reactive spherical geometry in the air transport accident. Because the S300 contains a large mass of polyethylene, which is a superior moderator and reflector than water, the most reactive case is essentially 210 g Pu-239 optimally moderated and reflected with polyethylene. The most reactive conditions has $k_s = 0.8930$, which is less than the USL of 0.9377. Note that the USL for the air transport analysis is different than for the primary analysis because it is based on a different computer program and a large set of thermal benchmarks.

The full analysis, including benchmarking, is fully described in Section 6.9.4, *Air Transport Criticality Analysis*.

6.8 Benchmark Evaluations

The Monte Carlo computer program MCNP5 v1.40 is utilized for this benchmark analysis[1]. MCNP has been used extensively in criticality evaluations for several decades and is considered a standard in the industry.

The ORNL USLSTATS program[2] is used to establish a USL for the analysis. USLSTATS provides a simple means of evaluating and combining the statistical error of the calculation, code biases, and benchmark uncertainties. The USLSTATS calculation uses the combined uncertainties and data to provide a linear trend and an overall uncertainty. Computed multiplication factors, k_{eff}, for the package are deemed to be adequately subcritical if the computed value of k_s is less than or equal to the USL as follows:

$$k_s = k_{eff} + 2\sigma \leq USL$$

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[1] MCNP5, "*MCNP – A General Monte Carlo N-Particle Transport Code, Version 5; Volume II: User's Guide,*" LA-CP-03-0245, Los Alamos National Laboratory, April 2003.

[2] USLSTATS, "*USLSTATS: A Utility To Calculate Upper Subcritical Limits For Criticality Safety Applications,*" Oak Ridge National Laboratory.

The USL includes the combined effects of code bias, uncertainty in the benchmark experiments, uncertainty in the computational evaluation of the benchmark experiments, and an administrative margin. This methodology has accepted precedence in establishing criticality safety limits for transportation packages complying with 10 CFR 71.

The same MCNP code and cross section library and the same computer platform were employed in the calculation of the multiplication factors for the benchmark experiments as for the model runs.

6.8.1 Applicability of Benchmark Experiments

The configurations modeled in the S300 analysis utilize either solid or aqueous plutonium with varying degrees of moderation. Because many of the S300 cases are neither fast nor thermal and fall into an intermediate energy spectrum, a combination of fast, intermediate, and thermal plutonium benchmarks are utilized. The critical experiment benchmarks are selected from the *International Handbook of Evaluated Criticality Safety Benchmark Experiments*[3] based upon their similarity to the packaging and contents.

A total of 102 critical benchmark experiments are used in the benchmark analysis. Of these, 26 are fast, 42 are intermediate, and 34 are thermal. Fast benchmarks have an energy corresponding to the average neutron lethargy causing fission (EALF) >100 keV, thermal benchmarks have an EALF < 0.625 eV, and intermediate benchmarks have an EALF that falls between these two bounds. The benchmark experiments utilized are listed in Table 6-16.

6.8.2 Bias Determination

The USL is calculated by application of the USLSTATS computer program. USLSTATS receives as input the k_{eff} as calculated by MCNP, the total 1-σ uncertainty (combined benchmark and MCNP uncertainties), and a trending parameter.

The uncertainty value, σ_{total}, assigned to each case is a combination of the benchmark uncertainty for each experiment, σ_{bench}, and the Monte Carlo uncertainty associated with the particular computational evaluation of the case, σ_{MCNP}, or:

$$\sigma_{total} = (\sigma_{bench}^2 + \sigma_{MCNP}^2)^{½}$$

These values are input into the USLSTATS program in addition to the following parameters, which are the values recommended by the USLSTATS user's manual:

- P, proportion of population falling above lower tolerance level = 0.995 (note that this parameter is required input but is not utilized in the calculation of USL Method 1)
- 1-γ, confidence on fit = 0.95
- α, confidence on proportion P = 0.95 (note that this parameter is required input but is not utilized in the calculation of USL Method 1)
- Δk_m, administrative margin used to ensure subcriticality = 0.05.

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[3] *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, Nuclear Energy Agency, NEA/NSC/DOC(95)03, September 2009.

These data are followed by triplets of trending parameter value, computed k_{eff}, and uncertainty for each case. A confidence band analysis is performed on the data for each trending parameter using USL Method 1. All benchmark data used as input to USLSTATS are reported in Table 6-17, Table 6-18, and Table 6-19 for fast, intermediate, and thermal spectra, respectively.

Two trending parameters are identified for determination of the bias. First, the EALF is used in order to characterize any code bias with respect to neutron spectral effects. The EALF is trended separately for each of the three spectral groups (e.g., fast, intermediate, and thermal), as well as over the entire benchmark set. The hydrogen to plutonium number density ratio (H/Pu) is also used as a trending parameter for the thermal solution benchmarks, as the general payload uses a homogenized representation.

The results of the USL analysis are summarized in Table 6-20. Of the four EALF benchmark sets, the minimum USL is achieved with the intermediate spectrum benchmarks, with a USL = 0.9257. The EALF based on H/Pu is 0.9403, which is significantly higher. Therefore, a USL of 0.9257 is recommended for this analysis.

The most reactive neutron source case (Case D32) has an EALF = 1.6607E-5 MeV, which is within the range of the intermediate benchmark experiments. The most reactive general payload case (Case G2) has an EALF = 1.0158E-6 MeV, which is also within the range of the intermediate benchmark experiments. Case G2 also has an H/Pu = 45.7, which is slightly below the range of the benchmark experiments (minimum = 86.7). However, the USL for this parameter is constant and rather high, and many of the fast benchmarks have no water (H/Pu = 0), which indicates that MCNP is behaving acceptably for this parameter.

Table 6-16 – Benchmark Experiments Utilized

Series	Title
Fast Benchmarks	
PU-MET-FAST-001	Bare Sphere Of Plutonium-239 Metal
PU-MET-FAST-002	^{240}Pu Jezebel: Bare Sphere of Plutonium-239 Metal
PU-MET-FAST-004	Unmoderated Plutonium Metal Cylinder Array - Phase II
PU-MET-FAST-005	Benchmark Critical Experiment of a Plutonium Sphere Reflected by Tungsten
PU-MET-FAST-006	Plutonium Sphere Reflected by Normal Uranium Using Flattop
PU-MET-FAST-008	Benchmark Critical Experiment of a Thorium Reflected Plutonium Sphere
PU-MET-FAST-009	Benchmark Critical Experiment of a Plutonium Sphere Reflected By Aluminum
PU-MET-FAST-010	Benchmark Critical Experiment of a Delta-Phase Plutonium Sphere Reflected By Normal Uranium
PU-MET-FAST-012	Uranium-Reflected Array of Plutonium Fuel Rods
PU-MET-FAST-013	Copper-Reflected Array of Plutonium Fuel Rods
PU-MET-FAST-014	Nickel-Reflected Array of Plutonium Fuel Rods
PU-MET-FAST-015	Iron-Reflected Array of Plutonium Fuel Rods
PU-MET-FAST-017	Moderated Plutonium Metal Cylinders Array - Phase II
PU-MET-FAST-018	Benchmark Critical Experiment of a Delta-Phase Plutonium Sphere Reflected By Beryllium
PU-MET-FAST-019	Sphere of Plutonium Reflected by Beryllium
PU-MET-FAST-020	Sphere of Plutonium Reflected by Depleted Uranium
PU-MET-FAST-021	Beryllium- and Beryllium Oxide-Reflected Cylinders of Plutonium
PU-MET-FAST-024	Polyethylene-Reflected Spherical Assembly of ^{239}Pu(δ, 98%)
PU-MET-FAST-025	Spherical Assembly of ^{239}Pu(δ, 98%) with 1.55-cm Steel Reflector
PU-MET-FAST-026	Spherical Assembly of ^{239}Pu(δ, 98%) with 11.9-cm Steel Reflector
PU-MET-FAST-031	Polyethylene-Reflected Spherical Assembly of ^{239}Pu(α, 88%)
PU-MET-FAST-032	Steel-Reflected Spherical Assembly of ^{239}Pu(α, 88%)
Intermediate Benchmarks	
PU-COMP-INTER-001	k_∞ Experiments in Intermediate Neutron Spectra for ^{239}Pu
PU-COMP-MIXED-001	Unreflected Slabs of Polystyrene-Moderated Plutonium Oxide
PU-COMP-MIXED-002	Plexiglas-Reflected Slabs of Polystyrene-Moderated Plutonium Oxide
PU-MET-MIXED-001	Critical Experiments with Heterogeneous Compositions of Plutonium, Silicon Dioxide, and Polyethylene
PU-MET-FAST-011	Benchmark Critical Experiment of a Water Reflected Alpha-Phase Plutonium Sphere
PU-MET-FAST-027	Polyethylene-Reflected Spherical Assembly of ^{239}Pu(δ, 89%)
Thermal Benchmarks	
PU-SOL-THERM-001	Water-Reflected 11.5-Inch Diameter Spheres Of Plutonium Nitrate Solutions
PU-SOL-THERM-002	Water-Reflected 12-Inch Diameter Spheres Of Plutonium Nitrate Solutions
PU-SOL-THERM-003	Water-Reflected 13-Inch Diameter Spheres Of Plutonium Nitrate Solutions
PU-SOL-THERM-004	Water-Reflected 14-Inch Diameter Spheres Of Plutonium Nitrate Solutions 0.54% To 3.43% Pu240

Table 6-17 – Fast Benchmark Experiments

Case ID	Filename	k	σ_{mcnp}	σ_{bench}	σ_{total}	EALF (MeV)
BF1	PUMF-001	1.0006	0.0006	0.0020	0.0021	1.26E+00
BF2	PUMF-002	1.0000	0.0006	0.0020	0.0021	1.27E+00
BF3	PUMF-004-C1	0.9983	0.0007	0.0030	0.0031	1.21E+00
BF4	PUMF-004-C2	0.9969	0.0006	0.0030	0.0031	1.17E+00
BF5	PUMF-005	1.0121	0.0006	0.0013	0.0014	9.84E-01
BF6	PUMF-006	1.0008	0.0007	0.0030	0.0031	1.06E+00
BF7	PUMF-008	1.0081	0.0007	0.0006	0.0009	1.05E+00
BF8	PUMF-009	1.0057	0.0006	0.0027	0.0028	1.15E+00
BF9	PUMF-010	1.0003	0.0006	0.0018	0.0019	1.17E+00
BF10	PUMF-012	1.0040	0.0007	0.0021	0.0022	9.52E-01
BF11	PUMF-013	1.0033	0.0007	0.0023	0.0024	7.88E-01
BF12	PUMF-014	1.0133	0.0006	0.0031	0.0032	7.86E-01
BF13	PUMF-015	1.0088	0.0007	0.0026	0.0027	9.64E-01
BF14	PUMF-017-C1	0.9970	0.0006	0.0030	0.0031	7.82E-01
BF15	PUMF-017-C2	0.9985	0.0007	0.0030	0.0031	3.98E-01
BF16	PUMF-018	1.0024	0.0006	0.0030	0.0031	9.02E-01
BF17	PUMF-019	1.0043	0.0006	0.0015	0.0016	7.64E-01
BF18	PUMF-020	0.9998	0.0007	0.0017	0.0018	1.13E+00
BF19	PUMF-021-C1	1.0068	0.0004	0.0026	0.0026	7.77E-01
BF20	PUMF-021-C2	0.9948	0.0006	0.0026	0.0027	8.64E-01
BF21	PUMF-024	1.0022	0.0007	0.0020	0.0021	6.36E-01
BF22	PUMF-025	1.0020	0.0006	0.0020	0.0021	1.19E+00
BF23	PUMF-026	1.0035	0.0007	0.0024	0.0025	1.09E+00
BF24	PUMF-031	1.0050	0.0007	0.0021	0.0022	1.88E-01
BF25	PUMF-032	1.0027	0.0007	0.0020	0.0021	1.17E+00
BF26	PUCM-001-C1	1.0232	0.0009	0.0041	0.0042	9.67E-01

Table 6-18 – Intermediate Benchmark Experiments

Case ID	Filename	k	σ_{mcnp}	σ_{bench}	σ_{total}	EALF (MeV)
BI1	PUCI-001-C1	1.0100	0.0008	0.0110	0.0110	2.98E-04
BI2	PUCM-001-C2	1.0290	0.0013	0.0068	0.0069	1.68E-03
BI3	PUCM-001-C3	1.0279	0.0013	0.0067	0.0068	3.16E-05
BI4	PUCM-001-C4	0.9975	0.0014	0.0066	0.0067	3.80E-05
BI5	PUCM-001-C5	1.0127	0.0014	0.0072	0.0073	1.54E-06
BI6	PUCM-002-C01	1.0300	0.0008	0.0046	0.0047	5.05E-03
BI7	PUCM-002-C02	1.0288	0.0011	0.0046	0.0047	4.42E-03
BI8	PUCM-002-C03	1.0229	0.0011	0.0046	0.0047	3.62E-03
BI9	PUCM-002-C04	1.0192	0.0011	0.0046	0.0047	2.66E-03
BI10	PUCM-002-C05	1.0155	0.0012	0.0046	0.0047	1.99E-03
BI11	PUCM-002-C06	1.0256	0.0012	0.0075	0.0076	9.57E-05
BI12	PUCM-002-C07	1.0244	0.0012	0.0075	0.0076	8.76E-05
BI13	PUCM-002-C08	1.0221	0.0013	0.0075	0.0076	7.10E-05
BI14	PUCM-002-C09	1.0202	0.0012	0.0075	0.0076	5.94E-05
BI15	PUCM-002-C10	1.0337	0.0014	0.0073	0.0074	4.25E-06
BI16	PUCM-002-C11	1.0327	0.0013	0.0073	0.0074	4.63E-06
BI17	PUCM-002-C12	1.0289	0.0013	0.0073	0.0074	5.22E-06
BI18	PUCM-002-C13	1.0294	0.0013	0.0073	0.0074	5.56E-06
BI19	PUCM-002-C14	1.0326	0.0013	0.0073	0.0074	5.69E-06
BI20	PUCM-002-C15	1.0318	0.0013	0.0073	0.0074	5.65E-06
BI21	PUCM-002-C16	1.0279	0.0013	0.0073	0.0074	5.25E-06
BI22	PUCM-002-C17	1.0047	0.0013	0.0055	0.0056	4.91E-06
BI23	PUCM-002-C18	1.0129	0.0012	0.0055	0.0056	6.37E-06
BI24	PUCM-002-C19	1.0103	0.0013	0.0055	0.0056	6.67E-06
BI25	PUCM-002-C20	1.0141	0.0013	0.0055	0.0057	6.69E-06
BI26	PUCM-002-C21	1.0139	0.0012	0.0055	0.0056	6.82E-06
BI27	PUCM-002-C22	1.0168	0.0013	0.0055	0.0056	6.54E-06
BI28	PUCM-002-C23	1.0075	0.0013	0.0068	0.0069	7.07E-07
BI29	PUCM-002-C24	1.0085	0.0013	0.0068	0.0069	7.15E-07
BI30	PUCM-002-C25	1.0105	0.0012	0.0068	0.0069	7.21E-07
BI31	PUCM-002-C26	1.0125	0.0013	0.0068	0.0069	7.29E-07
BI32	PUCM-002-C27	1.0110	0.0013	0.0068	0.0069	7.42E-07
BI33	PUCM-002-C28	1.0132	0.0013	0.0068	0.0069	7.44E-07
BI34	PUCM-002-C29	1.0133	0.0013	0.0068	0.0069	7.53E-07
BI35	PUMM-001-C81-1	1.0097	0.0008	0.0037	0.0038	4.67E-03
BI36	PUMM-001-C81-1A	1.0052	0.0008	0.0032	0.0033	3.41E-03
BI37	PUMM-001-C81-2	1.0082	0.0008	0.0025	0.0026	2.46E-04
BI38	PUMM-001-C81-3	1.0099	0.0009	0.0025	0.0026	5.57E-05
BI39	PUMM-001-C81-4	1.0100	0.0008	0.0025	0.0026	1.32E-06
BI40	PUMM-001-C81-5	1.0100	0.0008	0.0025	0.0026	1.28E-06
BI41	PUMF-011	0.9976	0.0007	0.0010	0.0012	8.68E-02
BI42	PUMF-027	1.0046	0.0007	0.0022	0.0023	7.11E-02

Table 6-19 – Thermal Benchmark Experiments

Case ID	Filename	k	σ_{mcnp}	σ_{bench}	σ_{total}	EALF (MeV)	H/Pu
BT1	PUST001_C01	1.0037	0.0010	0.0050	0.0051	8.74E-08	352.9
BT2	PUST001_C02	1.0055	0.0010	0.0050	0.0051	1.11E-07	258.1
BT3	PUST001_C03	1.0071	0.0010	0.0050	0.0051	1.34E-07	204.1
BT4	PUST001_C04	0.9997	0.0010	0.0050	0.0051	1.50E-07	181.0
BT5	PUST001_C05	1.0032	0.0010	0.0050	0.0051	1.58E-07	171.2
BT6	PUST001_C06	1.0061	0.0010	0.0050	0.0051	3.46E-07	86.7
BT7	PUST002_C01	1.0030	0.0010	0.0047	0.0048	7.08E-08	508.0
BT8	PUST002_C02	1.0036	0.0010	0.0047	0.0048	7.24E-08	489.2
BT9	PUST002_C03	1.0015	0.0010	0.0047	0.0048	7.73E-08	437.3
BT10	PUST002_C04	1.0043	0.0010	0.0047	0.0048	8.06E-08	407.5
BT11	PUST002_C05	1.0054	0.0010	0.0047	0.0048	8.43E-08	380.6
BT12	PUST002_C06	1.0026	0.0010	0.0047	0.0048	9.23E-08	333.5
BT13	PUST002_C07	1.0059	0.0010	0.0047	0.0048	9.96E-08	299.3
BT14	PUST003_C01	1.0022	0.0009	0.0047	0.0048	5.78E-08	774.1
BT15	PUST003_C02	1.0036	0.0009	0.0047	0.0048	5.91E-08	742.7
BT16	PUST003_C03	1.0050	0.0009	0.0047	0.0048	6.15E-08	677.2
BT17	PUST003_C04	1.0009	0.0009	0.0047	0.0048	6.23E-08	660.5
BT18	PUST003_C05	1.0059	0.0009	0.0047	0.0048	6.48E-08	607.2
BT19	PUST003_C06	1.0061	0.0010	0.0047	0.0048	6.86E-08	545.3
BT20	PUST003_C07	1.0046	0.0009	0.0047	0.0048	5.88E-08	714.8
BT21	PUST003_C08	1.0061	0.0010	0.0047	0.0048	5.95E-08	692.1
BT22	PUST004_C01	1.0030	0.0009	0.0047	0.0048	5.31E-08	981.7
BT23	PUST004_C02	0.9978	0.0008	0.0047	0.0048	5.33E-08	898.6
BT24	PUST004_C03	0.9998	0.0009	0.0047	0.0048	5.42E-08	864.0
BT25	PUST004_C04	0.9981	0.0009	0.0047	0.0048	5.53E-08	842.0
BT26	PUST004_C05	0.9993	0.0009	0.0047	0.0048	5.41E-08	780.2
BT27	PUST004_C06	1.0009	0.0008	0.0047	0.0048	5.44E-08	668.0
BT28	PUST004_C07	1.0054	0.0009	0.0047	0.0048	5.53E-08	573.3
BT29	PUST004_C08	1.0003	0.0009	0.0047	0.0048	5.60E-08	865.0
BT30	PUST004_C09	1.0004	0.0009	0.0047	0.0048	5.82E-08	872.2
BT31	PUST004_C10	0.9999	0.0009	0.0047	0.0048	6.26E-08	971.6
BT32	PUST004_C11	0.9989	0.0009	0.0047	0.0048	6.79E-08	929.6
BT33	PUST004_C12	1.0030	0.0009	0.0047	0.0048	5.55E-08	884.1
BT34	PUST004_C13	0.9996	0.0009	0.0047	0.0048	5.50E-08	925.5

Table 6-20 – USL Determination

Benchmark Set	Parameter	Range of Applicability	Minimum USL
Fast	EALF	0.18775 < X < 1.2668	0.9368
Intermediate	EALF	7.0677E-07 <= X <= 0.086784	0.9257
Thermal	EALF	5.3086E-08 <= X <= 3.4638E-07	0.9377
All	EALF	5.3086E-08 <= X <= 1.2668	0.9316
Thermal	H/Pu	86.700 < X < 981.70	0.9403

6.9 Appendices

6.9.1 PuBe Neutron Source Paper

The reference paper “Plutonium-Beryllium Neutron Sources, Their Fabrication and Neutron Yield” by R.E. Tate and A.S. Coffinberry (1958) is reproduced on the following pages.

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Plutonium–Beryllium Neutron Sources, Their Fabrication and Neutron Yield

By R. E. Tate and A. S. Coffinberry*

The (α, n) nuclear reaction has been utilized for twenty-five years as a source of neutrons. Mechanical mixtures were prepared from an alpha emitter, usually Ra^{226} or Po^{210}, and an element of low atomic number, usually beryllium. Now, however, nuclear reactors produce other alpha-emitting isotopes which can also be used as neutron sources when combined with beryllium.[1] Of the transuranic elements available as products of reactor operation, plutonium is the most abundant. An investigation of the neutron-emitting characteristics of plutonium–beryllium alloys was deemed desirable and such work was started at Los Alamos in 1949.

It was found that plutonium–beryllium alloys make very satisfactory neutron sources for low-flux applications. In particular, the compound $PuBe_{13}$ possesses several advantages over mechanical mixtures of polonium and beryllium or radium and beryllium, although the yield of neutrons per second per cubic centimeter is not as large. The neutron yield and energy spectrum of polonium–beryllium sources vary with the grain sizes of the constituents, as has been pointed out by Stewart.[2] These sources also require frequent time-dependent yield corrections. Disadvantages of radium–beryllium neutron sources include their high cost and their high gamma-ray background. The principal advantage of plutonium–beryllium sources is the stability of the neutron yield with respect to time, which derives from the 24,360-year half-life[3] of Pu^{239}. The growth in neutron flux is computed to be only 0.14% in 20 years if suitable plutonium is used. Another important characteristic of $PuBe_{13}$ is that it is the only commonly employed neutron source for which a specific weight of source material has a known and predictable neutron yield.

The metallurgical phase diagram of the plutonium–beryllium binary system has been reported by Konobeevsky[4] and by Schonfeld,[5] and it is characterized by a single compound $PuBe_{13}$ melting at a temperature estimated to be about 1950°C. The compound is face-centered cubic and has a measurable range of homogeneity.[6] Its density, as calculated from X-ray data, is 4.35 g/cm³. $PuBe_{13}$ is very brittle; its microhardness exceeds 575 kg/mm². It is resistant to oxidation and, unlike many intermetallic compounds of plutonium, does not disintegrate into hazardous powdery material in the laboratory atmosphere.

THE NEUTRON YIELDS

Stewart[2] has determined the neutron spectrum from a $PuBe_{13}$ source and by integration has obtained a total yield of 1.28×10^6 neutrons per second for the source, or 6.1×10^4 neutrons per second per gram of $PuBe_{13}$. Considering the possibilities for error in the method, this value appears to be in reasonably good agreement with an average value of 6.8×10^4 neutrons per second per gram obtained by comparing several specimens of $PuBe_{13}$ with Los Alamos secondary standards. A value of 6.7×10^4 neutrons per second per gram for $PuBe_{13}$ has been reported by Konobeevsky.[4] If, not knowing the isotopic composition, the specific activity of the plutonium used by Runnalls and Boucher[1] is assumed to be 1.4×10^8 disintegrations per minute per milligram, the neutron yield of $PuBe_{13}$ reported by them is calculated to be approximately 6.1×10^4 neutrons per second per gram.

When work on the plutonium–beryllium system was begun at Los Alamos in 1949, calculations were made to predict the neutron yield as a function of alloy composition. The method used was one that had been employed by Bethe[7] in calculating the proton yield of the (α, p) reaction for fluorine as compared to the proton yield of calcium fluoride. Because the form of the plutonium–beryllium phase diagram was completely unknown, and values of the highest possible neutron yields throughout the system were sought, it was assumed in making the calculations that all compositions consisted of a homogeneous single-phase alloy (i.e., the plutonium atoms were considered to be uniformly distributed throughout the beryllium atoms). It is apparent that, with respect to the (α, n) reaction, plutonium acts strongly as a diluent in alloys having a high plutonium content and beryllium similarly dilutes the beryllium-rich compositions, so that the maximum theoretical neutron yield for the hypothetical solid solutions, continuous from pure plutonium to pure beryllium, will occur at some intermediate composition determined as the resultant of two effects: (1) The energy of the alpha particles is dissipated by both plutonium and beryllium atoms in

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proportion to their numbers and to the stopping powers of the plutonium and beryllium atoms. (2) Alpha particles are supplied for the (α, n) reaction in proportion to the number of plutonium atoms present.

The yield of neutrons per alpha particle from the alloy is inversely proportional to the stopping power of the alloy per beryllium atom, i.e.,

$$\text{neutrons/alpha particle (alloy)} \sim \frac{1}{(N_{\mathrm{Pu}}S_{\mathrm{Pu}}+N_{\mathrm{Be}}S_{\mathrm{Be}})/N_{\mathrm{Be}}}. \quad (1)$$

where S_{Pu} and S_{Be} are the respective stopping powers per atom of plutonium and beryllium and N_{Pu} and N_{Be} are the numbers of plutonium and beryllium atoms. Then, in comparison with pure beryllium,

$$\frac{\text{neutrons/alpha particle (alloy)}}{\text{neutrons/alpha particle (pure Be)}} = \frac{S_{\mathrm{Be}}}{(N_{\mathrm{Pu}}S_{\mathrm{Pu}}+N_{\mathrm{Be}}S_{\mathrm{Be}})/N_{\mathrm{Be}}}. \quad (2)$$

Since the number of neutrons/alpha particle (pure Be) is the thick target yield Y for (α, n) reaction in Be,

$$\text{neutrons/alpha particle (alloy)} = Y\frac{N_{\mathrm{Be}}}{N_{\mathrm{Pu}}(S_{\mathrm{Pu}}/S_{\mathrm{Be}})+N_{\mathrm{Be}}}. \quad (3)$$

In the computation, $S_{\mathrm{Pu}}/S_{\mathrm{Be}}$ is assumed to be independent of energy, an assumption which seems to be approximately correct.[8]

The number of alpha particles per second per gram-atom of alloy may be written as

$$\text{alpha particles/sec/gram-atom} = 6.02\times10^{23}\lambda N_{\mathrm{Pu}}/(N_{\mathrm{Pu}}+N_{\mathrm{Be}}), \quad (4)$$

where λ is the decay constant for plutonium, i.e., the number of alpha particles per second per plutonium atom.

The product of expressions (3) and (4) is the number of neutrons per second per gram-atom of alloy. This calculation has been made for a series of compositions using the best currently available data for S_{Pu}, S_{Be}, Y and λ. The results are tabulated in Table 1 and plotted in Fig. 1. The yield of $\mathrm{PuBe_{13}}$ is listed in Table 1 as 18.1×10^5 neutrons per second per 6.02×10^{23} atoms. Conversion of this value to yield per gram of $\mathrm{PuBe_{13}}$ gives 7.1×10^4 neutrons per second, to be compared with the best Los Alamos experimental value mentioned above, 6.8×10^4 neutrons per second per gram of $\mathrm{PuBe_{13}}$.

If the actual phase diagram of the plutonium–beryllium system represented a continuous series of

Table 1. Calculation of the Theoretical Neutron Yields of Plutonium-Beryllium Alloys

Atom fraction beryllium	$N_{\mathrm{Pu}}\frac{S_{\mathrm{Pu}}}{S_{\mathrm{Be}}}$	$\frac{N_{\mathrm{Be}}S_{\mathrm{Be}}}{N_{\mathrm{Pu}}S_{\mathrm{Pu}}+N_{\mathrm{Be}}S_{\mathrm{Be}}}$	*Neutrons per alpha particle*	*Alpha particles per sec per 6.02×10^{23} atoms*	*Neutrons per sec per 6.02×10^{23} atoms*
0.00	5.88	0.0000	0.00	54.2×10^{10}	0.0
0.10	5.30	0.0185	1.26×10^{-6}	48.8	6.2×10^{5}
0.20	4.71	0.0407	2.77	43.4	12.0
0.30	4.12	0.0677	4.60	37.9	17.4
0.40	3.53	0.1018	6.92	32.5	22.5
0.50	2.94	0.1454	9.88	27.1	26.8
0.60	2.35	0.2063	14.0	21.7	30.4
0.70	1.77	0.2835	19.3	16.3	31.5
0.80	1.18	0.404	27.5	10.84	29.8
0.90	0.59	0.604	41.1	5.42	22.3
0.9286[a]	0.42	0.689	46.8	3.87	18.1
1.00	0.00	1.000	68.0	0.00	0.0

[a] $\mathrm{PuBe_1}$

Notes on the experimental data used in the calculations:

1. The mean energy for alpha particles from $\mathrm{Pu^{239}}$ is 5.14 Mev.[10]

2. The experimental stopping power of plutonium is not available. The stopping power of lead for alpha particles is used as an approximation. The mass stopping power of lead for 5.14 Mev alpha particles[11] is 0.225 Mev/mg/cm².

3. The experimental stopping power of beryllium for alpha particles is not available. The stopping power for protons is converted to the stopping power for alpha particles by the relation $S_\alpha = 4S_p$ at the same velocity; i.e., at one-fourth the energy.

The mass stopping power of beryllium for 1.25 Mev protons[11] is 0.220 Mev/mg/cm². Thus, the mass stopping power of beryllium for 5 Mev alpha particles is computed to be 0.88 Mev/mg/cm².

4. The mass stopping powers are given in footnotes (2) and (3). However, atomic stopping powers are required for the ratio $S_{\mathrm{Pu}}/S_{\mathrm{Be}}$. The atomic stopping power is related to the mass stopping power by the relation[12]

$$S_a = S_m A/N,$$

where A is the atomic weight and N is Avagadro's number. The ratio of the atomic stopping powers is, therefore,

$$\frac{S_{\mathrm{Pu}}}{S_{\mathrm{Be}}} = \frac{0.225\times207}{0.88\times9} = 5.88.$$

5. The thick target yield of beryllium for 5.14 Mev alpha particles is 68 neutrons per 10^6 alpha particles.[13]

6. The decay constant of plutonium is computed from the 24,360-year half-life[9] by the relation

$$\lambda = 0.6931/T.$$

solid solutions, then the theoretical neutron yields would be as expected. However, the existence of the compound $PuBe_{13}$, and the negligible solid solubility both of plutonium in beryllium and of beryllium in plutonium, give rise to alloys which, except in the case of pure $PuBe_{13}$, consist of crystals of $PuBe_{13}$ distributed throughout a matrix of either plutonium or beryllium. Thus the neutron yield of pure $PuBe_{13}$ should lie on the curve of Fig. 1 and have the value indicated for 92.86 atomic per cent beryllium. But, for all other compositions, the actual neutron yield will be less than that computed for solid solution alloys, and if there were no (α, n) interaction between the crystals of $PuBe_{13}$ and the matrix phase in which they are contained, the neutron yield per cubic centimeter of alloy would be simply proportional to the volume of $PuBe_{13}$ per unit volume of alloy. On a gram-atomic (instead of unit volume) basis, these yields would lie along the two dashed straight lines in Fig. 1 identified as "rule of mixtures" values.

In Fig. 1 are plotted some experimental points representing the neutron yields of real alloy specimens. It is seen that, in the two-phase alloys consisting of crystals of $PuBe_{13}$ in a matrix of plutonium, the experimental yields, although smaller than the solid-solution values, are always greater than those required by the rule of mixtures. This is because there are beryllium atoms near the surface of the $PuBe_{13}$ crystals that lie within the range of alpha particles originating in plutonium atoms of the matrix. The alpha radiation which passes through the interface from the matrix into $PuBe_{13}$ augments the alpha-particle flux within a zone bordering the interface and thus increases the rate of (α, n) reaction within this portion of the $PuBe_{13}$. Because the surface area to volume ratio depends on crystal size, it follows that, for a given composition of plutonium-beryllium alloy, the smaller the $PuBe_{13}$ crystals contained in the matrix phase, the larger the neutron yield will be. This effect is illustrated in Fig. 1 by the experimental points representing specimens containing different sizes of crystals. An extremely fine grain size of the $PuBe_{13}$ would, of course, approach the condition of uniformly distributed atoms realized ideally in a solid solution or in the crystal structure of pure $PuBe_{13}$. Thus, although higher neutron yields per gram-atom of alloy are obtainable from alloys richer in plutonium than $PuBe_{13}$, only for the exact composition $PuBe_{13}$ is the neutron yield predictable.

In alloys containing more than 92.86 atomic per cent beryllium the $PuBe_{13}$ crystals occur in a matrix of beryllium. Under these circumstances a much smaller contribution to neutron yield additional to the rule-of-mixtures value results from a flow of alpha particles across the interface between the $PuBe_{13}$ and the beryllium matrix. In this case, alpha particles from plutonium atoms within the $PuBe_{13}$, but near the surface of the crystals, react with beryllium atoms in the matrix, as well as with those within the compound. Although not shown in Fig. 1, experimental values for the neutron yields of these alloys were found to lie in the narrow region between the straight line and the curve at the extreme right of Fig. 1.

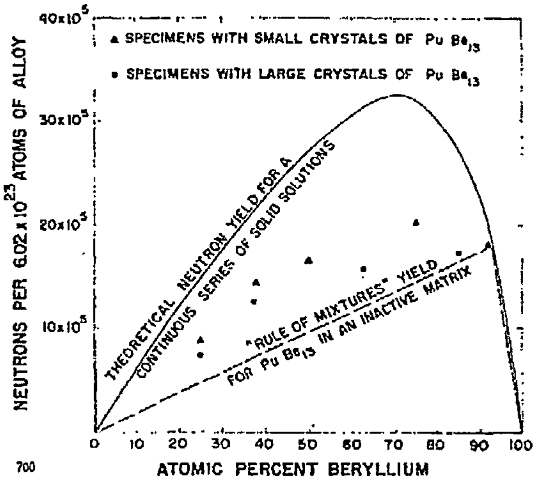

Figure 1. Neutron yield of plutonium-beryllium alloys

Runnalls and Boucher[1] have demonstrated nicely the dependence of neutron yield on the form and aggregational state of the component elements. In an investigation of beryllium-rich alloys of plutonium they observed, among other similar effects, a marked increase in neutron yield when the alloys melted.

Because plutonium is a product of the nuclear reactor, its isotopic composition is a function of reactor characteristics and operation. The stability of the neutron yield of a plutonium-beryllium source depends on the 24,360-year half-life of Pu^{239}. Other isotopes present are Pu^{238}, Pu^{240}, and Pu^{241}. The amount of Pu^{238} with its 89.6-year half-life in currently available plutonium is relatively small and the larger amounts of Pu^{240} have a 6580-year half-life. The effect of these isotopes on the rate of emission of neutrons is not significant for periods of ten to twenty years. If, however, an appreciable amount of Pu^{241} is present, the alpha-active daughter Am^{241} with its 12.9-year 470 half-life alters the number of alpha particles per second per gram-atom and the virtue of a neutron source of constant yield is lost.

Coon† has calculated that the growth in rate of emission from a plutonium-beryllium source is related to the Pu^{241} content in the following manner:

$$\frac{Q_t}{Q_0} = 1 + k[1 - \exp(-t/18.6)],$$

where

Q_t = the neutron emission rate at the time t years,
18.6 = the mean life of Pu^{241} in years,
t = the time in years from the start of Am^{241} accumulation due to beta decay of Pu^{241},

and

Q_0 = the neutron emission rate in the absence of any Am^{241}.

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† J. H. Coon, private communication.

The quantity k is obtained from the following expression:

$$k = \frac{1.27a(\mathrm{Pu}^{241})/T(\mathrm{Am}^{241})}{a(\mathrm{Pu}^{239})/T(\mathrm{Pu}^{239}) + a(\mathrm{Pu}^{240})/T(\mathrm{Pu}^{240}) + 1.27(a(\mathrm{Pu}^{238})/T(\mathrm{Pu}^{238}))},$$

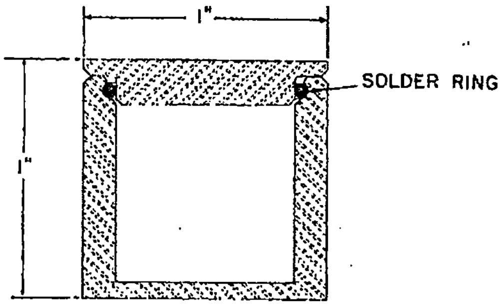
where

a = the relative abundance of the isotope,

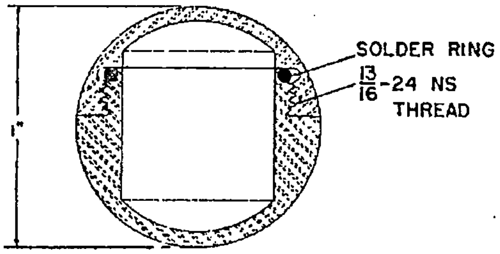
and T = the half-life of the isotope.

The numerical factor 1.27 appearing in this expression for k is the ratio of the number of neutrons produced by 5.48 Mev alpha particles (Am^{241} and Pu^{238}) and by 5.14 Mev alpha particles (Pu^{239} and Pu^{240}). This numerical value is taken from the experimental work of Runnalls and Boucher.[1]

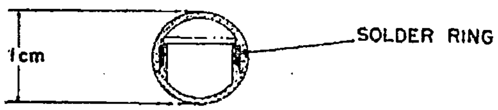
As a numerical example, the growth in the rate of neutron emission is 2.6% in 20 years from a plutonium–beryllium source prepared from plutonium containing 0.06% Pu^{241}. The growth is only 0.04% in 20 years from a similar source prepared from plutonium containing 0.003% Pu^{241}. Thus it is clear that the most useful neutron sources to be obtained from plutonium and beryllium have exactly the composition PuBe_{13} and are fabricated from plutonium containing a minimum amount of Pu^{241}.



2a CYLINDRICAL SOURCE CAPSULE



2b SPHERICAL SOURCE CAPSULE



2c SPHERICAL SOURCE CAPSULE 700

Figure 2. Nickel source containers for PuBe_{13}

FABRICATION OF THE SOURCES

Like all alloys of plutonium, those of plutonium and beryllium are prepared in suitably equipped gloveboxes in order to minimize the hazards of handling the plutonium. The first plutonium–beryllium alloys were prepared at Los Alamos in 1950 by F. W. Schonfeld, C. R. Tipton, and R. D. Moeller. A satisfactory method for preparing them is to weigh appropriate amounts of the two metals into a beryllium oxide crucible. It is important to load the heavy plutonium metal on top of the lighter beryllium metal. Because the size of the melts is kept small for health physics reasons, it is helpful to load a single piece of each metal in order to obtain good alloying. If several small pieces are loaded, some may hang onto the crucible wall and not enter the melt. The crucible is heated by means of a tantalum susceptor in an induction furnace containing an argon atmosphere. At compositions corresponding to PuBe_{13}, the two elements react vigorously as the temperature approaches 1150°C, and the heat of this reaction suddenly carries the temperature of the small mass to approximately 1400°C. This exothermic reaction yields a friable mass having the character of coke. If the mass is further heated to about 2000°C it coalesces. Upon cooling, a hard, brittle ingot of PuBe_{13} is obtained which possesses evidence of considerable solidification shrinkage. Runnalls and Boucher[1] have reported another method of preparation, namely, the reduction of plutonium trifluoride by powdered beryllium. After the reduction, beryllium trifluoride is distilled off leaving a fluoride-free alloy of plutonium and beryllium.

The alloys are encapsulated in order to permit their being handled in the laboratory without danger of spreading radioactive contamination. Capsules suitable for containing PuBe_{13} should meet the following requirements:

1. They must be rugged in order to minimize the possibility of breaking a container.
2. They must be easily loaded and permit rapid sealing in order to minimize neutron exposure to personnel preparing the sources.
3. The seal must be tight in order to preclude the possibility of spreading radioactive material.
4. Magnetic containers are desirable, as they lend themselves to remote handling by magnetic methods.

Three styles of containers which have been evolved at Los Alamos are illustrated in Fig. 2. The one-inch cylindrical container was designed for a source strength of 10^6 neutrons per second, the larger spherical container for 4.5×10^5 neutrons per second, and the smaller spherical container for 6×10^4 neutrons per second. Nickel has proved to be a satisfactory material from which to machine these capsules.

Loading and sealing the capsules is done in glove-boxes. The cylindrical container (Fig. 2*a*) is loaded with crushed PuBe$_{13}$. Lumps of the compound, either the coke-like material or dense material produced by melting, are placed in the container. The lumps are simultaneously crushed and packed to a bulk density of approximately 3.7 g/cm^3 by ramming them with a suitable tool. The spherical containers (Figs. 2*b* and 2*c*) are loaded with a lump of material that has been melted and solidified in a beryllium oxide crucible. Frequently, in breaking the crucible away from the compound, the lump of compound is broken. This may make it difficult to fit the material into the container. Even if the lump is a single piece, the most compact source suggested by the X-ray density is not obtained because of a pipe formed in the ingot on solidification.

Capsules are sealed by induction brazing, using a preplaced hard solder ring. A solder containing 56% silver, 22% copper, 17% zinc, and 5% tin (American Platinum Works Silvaloy No. 355) and a paste-type flux containing fluorides and borates (Handy and Harmon Handyflux) have been found to give satisfactory results. The joint and solder are coated with a minimum amount of flux, the solder ring is positioned, and the flux is permitted to dry before the capsule is placed in the contaminated glove-box. After the capsule is loaded, it is placed in a soldering jig. For the smallest source the soldering jig is also used to hold the capsule during loading. Heat for soldering is applied by means of a single-turn coil connected to a rf transformer. After soldering, traces of oxidation and flux are removed from the capsule by pickling it in a hot solution of hydrochloric acid and cupric chloride. It is then rinsed in hot water.

Before each capsule is considered to be satisfactory, it must pass a leak test. This test is conducted by placing the capsule in a small pressure vessel in which a helium atmosphere is raised to a pressure of 200 psi. After 30 minutes the pressure is released, and the capsule is dropped into ethanol or a similar liquid having low surface tension. Leaks are indicated by helium bubbles streaming from the capsule. Containers which leak may be resoldered, or they may be opened and the material recanned.

Because all of the canning operations have taken place in a group of contaminated glove-boxes, the exterior of the capsule is contaminated and must be cleaned. This is done best by scrubbing the capsule to remove loose material from the surface and then vapor plating it in an atmosphere of nickel carbonyl to form a coating 5 mils thick.

The final step in the preparation of these sources is to have them calibrated in a graphite column using the technique described by Graves and Froman.[9]

ACKNOWLEDGEMENTS

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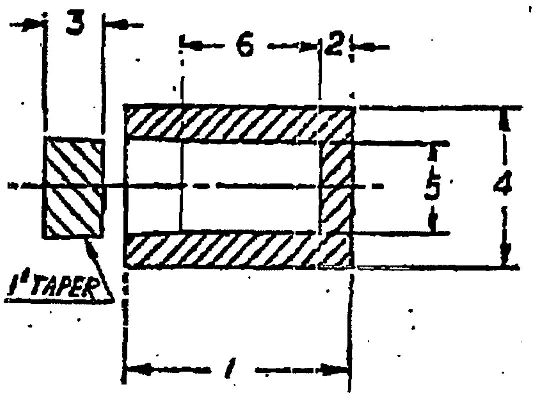
6.9.2 PuBe Source Dimensions

The following page shows a scanned copy of the original data sheet from Monsanto Research Corporation dated September 5, 1961 showing PuBe neutron source and container dimensions. This information is representative of PuBe neutron sources, but is not intended to represent actual dimensions of all sources to be placed in this container, since PuBe sources were also generated by other manufacturers and custom sizes may exist.

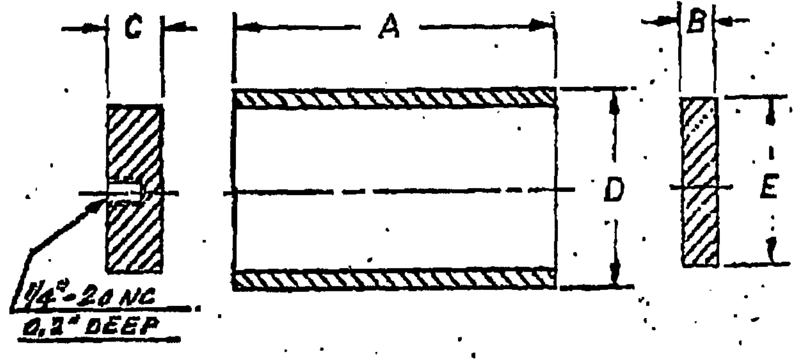
INNER CONTAINER DIMENSIONS (INCHES) — OUTER CONTAINER DIMENSIONS (INCHES)

Curie Range	Part No.						Part No.				
	1	2	3	4	5	6	A	B	C	D	E
1	1.05	0.100	0.200	0.934	0.814	0.750	1.40	0.100	0.25	0.998	0.938
2	1.80	0.100	0.200	0.934	0.814	1.50	2.15	0.100	0.25	0.998	0.938
3	2.55	0.100	0.200	0.934	0.814	2.25	2.90	0.100	0.25	0.998	0.938
4	3.30	0.100	0.200	0.934	0.814	3.00	3.65	0.100	0.25	0.998	0.938
5	4.05	0.100	0.200	0.934	0.814	3.75	4.40	0.100	0.25	0.998	0.938
5	2.50	0.100	0.200	1.184	1.064	2.20	2.85	0.100	0.25	1.248	1.188
7	3.40	0.100	0.200	1.184	1.064	3.10	3.75	0.100	0.25	1.248	1.188
10	3.25	0.100	0.200	1.434	1.300	2.95	3.60	0.100	0.25	1.498	1.438

All dimensions ± 0.002



INNER CONTAINER – TANTALUM



OUTER CONTAINER – 304 STAINLESS STEEL

DRAWN 9.5.61 L.W.
CHECKED
APPD.
SCALE NONE

MONSANTO RESEARCH CORP.
DAYTON, OHIO

PU BE SOURCE CONTAINER

LOCATION DAYTON, OHIO
AREA
AUTH. NO.
DWG. NO. NS-8

6.9.3 Computer Input Listing

Four sample array cases are provided to illustrate the various packaging and payload models. The single package cases have the same geometry except with a 12 inches water reflector.

- NCT Array, Case C1, Filename NA_II_W000
- HAC Array, Case D32, Filename HA_II_R3_WI100_WT000
- HAC Array, Case G2, Filename HAF_II_C2
- HAC Array, Case H5, Filename HAF_III_C2_W100

Case C1, Filename NA_II_W000

```
S300
10     4 -3.7    11 -21 -20              imp:n=1 $ PuBe
15     0         (20:21) 11 -12 -14      imp:n=1 $ inside SFC
20     2 -7.94   (-11:12:14) 10 -13 -15  imp:n=1 $ SFC
30     1 -0.92   (-10:13:15) 33 -34 -30  imp:n=1 $ poly
40     2 -7.94   (-33:34:30) 32 -35 -31  imp:n=1 $ pipe
50     0         (-32:35:31) -50         imp:n=1 $ water
999    0         50                      imp:n=0

10     pz 0        $ bottom of SFC
11     pz 1.27     $ inside bot SFC
12     pz 25.9588  $ inside top SFC
13     pz 29.845   $ top of SFC
14     cz 2.6194   $ IR SFC
15     cz 3.81     $ OR SFC
c
20     cz 1.6510   $ PuBe radius
21     pz 17.7302  $ PuBe height (-1.27)
c
30     cz 15.6997  $ IR pipe
31     cz 16.256   $ OR pipe
32     pz -15.7963 $ bottom of pipe
33     pz -15.24   $ inside bot of pipe
34     pz  45.085  $ inside top of pipe
35     pz  45.6413 $ top of pipe
c
40     cz 46.736   $ reflector
41     pz -46.2763 $ reflector
42     pz 76.1213  $ reflector
c
*50    hex 0 0 -15.8 0 0 61.5 0 16.257 0

mode  n
c
c  pure polyethylene (density = 0.92 g/cc)
m1    1001.62c      2 $MAT
      6000.66c      1
mt1   poly.60t
c
c  304SS (density = 7.94 g/cc)
m2     6000.66c  -0.08
```

```
       14000.60c  -1.0
       15031.66c  -0.045
       24000.50c  -19.0
       25055.62c  -2.0
       26000.55c  -68.375
       28000.50c  -9.5
c
m3     1001.62c   2 $ water
       8016.62c   1
mt3    lwtr.60t
c
c   source material Pu-Be13 (density = 3.7 g/cc)
m4     94239.69c   1
        4009.62c   13
c
kcode     2500 1.0 50 250
sdef      pos=0.0 0.0 1.27
          ext=d2 rad=d3 axs=0 0 1 cel=10
si2       0 16.4602
si3       1.651
```

Case D32, Filename HA_II_R3_WI100_WT000

```
S300
10     0        -51 10 -53 fill=2        imp:n=1
15     3 -1.0   (51:-10:53) 54 -55 -52 imp:n=1
999    0        -54:55:52                imp:n=0
c
c      Universe 1: SFC
c
100    4 -3.7   11 -21 -20               imp:n=1 u=1 $ PuBe
105    3 -1.0   11 -21 20 -14            imp:n=1 u=1 $ water beside PuBe
110    0        21 -12 -14               imp:n=1 u=1 $ water above PuBe
120    2 -7.94  (-11:12:14) 10 -13 -15 imp:n=1 u=1 $ SFC
130    0        -10:13:15                imp:n=1 u=1 $ between
c
c      Universe 2: Array
c
200    0        -50 fill=1 lat=2         imp:n=1 u=2

10     pz 0        $ bottom of SFC
11     pz 1.27     $ inside bot SFC
12     pz 25.9588  $ inside top SFC
13     pz 29.845   $ top of SFC
14     cz 2.6194   $ IR SFC
15     cz 3.81     $ OR SFC
c
20     cz 1.6510   $ PuBe radius
21     pz 17.7302  $ PuBe height (-1.27)
c
50    hex 0 0 0      0 0 29.845   3.811 0 0     $ lattice
51    cz 43.2679    $ inner reflector
52    cz 73.7479    $ outer reflector
53    pz 89.535     $ top of array
54    pz -30.48     $ bottom reflector
55    pz 120.015    $ top reflector
```

```
mode  n
c
c  pure polyethylene (density = 0.92 g/cc)
m1    1001.62c      2 $MAT
      6000.66c      1
mt1   poly.60t
c
c  304SS (density = 7.94 g/cc)
m2     6000.66c  -0.08
      14000.60c  -1.0
      15031.66c  -0.045
      24000.50c  -19.0
      25055.62c  -2.0
      26000.55c  -68.375
      28000.50c  -9.5
c
m3    1001.62c   2 $ water
      8016.62c   1
mt3   lwtr.60t
c
c   source material Pu-Be13 (density = 3.7 g/cc)
m4    94239.69c   1
       4009.62c   13
c
kcode    2500 1.0 50 250
sdef     pos=0.0 0.0 0.0 ext=d2 rad=d3 axs=0 0 1
si2      0 77
si3      44
```

Case G2, Filename HAF_II_C2

```
S300
10      0       -51 10 -13 fill=2       imp:n=1
15      3 -1.0   (51:-10:13) 54 -55 -52 imp:n=1
999     0        -54:55:52              imp:n=0
c
c       Universe 1: SFC
c
100     4 9.8852E-02 11 -12 -14         imp:n=1 u=1 $ Pu homo
120     2 -7.94  (-11:12:14) 10 -13 -15 imp:n=1 u=1 $ SFC
130     3 -1.0   -10:13:15              imp:n=1 u=1 $ between
c
c       Universe 2: Array
c
200     0        -50  lat=2   imp:n=1 u=2
        fill=-5:5 -5:5 0:0
        3 3 3 3 3 3 3 3 3 3 3
        3 3 3 3 3 3 3 3 3 3 3
        3 3 3 3 3 3 3 3 3 3 3
        3 3 3 3 1 1 1 1 1 3 3
        3 3 3 1 1 1 1 1 1 3 3
        3 3 3 1 1 1 1 1 3 3 3
        3 3 1 1 1 1 1 1 3 3 3
        3 3 3 1 1 1 3 3 3 3 3
        3 3 3 3 3 3 3 3 3 3 3
        3 3 3 3 3 3 3 3 3 3 3
        3 3 3 3 3 3 3 3 3 3 3
```

```
c
c       Universe 3: Water
c
300     3 -1.0 -56 imp:n=1 u=3
301     3 -1.0  56 imp:n=1 u=3

10      pz 0          $ bottom of SFC
11      pz 1.27       $ inside bot SFC
12      pz 25.9588    $ inside top SFC
13      pz 29.845     $ top of SFC
14      cz 2.6194     $ IR SFC
15      cz 3.81       $ OR SFC
c
20      cz 1.4107     $ Pu radius
21      pz 4.0915     $ Pu height (-1.27)
c
50     hex 0 0 0       0 0 29.845   3.811 0 0      $ lattice
51     cz 25         $ inner reflector
52     cz 55.48        $ outer reflector
53     pz 89.535       $ top of array
54     pz -30.48       $ bottom reflector
55     pz 60.325       $ top reflector
56     so  100000      $ dummy

mode  n
c
c  pure polyethylene (density = 0.92 g/cc)
m1     1001.62c      2 $MAT
       6000.66c      1
mt1    poly.60t
c
c  304SS (density = 7.94 g/cc)
m2      6000.66c  -0.08
       14000.60c  -1.0
       15031.66c  -0.045
       24000.50c  -19.0
       25055.62c  -2.0
       26000.55c  -68.375
       28000.50c  -9.5
c
m3     1001.62c   2 $ water
       8016.62c   1
mt3    lwtr.60t
c
c   source material Pu
m4     94239.69c 1.4201E-03
        1001.62c 6.4955E-02
        8016.62c 3.2477E-02
c          Total 9.8852E-02
mt4    lwtr.60t
c
kcode     2500 1.0 50 250
sdef      pos=0.0 0.0 0.0 ext=d2 rad=d3 axs=0 0 1
si2       0 25
si3       18
```

Case H5, Filename HAF_III_C2_W100

```
S300
10      0         -51 10 -13 fill=2       imp:n=1
15      3 -1.0    (51:-10:13) 54 -55 -52 imp:n=1
999     0          -54:55:52              imp:n=0
c
c       Universe 1: SFC
c
100     4 9.7462E-02 11 -12 -14           imp:n=1 u=1 $ Pu homo
120     2 -7.94   (-11:12:14) 10 -13 -15 imp:n=1 u=1 $ SFC
130     3 -1.0    -10:13:15               imp:n=1 u=1 $ between
c
c       Universe 2: Array
c
200     0          -50  lat=2   imp:n=1 u=2
        fill=-5:5 -5:5 0:0
        3 3 3 3 3 3 3 3 3 3 3
        3 3 3 3 3 3 3 3 3 3 3
        3 3 3 3 3 3 3 3 3 3 3
        3 3 3 3 1 1 1 1 1 3 3
        3 3 3 1 1 1 1 1 1 3 3
        3 3 3 1 1 1 1 1 3 3 3
        3 3 1 1 1 1 1 1 3 3 3
        3 3 3 1 1 1 3 3 3 3 3
        3 3 3 3 3 3 3 3 3 3 3
        3 3 3 3 3 3 3 3 3 3 3
        3 3 3 3 3 3 3 3 3 3 3
c
c       Universe 3: Water
c
300     3 -1.0 -56 imp:n=1 u=3
301     3 -1.0  56 imp:n=1 u=3

10      pz 0        $ bottom of SFC
11      pz 1.27     $ inside bot SFC
12      pz 13.8906  $ inside top SFC
13      pz 17.78    $ top of SFC
14      cz 1.905    $ IR SFC
15      cz 3.175    $ OR SFC
c
20      cz 1.4107   $ Pu radius
21      pz 4.0915   $ Pu height (-1.27)
c
50     hex 0 0 0      0 0 29.845   3.176 0 0     $ lattice
51     cz 21          $ inner reflector
52     cz 51.48       $ outer reflector
53     pz 35.56       $ top of array
54     pz -30.48      $ bottom reflector
55     pz 48.26       $ top reflector
56     so  100000     $ dummy

mode  n
c
c  pure polyethylene (density = 0.92 g/cc)
m1     1001.62c       2 $MAT
       6000.66c       1
```

```
mt1   poly.60t
c
c  304SS (density = 7.94 g/cc)
m2      6000.66c  -0.08
       14000.60c  -1.0
       15031.66c  -0.045
       24000.50c  -19.0
       25055.62c  -2.0
       26000.55c  -68.375
       28000.50c  -9.5
c
m3     1001.62c   2 $ water
       8016.62c   1
mt3    lwtr.60t
c
c   source material Pu
m4     94239.69c 2.8012E-03 $H= 12.6206
        1001.62c 6.3107E-02 $M= 160
        8016.62c 3.1554E-02
c          Total 9.7462E-02
mt4    lwtr.60t
c
kcode     2500 1.0 50 250
sdef      pos=0.0 0.0 0.0 ext=d2 rad=d3 axs=0 0 1
si2       0 14
si3       18
```

6.9.4 Air Transport Criticality Analysis

The applicable licensing requirements for air transport of fissile material are contained in 10 CFR 71.55(f) and TS-R-1, §680. These requirements are implemented by assuming that the S300 packaging materials and contents are reconfigured in the most reactive spherical geometry, reflected by 20 cm of water.

The analysis is performed for 210 g Pu-239, which bounds the non-exclusive use limiting value of 206 g Pu-239. The analysis demonstrates that the package is safely subcritical when reconfigured as described above. The air transport analysis applies to both the neutron source payload and general payload, as separation of the plutonium and beryllium is considered.

The criticality analysis for air transport is performed using the KENO V.a module of the SCALE5 code package. Note that the criticality analysis in the earlier part of this chapter was performed using MCNP5 v1.40. KENO rather than MCNP is utilized for the air transport calculations. Both programs are well-accepted in the criticality community and generate similar results. Because KENO V.a is used in the air transport analysis, the air transport analysis utilizes its own benchmarks and has a separate USL.

The approach is to assume that all of the contents and packaging material arrange in the most reactive spherical geometry in the air transport accident. Because the S300 contains a large mass of polyethylene, which is a superior moderator and reflector than water, the most reactive case is essentially 210 g Pu-239 optimally moderated and reflected with polyethylene. The most reactive conditions has $k_s = 0.8930$, which is less than the USL of 0.9377.

6.9.4.1 General Considerations

6.9.4.1.1 Model Configuration

Because the package will likely be severely damaged or destroyed as the result of a design basis aircraft accident, it is assumed that all source and packaging material for a single S300 may reconfigure in the most reactive geometry. The source may be moderated with the packaging materials, but it is assumed that the source is not moderated with water (i.e., no water intrusion). This approach is consistent with 10 CFR 71.55(f)(2). In any case, because the S300 has a large mass of polyethylene, which is a superior moderator and reflector compared to water, allowing water intrusion into the fissile sphere would reduce the reactivity.

Before the model can be defined, the mass of the constituent materials must first be determined. The S300 source and packaging materials are defined in Table 6-21. The densities reported are from the SCALE5 manual[4]. Note that the plutonium and beryllium densities are for pure metals, and not the densities within the PuBe source material. The dunnage (made of fibrous cellulose material) is neglected because it will have a negligible effect on the reactivity compared to the other materials.

The source is assumed to be comprised of 210 g of plutonium. Because the ratio of beryllium to plutonium atoms is 13:1 within the PuBe source, the mass of beryllium is computed to be 103 g.

The total polyethylene mass includes both the shield insert and drum liner. The mass of polyethylene used, 120 lb, bounds the summed masses of the 90-lb shield insert (Table 2-1) and of the 110-mil, Type IV poly drum liner. Because the quantity of polyethylene is large, there is sufficient polyethylene to both optimally moderate and reflect the plutonium.

The PuBe source may be clad in an inner layer of tantalum and an outer layer of stainless steel. The dimensions of these materials are shown in Section 6.9.2, *PuBe Source Dimensions*. Because the source mass (210 g Pu) does not correspond to an actual physical source, the masses of stainless steel and tantalum in the source are computed in an approximate manner by multiplying the respective quantities for a 160 g Pu source by 1.5. These values are reported in Table 6-21. The analysis shows, however, that the mass of tantalum and stainless steel do not affect the conclusions and are not required to be present as sealed source cladding.

Stainless steel is also present in both the special form capsule and the pipe component. The mass of a Model II special form capsule may be derived from the dimensions provided on Figure 1-3. From this figure, the overall length and OD is 11.75-in and 3-in, respectively. The inner cavity has a diameter of 2.0625-in and length of approximately 11.75 – 0.75 – 0.78 = 10.22-in. Based on these dimensions, the Model II mass is computed to be 6.4 kg. From Table 2-1, the pipe component has a mass of 180 pounds. Therefore, the total mass of stainless steel, when combining the source cladding, special form capsule, and pipe component, is approximately 88.3 kg.

The drum is fabricated of carbon steel with an approximate mass of 60 pounds, or 27.3 kg.

A number of model configurations are developed. Each model is composed of concentric spheres, with the innermost sphere as a mixture of plutonium and polyethylene. The remaining

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[4] *Standard Composition Library*, ORNL/TM-2005/39, Version 6, Vol. III, Sec. M8, January 2009.

packaging materials are utilized as reflectors, and the outermost layer is always 20 cm of water. The beryllium, while bound to the plutonium, is modeled both within the fissile sphere and external to the fissile sphere to determine the most reactive configuration. In each series of cases, the H/Pu ratio is adjusted over the range from 600 to 1,300 to determine the most reactive condition.

A total of five configurations are developed. These configurations are summarized in Table 6-22. In Configurations A through D, the plutonium and beryllium are assumed to separate, while in Configuration E, the plutonium and beryllium are assumed to remain mixed. In Configuration A, only sufficient polyethylene needed to moderate the fissile sphere is utilized. The remaining polyethylene is ignored and the fissile sphere is reflected with water. Configuration B is similar to Configuration A, although the polyethylene not needed to moderate the fissile sphere is treated as a reflector. Configuration C is similar to Configuration B, although the beryllium is treated as an additional reflector. Configuration D is similar to Configuration C, except the carbon steel, stainless steel, and tantalum are treated as additional reflectors. Configuration E is similar to Configuration B, although beryllium is added to the fissile sphere.

The radius of each region is determined using the masses and densities defined in Table 6-21. The geometry of each configuration is summarized in Table 6-23. The number densities within the fissile sphere are also provided in this table.

As an example, the geometry of Configuration B is shown in Figure 6-8. The geometries of the other configurations are similar and may be inferred from the data in Table 6-22 and Table 6-23.

6.9.4.1.2 Material Properties

The fissile sphere number densities are provided in Table 6-23.

The reflecting materials are comprised of stainless steel, carbon steel, beryllium, polyethylene, tantalum, and water. The default material properties and densities within SCALE are utilized for these materials.

6.9.4.1.3 Computer Code and Cross Section Libraries

Calculations are performed with the three-dimensional Monte Carlo transport theory code, KENO-V.a v5.0.2[5]. Note that in the standard single package and array criticality analyses, MCNP5 and not KENO is used in the analysis. KENO is used for the air transport calculations because the geometry is simple, and the use of KENO facilitates the input preparation.

The SCALE-PC v5, CSAS25 utility is used as a driver for the KENO code. In this role, CSAS25 determines nuclide number densities, performs resonance processing, and automatically prepares the necessary input for the KENO code based on a simplified input description. The 238 energy-group (238GROUPNDF5), cross-section library based on ENDF/B-V cross-section data is used as the nuclear data library for the KENO-V.a code.

The KENO code has been used extensively in the criticality safety industry. KENO-V.a is an extension of earlier versions of the KENO code and includes many versatile geometry capabilities and screen plots to facilitate geometry verification. The KENO-V.a code and the

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[5] *SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation,* ORNL/TM-2005/39, Version 5, Vols. I-III, April 2005.

associated 238GROUPNDF5 cross-section data set are validated for proper operation on the PC platform by performing criticality analyses of a number of relevant benchmark criticality experiments. A description of these benchmark calculations, along with justification for the computed bias in the code and library for the relevant region of applicability, is provided in Section 6.9.4.3, *Air Transport Benchmarking Evaluation.*

Models are run with 1000 neutrons per generation for 850 generations, skipping the first 50. The 1-sigma uncertainty is approximately 0.001 for all cases.

6.9.4.1.4 Demonstration of Maximum Reactivity

Maximum reactivity is demonstrated by optimally moderating and reflecting 210 g of Pu-239 with the available polyethylene and 20 cm of water. The stainless steel, carbon steel, and tantalum are also used as reflectors, but are less reactive than the polyethylene reflector and therefore are not required to be present as sealed source cladding. The configuration that utilizes beryllium mixed with plutonium is statistically equivalent to the configuration that utilizes beryllium as an independent reflector. The most reactive case is Configuration E, Case TE5, with H/Pu = 1000 and $k_s = 0.8930$. This value is less than the USL of 0.9377.

Table 6-21 – Packaging/Source Materials and Masses

Material	Solid Density (g/cm^3)	Item	Mass (lb)	Mass (kg)
Pu-239	19.84	Source	--	0.21
Beryllium	1.85	Source	--	0.10
Tantalum	16.6	Source	--	0.4
Polyethylene	0.92	Packaging	120	54.4
Stainless steel	7.94	Source	--	0.3
		Special form capsule	--	6.4
		Pipe component	180	81.6
		Total	--	88.3
Carbon steel	7.8212	Drum	60	27.2

Table 6-22 – Model Configurations

Configuration	Fissile Sphere (R_1)	Reflector
A	Plutonium/polyethylene	R_2: Water
B	Plutonium/polyethylene	R_2: Polyethylene R_3: Water
C	Plutonium/polyethylene	R_2: Beryllium R_3: Polyethylene R_4: Water
D	Plutonium/polyethylene	R_2: Beryllium R_3: Carbon steel R_4: Stainless steel R_5: Tantalum R_6: Polyethylene R_7: Water
E	Plutonium/polyethylene/beryllium	R_2: Polyethylene R_3: water

Table 6-23 – Geometry and Number Densities

Configuration A					
H/Pu	R_1 (cm)	R_2 (cm)	Pu-239 (atom/b-cm)	H (atom/b-cm)	C (atom/b-cm)
600	9.8709	29.8709	1.3131E-04	7.8789E-02	3.9394E-02
700	10.3900	30.3900	1.1260E-04	7.8818E-02	3.9409E-02
800	10.8619	30.8619	9.8551E-05	7.8841E-02	3.9420E-02
900	11.2960	31.2960	8.7620E-05	7.8858E-02	3.9429E-02
1000	11.6991	31.6991	7.8872E-05	7.8872E-02	3.9436E-02
1100	12.0762	32.0762	7.1712E-05	7.8883E-02	3.9441E-02
1200	12.4311	32.4311	6.5744E-05	7.8892E-02	3.9446E-02
1300	12.7668	32.7668	6.0693E-05	7.8900E-02	3.9450E-02

Configuration B				
H/Pu	R_1 (cm)	R_2 (cm)	R_3 (cm)	Number Densities
600	9.8709	24.1727	44.1727	Number densities the same as Configuration A
700	10.3900	24.1727	44.1727	
800	10.8619	24.1727	44.1727	
900	11.2960	24.1727	44.1727	
1000	11.6991	24.1727	44.1727	
1100	12.0762	24.1727	44.1727	
1200	12.4311	24.1727	44.1727	
1300	12.7668	24.1727	44.1727	

(continued)

Table 6-23 – Geometry and Number Densities (concluded)

Configuration C					
H/Pu	**R_1 (cm)**	**R_2 (cm)**	**R_3 (cm)**	**R_4 (cm)**	**Number Densities**
600	9.8709	9.9161	24.1802	44.1802	Number densities the same as Configuration A
700	10.3900	10.4309	24.1802	44.1802	
800	10.8619	10.8993	24.1802	44.1802	
900	11.2960	11.3306	24.1802	44.1802	
1000	11.6991	11.7314	24.1802	44.1802	
1100	12.0762	12.1065	24.1802	44.1802	
1200	12.4311	12.4596	24.1802	44.1802	
1300	12.7668	12.7939	24.1802	44.1802	

Configuration D								
H/Pu	**R_1 (cm)**	**R_2 (cm)**	**R_3 (cm)**	**R_4 (cm)**	**R_5 (cm)**	**R_6 (cm)**	**R_7 (cm)**	**Number Densities**
600	9.8709	9.9161	12.1770	16.4603	16.4675	26.0258	46.0258	Number densities the same as Configuration A
700	10.3900	10.4309	12.5263	16.6546	16.6618	26.0258	46.0258	
800	10.8619	10.8993	12.8571	16.8446	16.8516	26.0258	46.0258	
900	11.2960	11.3306	13.1718	17.0303	17.0372	26.0258	46.0258	
1000	11.6991	11.7314	13.4720	17.2121	17.2188	26.0258	46.0258	
1100	12.0762	12.1065	13.7595	17.3902	17.3967	26.0258	46.0258	
1200	12.4311	12.4596	14.0354	17.5646	17.5710	26.0258	46.0258	
1300	12.7668	12.7939	14.3008	17.7357	17.7420	26.0258	46.0258	

Configuration E							
H/Pu	**R_1 (cm)**	**R_2 (cm)**	**R_3 (cm)**	**Pu-239 (atom/b-cm)**	**H (atom/b-cm)**	**C (atom/b-cm)**	**Be (atom/b-cm)**
600	9.9161	24.1802	44.1802	1.2953E-04	7.7716E-02	3.8858E-02	1.6838E-03
700	10.4309	24.1802	44.1802	1.1128E-04	7.7896E-02	3.8948E-02	1.4466E-03
800	10.8993	24.1802	44.1802	9.7540E-05	7.8032E-02	3.9016E-02	1.2680E-03
900	11.3306	24.1802	44.1802	8.6820E-05	7.8138E-02	3.9069E-02	1.1287E-03
1000	11.7314	24.1802	44.1802	7.8223E-05	7.8223E-02	3.9111E-02	1.0169E-03
1100	12.1065	24.1802	44.1802	7.1175E-05	7.8293E-02	3.9146E-02	9.2528E-04
1200	12.4596	24.1802	44.1802	6.5292E-05	7.8351E-02	3.9175E-02	8.4880E-04
1300	12.7939	24.1802	44.1802	6.0308E-05	7.8400E-02	3.9200E-02	7.8400E-04

6.9.4.2 Air Transport Results

The geometry and materials of the various configurations investigated are summarized in Section 6.9.4.1.1, *Model Configuration*, and Section 6.9.4.1.2, *Material Properties*. The results of the five configurations analyzed are reported in Table 6-24. The most reactive case for each configuration is listed in boldface. Note that in all cases, the most reactive condition occurs for H/Pu of either 900 or 1000. These variations are most likely the result of statistical fluctuation.

In Configuration A, water is the only reflector, while in Configuration B, the polyethylene not used to moderate the plutonium is also used as a reflector. Configuration B is more reactive than Configuration A, which is expected because polyethylene is a superior neutron reflector than water.

Beryllium is a superior neutron reflector than polyethylene, so in Configuration C, a beryllium reflector is added next to the fissile sphere. However, because very little beryllium is available, the thickness of the beryllium reflector is small, and the reactivities of Configurations B and C are statistically equivalent.

In Configuration D, the remaining metals (i.e., carbon steel, stainless steel, and tantalum) are added in successive layers between the beryllium and polyethylene reflectors. The reactivity drops slightly, indicating that the reflection provided by the metals is slightly less than the reflection provided by the polyethylene. Therefore, it is conservative to neglect these metals.

In Configuration E, the beryllium is assumed to remain bound to the plutonium, which is the most likely scenario based on the nature of the PuBe alloy. Only polyethylene and water are used as reflectors, as it has been established that inclusion of the metals lowers the reactivity. The reactivity of Configuration E, Case TE5, is the most reactive of all models, with H/Pu = 1000 and $k_s = 0.8930$. However, the maximum reactivities of Configurations B, C, and E are statistically equivalent, and the presence of beryllium in the model has essentially no influence on the results. All results are below the USL of 0.9377.

Table 6-24 – Air Transport Results

Configuration A					
Case ID	Filename	H/X	k	σ	k+2σ
TA1	PW	600	0.8539	0.0011	0.8561
TA2	PW	700	0.8682	0.0012	0.8706
TA3	PW	800	0.8765	0.0010	0.8785
TA4	PW	900	0.8781	0.0010	0.8801
TA5	**PW**	**1000**	**0.8801**	**0.0009**	**0.8819**
TA6	PW	1100	0.8799	0.0010	0.8818
TA7	PW	1200	0.8768	0.0011	0.8790
TA8	PW	1300	0.8723	0.0009	0.8741
Configuration B					
Case ID	Filename	H/X	k	σ	k+2σ
TB1	PPW	600	0.8697	0.0010	0.8717
TB2	PPW	700	0.8814	0.0010	0.8833
TB3	PPW	800	0.8864	0.0010	0.8884
TB4	PPW	900	0.8894	0.0010	0.8914
TB5	**PPW**	**1000**	**0.8905**	**0.0010**	**0.8925**
TB6	PPW	1100	0.8885	0.0010	0.8905
TB7	PPW	1200	0.8859	0.0009	0.8877
TB8	PPW	1300	0.8807	0.0010	0.8827
Configuration C					
Case ID	Filename	H/X	k	σ	k+2σ
TC1	PBPW	600	0.8716	0.0010	0.8736
TC2	PBPW	700	0.8804	0.0011	0.8826
TC3	PBPW	800	0.8881	0.0010	0.8901
TC4	**PBPW**	**900**	**0.8904**	**0.0011**	**0.8926**
TC5	PBPW	1000	0.8905	0.0010	0.8925
TC6	PBPW	1100	0.8884	0.0009	0.8903
TC7	PBPW	1200	0.8863	0.0011	0.8885
TC8	PBPW	1300	0.8792	0.0009	0.8810
Configuration D					
Case ID	Filename	H/X	k	σ	k+2σ
TD1	PBCSTPW	600	0.8666	0.0011	0.8688
TD2	PBCSTPW	700	0.8797	0.0009	0.8815
TD3	PBCSTPW	800	0.8857	0.0010	0.8877
TD4	**PBCSTPW**	**900**	**0.8871**	**0.0010**	**0.8891**
TD5	PBCSTPW	1000	0.8867	0.0010	0.8887
TD6	PBCSTPW	1100	0.8851	0.0010	0.8870
TD7	PBCSTPW	1200	0.8789	0.0010	0.8809
TD8	PBCSTPW	1300	0.8753	0.0009	0.8771

(continued)

Table 6-24 – Air Transport Results (concluded)

Configuration E					
Case ID	**Filename**	**H/X**	**k**	**σ**	**k+2σ**
TE1	PBMIXPW	600	0.8657	0.0010	0.8677
TE2	PBMIXPW	700	0.8801	0.0010	0.8821
TE3	PBMIXPW	800	0.8869	0.0010	0.8888
TE4	PBMIXPW	900	0.8901	0.0010	0.8921
TE5	**PBMIXPW**	**1000**	**0.8910**	**0.0010**	**0.8930**
TE6	PBMIXPW	1100	0.8887	0.0010	0.8907
TE7	PBMIXPW	1200	0.8836	0.0010	0.8855
TE8	PBMIXPW	1300	0.8809	0.0010	0.8829

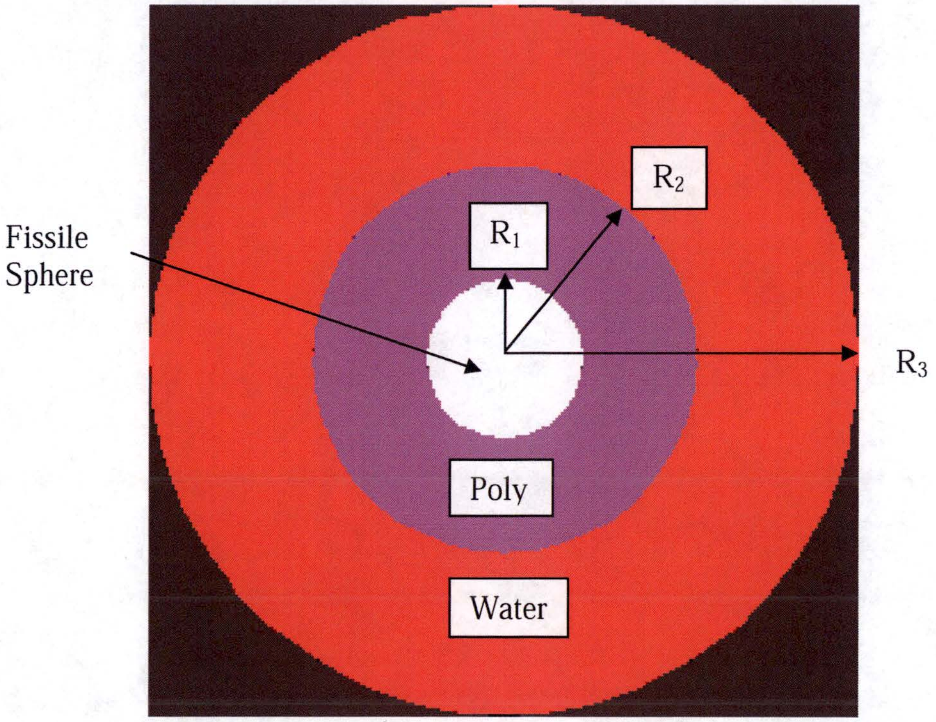

Figure 6-8 – Configuration B Sample Geometry

6.9.4.3 Air Transport Benchmarking Evaluation

The KENO-V.a Monte Carlo criticality code has been used extensively in criticality evaluations. The 238 energy-group, ENDF/B-V cross-section library employed here has been selected based on its relatively fine neutron energy group structure. This section justifies the validity of this computation tool and data library combination for application to the S300 air transport criticality analysis.

The ORNL USLSTATS code, described in Appendix C, *User's Manual for USLSTATS V1.0*, of NUREG/CR-6361[6], is used to establish an upper subcriticality limit, USL, for the analysis. Computed multiplication factors, k_{eff}, are deemed to be adequately subcritical if the computed value of k_{eff} plus two standard deviations is below the USL as follows:

$$k_s = k_{eff} + 2\sigma \leq USL$$

The USL includes the combined effects of code bias, uncertainty in the benchmark experiments, uncertainty in the computational evaluation of the benchmark experiments, and an administrative margin of subcriticality. The USL is determined using the confidence band with administrative margin technique (USLSTATS Method 1). The result of the statistical analysis of the benchmark experiments is a USL of 0.9377. Due to the significant positive bias exhibited by the code and library for the benchmark experiments, the USL is constant with respect to the various parameters selected for the benchmark analysis.

6.9.4.3.1 Applicability of Benchmark Evaluations

A total of 196 benchmark experiments of water-reflected solutions of plutonium nitrate are evaluated using the KENO-V.a Monte Carlo criticality code with the SCALE-PC v5, 238 energy-group, ENDF/B-V cross-section library. The benchmark cases are evaluated with respect to two independent parameters: 1) the H/Pu ratio, and 2) the average fission energy group (AEG).

Detailed descriptions of the benchmark experiments are obtained from the OECD Nuclear Energy Agency's *International Handbook of Evaluated Criticality Safety Benchmark Experiments*[7]. The critical experiments selected for this analysis are presented in Table 6-25. Experiments with beryllium and Pu as the fissile component are not available. The only experiments with beryllium in the thermal energy range identified from the OECD Handbook contained U-233 as the fissile isotope. Thus, 31 benchmarks with U-233 and beryllium in the thermal energy range and 15 benchmarks with U-233 and no beryllium also in the thermal energy range are evaluated. With respect to validation of polyethylene, CH_2, in the models, some of the U-233 benchmarks contained polyethylene and some of the plutonium experiments contained Plexiglas, which also contains carbon.

All criticality models fall within the range of applicability of the benchmark experiments for the H/Pu ratio and AEG trending parameters as follows:

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[6] NUREG/CR-6361, *Criticality Benchmark Guide for Light-Water-Reactor Fuel in Transportation and Storage Packages*, March 1997.

[7] *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, Nuclear Energy Agency, NEA/NSC/DOC(95)03, September 2007.

Range of Applicability for S300 Package Criticality Analysis	**Range of Applicability for Trending Parameters**
$600 \leq$ H/Pu Ratio $\leq 1{,}300$ $214 \leq$ AEG ≤ 218	$45 \leq$ H/Pu Ratio $\leq 2{,}730$ $171 \leq$ AEG ≤ 220

Only thermal benchmark experiments are analyzed, as all S300 air transport models are highly moderated.

6.9.4.3.2 Bias Determination

The USL is calculated by application of the USLSTATS computer program. USLSTATS receives as input the k_{eff} as calculated by KENO, the total 1-σ uncertainty (combined benchmark and KENO uncertainties), and a trending parameter.

The uncertainty value, σ_{total}, assigned to each case is a combination of the benchmark uncertainty for each experiment, σ_{bench}, and the Monte Carlo uncertainty associated with the particular computational evaluation of the case, σ_{KENO}, or:

$$\sigma_{total} = (\sigma_{bench}^2 + \sigma_{KENO}^2)^{½}$$

These values are input into the USLSTATS program in addition to the following parameters, which are the values recommended by the USLSTATS user's manual:

- P, proportion of population falling above lower tolerance level = 0.995 (note that this parameter is required input but is not utilized in the calculation of USL Method 1)
- 1-γ, confidence on fit = 0.95
- α, confidence on proportion P = 0.95 (note that this parameter is required input but is not utilized in the calculation of USL Method 1)
- Δk_m, administrative margin used to ensure subcriticality = 0.05.

These data are followed by triplets of trending parameter value, computed k_{eff}, and uncertainty for each case. A confidence band analysis is performed on the data for each trending parameter using USL Method 1. All benchmark data used as input to USLSTATS are reported in Table 6-26.

Two trending parameters are identified for determination of the bias. First, the AEG is used in order to characterize any code bias with respect to neutron spectral effects. The USL is calculated vs. AEG separately for four scenarios:

1. U-233 experiments without beryllium
2. U-233 experiments with beryllium
3. Pu experiments
4. Combined Pu experiments and U-233 experiments with beryllium

Note that several of the U-233 benchmarks (with beryllium) are quite poor (k ~ 0.97). Because the U-233 fissile isotope introduces a component that is not relative to the calculations performed for the S300 package and may have a distinct bias of its own, comparison of the USL for the U-233 experiments with beryllium to the USL for those without beryllium allows the effect of the beryllium reflector to be separated from the effect of the U-233 isotope. Next, the H/Pu ratio of each experimental case containing Pu is used in order to characterize the material and geometric properties of each sphere. The U-233 results are not considered in the trending with respect to H/Pu as this parameter is not directly applicable. Finally, the Pu experiments are combined with the U-233 (with beryllium) experiments.

The USLs calculated using USLSTATS Method 1 for the benchmark combinations discussed above are tabulated in Table 6-27. The USL (AEG) calculated based on the combined results of the U-233 (with beryllium) and Pu experiments of 0.9377 is chosen as the USL for this analysis. This USL value is 0.0017 below that of the Pu experiments alone.

At the high AEG values applicable to S300 package, the U-233 benchmarks without beryllium result in a lower USL (0.0019) than calculated from the U-233 benchmarks with beryllium. Both of the U-233 USL values are lower than the Pu experiment USL values, indicating that the U-233 isotope in the experiments has a more significant effect on the USL than the beryllium. Thus, the USL based on the combined results of the U-233 (with beryllium) and Pu experiments chosen adequately accounts for any bias attributable to beryllium.

In addition, the USL calculated for the Pu experiments using the H/Pu ratio as the trending parameter do not differ significantly from the USL for the Pu experiments using AEG, and are bounded by the chosen USL value of 0.9377. USLSTATS calculates constant USL values with respect to the H/Pu ratio, indicating no appreciable trend with respect to this parameter.

Table 6-25 – Benchmark Experiments Utilized

Series	Title
PU-SOL-THERM-001	Water-Reflected 11.5-Inch Diameter Spheres Of Plutonium Nitrate Solutions
PU-SOL-THERM-002	Water-Reflected 12-Inch Diameter Spheres Of Plutonium Nitrate Solutions
PU-SOL-THERM-003	Water-Reflected 13-Inch Diameter Spheres Of Plutonium Nitrate Solutions
PU-SOL-THERM-004	Water-Reflected 14-Inch Diameter Spheres Of Plutonium Nitrate Solutions 0.54% To 3.43% Pu240
PU-SOL-THERM-005	Water-Reflected 14-Inch Diameter Spheres Of Plutonium Nitrate Solutions 4.05% And 4.40% Pu240
PU-SOL-THERM-006	Water-Reflected 15-Inch Diameter Spheres Of Plutonium Nitrate Solutions
PU-SOL-THERM-007	Water-Reflected 11.5-Inch Diameter Spheres Partly Filled with Plutonium Nitrate Solutions
PU-SOL-THERM-009	Unreflected 48-Inch-Diameter Sphere Of Plutonium Nitrate Solution
PU-SOL-THERM-010	Water-Reflected 9-, 10-, 11-, And 12-Inch-Diameter Cylinders Of Plutonium Nitrate Solutions
PU-SOL-THERM-011	Bare 16- And 18-Inch-Diameter Spheres Of Plutonium Nitrate Solutions
PU-SOL-THERM-014	Interacting Cylinders of 300-mm Diameter Spheres of Plutonium Nitrate Solution (115.1gPu/L) in Air
PU-SOL-THERM-015	Interacting Cylinders of 300-mm Diameter with Plutonium Nitrate Solution (152.5gPu/L) in Air
PU-SOL-THERM-016	Interacting Cylinders of 300-mm and 256-mm Diameters with Plutonium Nitrate Solution (152.5 and 115.1 gPu/L) and Nitric Acid (2n) in Air
PU-SOL-THERM-017	Interacting Cylinders of 256-mm and 300-mm Diameters with Plutonium Nitrate Solution (115.1 gPu/L) in Air
PU-SOL-THERM-020	Water-Reflected and Water-Cadmium Reflected 14-inch Diameter Spheres of Plutonium Nitrate Solutions
PU-SOL-THERM-021	Water-Reflected and Bare 15.2-inch Diameter Spheres of Plutonium Nitrate Solutions
PU-SOL-THERM-024	Slabs of Plutonium Nitrate Solutions Reflected by 1-inch Thick Plexiglas
U233-SOL-THERM-001	Unreflected Spheres of ^{233}U Nitrate Solutions
U233-SOL-THERM-003	Paraffin-Reflected 5-, 5.4-, 6-, 6.6-, 7.5-, 8-, 8.5-, 9-, and 12-inch Diameter Cylinders of ^{233}U Uranyl Fluoride Solutions
U233-SOL-THERM-015	Uranyl-Fluoride (^{233}U) Solutions in Spherical Stainless Steel Vessels with Reflectors of Be, CH_2, and Be-CH_2 Composites

Table 6-26 – Benchmark Experiment Data

No.	Case Name	k_{eff}	σ_{KENO}	σ_{BENCH}	σ_{TOTAL}	AEG	H/Pu
1	PUST001_CASE_1	1.0080	0.0011	0.0050	0.0051	212.494	352.9
2	PUST001_CASE_2	1.0102	0.0010	0.0050	0.0051	209.982	258.1
3	PUST001_CASE_3	1.0126	0.0011	0.0050	0.0051	207.749	204.1
4	PUST001_CASE_4	1.0068	0.0010	0.0050	0.0051	206.409	181
5	PUST001_CASE_5	1.0095	0.0011	0.0050	0.0051	205.787	171.2
6	PUST001_CASE_6	1.0085	0.0010	0.0050	0.0051	195.740	86.7
7	PUST002_CASE_1	1.0076	0.0010	0.0047	0.0048	214.684	508
8	PUST002_CASE_2	1.0093	0.0009	0.0047	0.0048	214.459	489.2
9	PUST002_CASE_3	1.0066	0.0010	0.0047	0.0048	213.805	437.3
10	PUST002_CASE_4	1.0104	0.0009	0.0047	0.0048	213.351	407.5
11	PUST002_CASE_5	1.0125	0.0010	0.0047	0.0048	212.894	380.6
12	PUST002_CASE_6	1.0080	0.0010	0.0047	0.0048	211.961	333.5
13	PUST002_CASE_7	1.0113	0.0012	0.0047	0.0049	211.138	299.3
14	PUST003_CASE_1	1.0066	0.0010	0.0047	0.0048	216.626	774.1
15	PUST003_CASE_2	1.0067	0.0010	0.0047	0.0048	216.438	742.7
16	PUST003_CASE_3	1.0084	0.0009	0.0047	0.0048	216.067	677.2
17	PUST003_CASE_4	1.0086	0.0010	0.0047	0.0048	215.944	660.5
18	PUST003_CASE_5	1.0115	0.0010	0.0047	0.0048	215.528	607.2
19	PUST003_CASE_6	1.0100	0.0010	0.0047	0.0048	214.967	545.3
20	PUST003_CASE_7	1.0112	0.0009	0.0047	0.0048	216.485	714.8
21	PUST003_CASE_8	1.0097	0.0010	0.0047	0.0048	216.331	692.1
22	PUST004_CASE_1	1.0076	0.0010	0.0047	0.0048	217.461	981.7
23	PUST004_CASE_2	1.0043	0.0009	0.0047	0.0048	217.415	898.6
24	PUST004_CASE_3	1.0041	0.0009	0.0047	0.0048	217.240	864
25	PUST004_CASE_4	1.0043	0.0010	0.0047	0.0048	217.028	842
26	PUST004_CASE_5	1.0034	0.0010	0.0047	0.0048	217.259	780.2
27	PUST004_CASE_6	1.0065	0.0009	0.0047	0.0048	217.190	668
28	PUST004_CASE_7	1.0099	0.0009	0.0047	0.0048	217.033	573.3
29	PUST004_CASE_8	1.0041	0.0010	0.0047	0.0048	216.915	865
30	PUST004_CASE_9	1.0048	0.0010	0.0047	0.0048	216.587	872.2
31	PUST004_CASE_10	1.0070	0.0009	0.0047	0.0048	215.880	971.6
32	PUST004_CASE_11	1.0052	0.0009	0.0047	0.0048	215.116	929.6
33	PUST004_CASE_12	1.0065	0.0009	0.0047	0.0048	217.031	884.1
34	PUST004_CASE_13	1.0048	0.0009	0.0047	0.0048	217.078	925.5
35	PUST005_CASE_1	1.0079	0.0009	0.0047	0.0048	217.079	866.4
36	PUST005_CASE_2	1.0089	0.0010	0.0047	0.0048	216.910	832.7
37	PUST005_CASE_3	1.0076	0.0011	0.0047	0.0048	216.726	800.7
38	PUST005_CASE_4	1.0099	0.0009	0.0047	0.0048	216.361	734.4
39	PUST005_CASE_5	1.0095	0.0008	0.0047	0.0048	215.902	666.1
40	PUST005_CASE_6	1.0097	0.0010	0.0047	0.0048	215.448	607.9
41	PUST005_CASE_7	1.0069	0.0009	0.0047	0.0048	214.994	557.2
42	PUST005_CASE_8	1.0048	0.0008	0.0047	0.0048	216.897	830.6
43	PUST005_CASE_9	1.0040	0.0010	0.0047	0.0048	216.677	788.9
44	PUST006_CASE_1	1.0056	0.0009	0.0035	0.0036	217.611	1028.2
45	PUST006_CASE_2	1.0078	0.0009	0.0035	0.0036	217.462	986.2
46	PUST006_CASE_3	1.0072	0.0009	0.0035	0.0036	217.147	910.9

No.	Case Name	k_{eff}	σ_{KENO}	σ_{BENCH}	σ_{TOTAL}	AEG	H/Pu
47	PUST007_CASE_2	1.0092	0.0010	0.0047	0.0048	198.875	102.6
48	PUST007_CASE_3	1.0046	0.0010	0.0047	0.0048	199.604	110.11
49	PUST007_CASE_5	1.0089	0.0010	0.0047	0.0048	209.856	253.3
50	PUST007_CASE_6	1.0061	0.0010	0.0047	0.0048	209.694	247.3
51	PUST007_CASE_7	1.0076	0.0010	0.0047	0.0048	209.796	250.5
52	PUST007_CASE_8	1.0011	0.0010	0.0047	0.0048	209.565	246.5
53	PUST007_CASE_9	0.9988	0.0010	0.0047	0.0048	209.627	246.5
54	PUST007_CASE_10	1.0027	0.0011	0.0047	0.0048	210.442	275.5
55	PUST009_CASE_1	1.0197	0.0007	0.0033	0.0034	219.728	2579.3
56	PUST009_CASE_2	1.0245	0.0008	0.0033	0.0034	219.816	2706.5
57	PUST009_CASE_3	1.0240	0.0006	0.0033	0.0034	219.832	2729.8
58	PUST010_CASE_1.11	1.0161	0.0010	0.0048	0.0049	214.116	471.3
59	PUST010_CASE_1.12	1.0130	0.0010	0.0048	0.0049	214.881	527.7
60	PUST010_CASE_1.9	1.0211	0.0010	0.0048	0.0049	210.101	259.3
61	PUST010_CASE_2.11	1.0134	0.0010	0.0048	0.0049	214.879	542.3
62	PUST010_CASE_2.12	1.0139	0.0009	0.0048	0.0049	215.519	600.5
63	PUST010_CASE_2.9	1.0182	0.0009	0.0048	0.0049	212.377	346.8
64	PUST010_CASE_3.11	1.0126	0.0009	0.0048	0.0049	215.027	542.3
65	PUST010_CASE_3.12	1.0200	0.0010	0.0048	0.0049	216.242	707
66	PUST010_CASE_3.9	1.0126	0.0010	0.0048	0.0049	214.301	470.4
67	PUST010_CASE_4.11	1.0064	0.0010	0.0048	0.0049	215.363	588.7
68	PUST010_CASE_4.12	1.0150	0.0009	0.0048	0.0049	216.856	825.1
69	PUST010_CASE_5.11	1.0061	0.0010	0.0048	0.0049	215.735	646.5
70	PUST010_CASE_6.11	1.0176	0.0010	0.0048	0.0049	213.329	402.3
71	PUST010_CASE_7.11	1.0055	0.0010	0.0048	0.0049	214.804	519.8
72	PUST011_CASE_1.16	1.0142	0.0010	0.0052	0.0053	215.821	733
73	PUST011_CASE_1.18	1.0001	0.0009	0.0052	0.0053	217.686	1157.3
74	PUST011_CASE_2.16	1.0199	0.0010	0.0052	0.0053	215.637	705.5
75	PUST011_CASE_2.18	1.0071	0.0009	0.0052	0.0053	217.520	1103.2
76	PUST011_CASE_3.16	1.0214	0.0010	0.0052	0.0053	215.294	662.8
77	PUST011_CASE_3.18	1.0024	0.0009	0.0052	0.0053	217.526	1109.8
78	PUST011_CASE_4.16	1.0131	0.0010	0.0052	0.0053	215.190	653.4
79	PUST011_CASE_4.18	0.9990	0.0009	0.0052	0.0053	217.314	1053.7
80	PUST011_CASE_5.16	1.0109	0.0011	0.0052	0.0053	214.156	550.7
81	PUST011_CASE_5.18	1.0086	0.0009	0.0052	0.0053	217.078	995.4
82	PUST011_CASE_6.18	1.0055	0.0009	0.0052	0.0053	216.477	870.4
83	PUST011_CASE_7.18	1.0066	0.0010	0.0052	0.0053	217.354	1056.4
84	PUST014_CASE_1	1.0077	0.0012	0.0032	0.0034	205.465	210.2
85	PUST014_CASE_3	1.0054	0.0010	0.0032	0.0034	205.499	210.2
86	PUST014_CASE_4	1.0035	0.0011	0.0032	0.0034	205.494	210.2
87	PUST014_CASE_5	1.0065	0.0011	0.0032	0.0034	205.508	210.2
88	PUST014_CASE_6	1.0072	0.0011	0.0032	0.0034	205.514	210.2
89	PUST014_CASE_7	1.0070	0.0010	0.0043	0.0044	205.439	210.2
90	PUST014_CASE_8	1.0063	0.0010	0.0032	0.0034	205.438	210.2
91	PUST014_CASE_9	1.0044	0.0010	0.0032	0.0034	205.480	210.2
92	PUST014_CASE_10	1.0069	0.0011	0.0032	0.0034	205.499	210.2
93	PUST014_CASE_11	1.0054	0.0010	0.0032	0.0034	205.519	210.2

No.	Case Name	k_{eff}	σ_{KENO}	σ_{BENCH}	σ_{TOTAL}	AEG	H/Pu
94	PUST014_CASE_12	1.0057	0.0010	0.0032	0.0034	205.525	210.2
95	PUST014_CASE_13	1.0078	0.0010	0.0043	0.0044	205.424	210.2
96	PUST014_CASE_14	1.0047	0.0010	0.0043	0.0044	205.440	210.2
97	PUST014_CASE_15	1.0069	0.0010	0.0043	0.0044	205.509	210.2
98	PUST014_CASE_16	1.0070	0.0011	0.0043	0.0044	205.533	210.2
99	PUST014_CASE_17	1.0069	0.0010	0.0043	0.0044	205.527	210.2
100	PUST014_CASE_18	1.0080	0.0011	0.0043	0.0044	205.442	210.2
101	PUST014_CASE_19	1.0070	0.0010	0.0043	0.0044	205.456	210.2
102	PUST014_CASE_20	1.0063	0.0010	0.0043	0.0044	205.508	210.2
103	PUST014_CASE_21	1.0065	0.0010	0.0043	0.0044	205.516	210.2
104	PUST014_CASE_22	1.0039	0.0011	0.0043	0.0044	205.533	210.2
105	PUST014_CASE_23	1.0062	0.0011	0.0043	0.0044	205.534	210.2
106	PUST014_CASE_24	1.0080	0.0011	0.0043	0.0044	205.385	210.2
107	PUST014_CASE_25	1.0041	0.0011	0.0043	0.0044	205.430	210.2
108	PUST014_CASE_26	1.0056	0.0010	0.0043	0.0044	205.479	210.2
109	PUST014_CASE_27	1.0041	0.0011	0.0043	0.0044	205.516	210.2
110	PUST014_CASE_28	1.0073	0.0011	0.0043	0.0044	205.524	210.2
111	PUST014_CASE_29	1.0053	0.0011	0.0043	0.0044	205.527	210.2
112	PUST014_CASE_30	1.0073	0.0011	0.0043	0.0044	205.427	210.2
113	PUST014_CASE_31	1.0013	0.0012	0.0043	0.0045	205.417	210.2
114	PUST014_CASE_33	1.0036	0.0010	0.0043	0.0044	205.477	210.2
115	PUST014_CASE_34	1.0049	0.0010	0.0043	0.0044	205.480	210.2
116	PUST015_CASE_1	1.0056	0.0011	0.0038	0.0040	201.235	155.3
117	PUST015_CASE_2	1.0079	0.0010	0.0038	0.0039	201.270	155.3
118	PUST015_CASE_3	1.0064	0.0011	0.0038	0.0040	201.276	155.3
119	PUST015_CASE_4	1.0078	0.0011	0.0038	0.0040	201.307	155.3
120	PUST015_CASE_5	1.0064	0.0010	0.0038	0.0039	201.319	155.3
121	PUST015_CASE_6	1.0090	0.0011	0.0038	0.0040	201.342	155.3
122	PUST015_CASE_7	1.0077	0.0010	0.0047	0.0048	201.232	155.3
123	PUST015_CASE_8	1.0054	0.0011	0.0047	0.0048	201.244	155.3
124	PUST015_CASE_9	1.0057	0.0011	0.0047	0.0048	201.284	155.3
125	PUST015_CASE_10	1.0066	0.0010	0.0047	0.0048	201.338	155.3
126	PUST015_CASE_11	1.0052	0.0011	0.0047	0.0048	201.213	155.3
127	PUST015_CASE_12	1.0026	0.0011	0.0047	0.0048	201.247	155.3
128	PUST015_CASE_13	1.0049	0.0010	0.0047	0.0048	201.292	155.3
129	PUST015_CASE_14	1.0060	0.0012	0.0047	0.0049	201.329	155.3
130	PUST015_CASE_15	1.0085	0.0010	0.0047	0.0048	201.196	155.3
131	PUST015_CASE_16	1.0056	0.0010	0.0047	0.0048	201.233	155.3
132	PUST015_CASE_17	1.0073	0.0010	0.0047	0.0048	201.285	155.3
133	PUST016_CASE_1	1.0056	0.0011	0.0043	0.0044	201.232	155.3
134	PUST016_CASE_2	1.0050	0.0010	0.0043	0.0044	201.259	155.3
135	PUST016_CASE_3	1.0071	0.0010	0.0043	0.0044	201.300	155.3
136	PUST016_CASE_4	1.0068	0.0011	0.0043	0.0044	201.297	155.3
137	PUST016_CASE_5	1.0065	0.0011	0.0038	0.0040	205.458	210.2
138	PUST016_CASE_6	1.0053	0.0011	0.0038	0.0040	205.487	210.2
139	PUST016_CASE_7	1.0064	0.0010	0.0038	0.0039	205.503	210.2
140	PUST016_CASE_8	1.0081	0.0012	0.0038	0.0040	205.531	210.2

No.	Case Name	k_{eff}	σ_{KENO}	σ_{BENCH}	σ_{TOTAL}	AEG	H/Pu
141	PUST016_CASE_9	1.0056	0.0010	0.0033	0.0034	205.610	210.2
142	PUST016_CASE_10	1.0062	0.0011	0.0033	0.0035	205.553	210.2
143	PUST016_CASE_11	1.0060	0.0011	0.0033	0.0035	205.527	210.2
144	PUST017_CASE_1	1.0047	0.0010	0.0038	0.0039	205.532	210.2
145	PUST017_CASE_2	1.0059	0.0011	0.0038	0.0040	205.502	210.2
146	PUST017_CASE_3	1.0064	0.0011	0.0038	0.0040	205.497	210.2
147	PUST017_CASE_4	1.0035	0.0012	0.0038	0.0040	205.497	210.2
148	PUST017_CASE_5	1.0054	0.0011	0.0038	0.0040	205.494	210.2
149	PUST017_CASE_6	1.0073	0.0011	0.0038	0.0040	205.493	210.2
150	PUST017_CASE_7	1.0061	0.0010	0.0038	0.0039	205.494	210.2
151	PUST017 CASE 8	1.0076	0.0011	0.0038	0.0040	205.514	210.2
152	PUST017_CASE_9	1.0028	0.0011	0.0038	0.0040	205.490	210.2
153	PUST017_CASE_10	1.0059	0.0012	0.0038	0.0040	205.496	210.2
154	PUST017_CASE_11	1.0061	0.0011	0.0038	0.0040	205.526	210.2
155	PUST017_CASE_12	1.0063	0.0010	0.0038	0.0039	205.520	210.2
156	PUST017_CASE_13	1.0064	0.0011	0.0038	0.0040	205.495	210.2
157	PUST017_CASE_14	1.0056	0.0012	0.0038	0.0040	205.475	210.2
158	PUST017_CASE_15	1.0066	0.0011	0.0038	0.0040	205.535	210.2
159	PUST017_CASE_16	1.0063	0.0011	0.0038	0.0040	205.496	210.2
160	PUST017_CASE_17	1.0072	0.0011	0.0038	0.0040	205.509	210.2
161	PUST017_CASE_18	1.0056	0.0010	0.0038	0.0039	205.509	210.2
162	PUST020_CASE_1	1.0086	0.0009	0.0059	0.0060	215.478	596.5
163	PUST020 CASE 2	1.0086	0.0010	0.0059	0.0060	215.614	615.6
164	PUST020_CASE_3	1.0063	0.0009	0.0059	0.0060	216.510	743.8
165	PUST020_CASE_5	1.0085	0.0010	0.0059	0.0060	213.989	462.9
166	PUST020_CASE_6	1.0091	0.0011	0.0059	0.0060	213.643	450.5
167	PUST020_CASE_7	1.0024	0.0009	0.0059	0.0060	216.280	722.9
168	PUST020_CASE_8	1.0078	0.0011	0.0059	0.0060	210.643	341.1
169	PUST020_CASE_9	1.0001	0.0010	0.0059	0.0060	214.044	543.2
170	PUST021_CASE_7	1.0107	0.0010	0.0032	0.0034	215.394	662
171	PUST021_CASE_8	1.0034	0.0010	0.0065	0.0066	197.693	125
172	PUST021_CASE_9	1.0111	0.0009	0.0032	0.0033	215.118	634
173	PUST021_CASE_10	1.0114	0.0008	0.0025	0.0026	218.032	1107
174	PUST024_CASE_1	1.0004	0.0009	0.0062	0.0063	191.669	87.5
175	PUST024 CASE 2	1.0010	0.0011	0.0062	0.0063	191.830	87.5
176	PUST024_CASE_3	0.9998	0.0009	0.0062	0.0063	191.900	87.5
177	PUST024_CASE_4	1.0023	0.0010	0.0062	0.0063	192.020	87.5
178	PUST024_CASE_5	0.9990	0.0010	0.0062	0.0063	192.017	87.5
179	PUST024_CASE_6	0.9992	0.0009	0.0077	0.0077	173.510	44.9
180	PUST024_CASE_7	1.0096	0.0010	0.0053	0.0054	201.087	143.9
181	PUST024_CASE_8	1.0073	0.0010	0.0053	0.0054	201.162	143.9
182	PUST024_CASE_9	1.0062	0.0010	0.0053	0.0054	201.192	143.9
183	PUST024 CASE 10	1.0082	0.0010	0.0053	0.0054	201.338	143.9
184	PUST024_CASE_11	1.0064	0.0010	0.0053	0.0054	201.377	143.9
185	PUST024_CASE_12	1.0065	0.0009	0.0053	0.0054	201.435	143.9
186	PUST024_CASE_13	1.0051	0.0009	0.0053	0.0054	201.438	143.9
187	PUST024 CASE 14	1.0021	0.0010	0.0053	0.0054	197.700	115.8

No.	Case Name	k_{eff}	σ_{KENO}	σ_{BENCH}	σ_{TOTAL}	AEG	H/Pu
188	PUST024_CASE_15	1.0008	0.0010	0.0053	0.0054	197.735	115.8
189	PUST024_CASE_16	1.0010	0.0010	0.0053	0.0054	197.813	115.8
190	PUST024_CASE_17	1.0032	0.0011	0.0053	0.0054	197.945	115.8
191	PUST024_CASE_18	1.0079	0.0010	0.0051	0.0052	211.991	367.3
192	PUST024_CASE_19	1.0093	0.0010	0.0051	0.0052	212.024	367.3
193	PUST024_CASE_20	1.0074	0.0010	0.0051	0.0052	212.035	367.3
194	PUST024_CASE_21	1.0100	0.0009	0.0051	0.0052	212.085	367.3
195	PUST024_CASE_22	1.0062	0.0009	0.0051	0.0052	212.110	367.3
196	PUST024_CASE_23	1.0050	0.0010	0.0051	0.0052	212.118	367.3
197	233ST001CASE_1	0.9953	0.0008	0.0031	0.0032	218.369	NA
198	233ST001CASE 2	0.9970	0.0007	0.0033	0.0034	218.181	NA
199	233ST001CASE_3	0.9970	0.0007	0.0033	0.0034	218.001	NA
200	233ST001CASE_4	0.9962	0.0007	0.0033	0.0034	217.823	NA
201	233ST001CASE_5	0.9953	0.0007	0.0033	0.0034	217.647	NA
202	233ST003CASE_40	1.0027	0.0011	0.0087	0.0088	192.739	NA
203	233ST003CASE_41	1.0157	0.0011	0.0151	0.0151	191.259	NA
204	233ST003CASE_42	1.0018	0.0010	0.0087	0.0088	191.871	NA
205	233ST003CASE_45	1.0044	0.0011	0.0126	0.0126	180.273	NA
206	233ST003CASE_55	1.0090	0.0013	0.0122	0.0123	176.193	NA
207	233ST003CASE_57	1.0200	0.0012	0.0087	0.0088	203.986	NA
208	233ST003CASE_58	1.0118	0.0011	0.0087	0.0088	209.418	NA
209	233ST003CASE_61	1.0066	0.0011	0.0087	0.0088	211.700	NA
210	233ST003CASE 62	1.0033	0.0010	0.0087	0.0088	213.014	NA
211	233ST003CASE_65	1.0022	0.0010	0.0087	0.0088	216.508	NA
212	233ST015_CASE_1	0.9908	0.0011	0.0075	0.0076	175.184	NA
213	233ST015_CASE_2	0.9857	0.0011	0.0070	0.0071	173.488	NA
214	233ST015_CASE_3	0.9879	0.0011	0.0068	0.0069	181.085	NA
215	233ST015_CASE_4	0.9879	0.0011	0.0041	0.0042	181.085	NA
216	233ST015_CASE_5	0.9850	0.0012	0.0055	0.0056	172.110	NA
217	233ST015_CASE_6	0.9725	0.0011	0.0099	0.0100	171.621	NA
218	233ST015_CASE_7	0.9833	0.0011	0.0070	0.0071	179.940	NA
219	233ST015_CASE_8	0.9714	0.0011	0.0067	0.0068	171.274	NA
220	233ST015_CASE_9	0.9654	0.0011	0.0050	0.0051	171.006	NA
221	233ST015_CASE_10	0.9848	0.0013	0.0051	0.0053	174.998	NA
222	233ST015 CASE 11	0.9930	0.0012	0.0075	0.0076	181.573	NA
223	233ST015_CASE_12	0.9940	0.0012	0.0069	0.0070	180.251	NA
224	233ST015_CASE_13	0.9886	0.0012	0.0069	0.0070	179.462	NA
225	233ST015_CASE_14	0.9954	0.0011	0.0036	0.0038	187.100	NA
226	233ST015_CASE_15	0.9862	0.0011	0.0060	0.0061	178.849	NA
227	233ST015_CASE_16	0.9854	0.0012	0.0043	0.0045	178.537	NA
228	233ST015_CASE_17	0.9896	0.0013	0.0029	0.0032	186.127	NA
229	233ST015_CASE_18	0.9718	0.0012	0.0056	0.0057	178.030	NA
230	233ST015 CASE 19	0.9694	0.0012	0.0052	0.0053	177.852	NA
231	233ST015_CASE_20	0.9920	0.0011	0.0079	0.0080	193.394	NA
232	233ST015_CASE_21	0.9947	0.0011	0.0070	0.0071	192.209	NA
233	233ST015_CASE_22	0.9924	0.0011	0.0062	0.0063	191.601	NA
234	233ST015 CASE 23	0.9931	0.0011	0.0055	0.0056	191.115	NA

No.	Case Name	k_{eff}	σ_{KENO}	σ_{BENCH}	σ_{TOTAL}	AEG	H/Pu
235	233ST015_CASE_24	0.9870	0.0012	0.0051	0.0052	190.756	NA
236	233ST015_CASE_25	0.9946	0.0010	0.0023	0.0025	196.906	NA
237	233ST015_CASE_26	0.9907	0.0011	0.0066	0.0067	204.058	NA
238	233ST015_CASE_27	0.9956	0.0010	0.0063	0.0064	203.644	NA
239	233ST015_CASE_28	0.9925	0.0010	0.0058	0.0059	203.384	NA
240	233ST015_CASE_29	0.9911	0.0011	0.0051	0.0052	203.169	NA
241	233ST015_CASE_30	0.9900	0.0010	0.0048	0.0049	203.045	NA
242	233ST015_CASE_31	0.9901	0.0011	0.0055	0.0056	202.981	NA

Table 6-27 – Calculation of USL

Benchmark Set	Case	Number of Cases	USL vs. AEG	USL vs. H/Pu
U-233 without Be	197-211	15	0.9273	NA
U-233 with Be	212-242	31	0.9292⁽¹⁾	NA
Pu	1-196	196	0.9394	0.9392
Pu + U-233 with Be	1-196, 212-242	227	0.9377⁽²⁾	NA

(1) Calculated at maximum AEG of the set (204.06). USL increases with AEG such that this is conservative for the AEG of the S300 package calculations (approximately 214 to 218).
(2) Range of applicability is 198.11 ≤ AEG ≤ 219.83

6.9.4.4 Sample Air Transport Model

A sample model is provided for the most reactive case (PBMIXPW for H/Pu = 1000)

```
=csas25
HAC single     H/X=  1000  mass= 210
238groupndf5 infhommedium
pu-239   1  0  7.8223E-05  end
h-poly   1  0  7.8223E-02  end
c     1  0  3.9111E-02  end
bebound  1  0  1.0169E-03  end
bebound  2        1.0   end
ta-181   3  den=16.6 1.0   end
carbonsteel 4        1.0   end
ss304    5        1.0   end
h2o      6        1.0   end
polyethylene      7  1.0   end
end comp
dummy
read param nsk=50 gen=850 end param
read geom
global unit 1
sphere   1 1   11.7314
sphere   7 1   24.1802
sphere   6 1   44.1802
cuboid   0 1   44.1802 -44.1802 44.1802 -44.1802 44.1802 -44.1802
end geom
end data
end
```

7. PACKAGE OPERATIONS

This section describes the procedures used for opening, loading, closing, and unloading the S300 package.

7.1 Package Loading

7.1.1 Preparation for Loading

The S300 package should be loaded in a clean area that is protected from inclement weather. Provisions should be made for personnel protection and ALARA.

After placing the S300 package in position and securing the work area, loosen the drum clamping ring locknut and bolt and remove the drum lid, inner liner lid, and the top spacer and shims, exposing the lid of the pipe component.

Using the lifting ring(s) on the top of the pipe component, lift the pipe component from the S300 package. Alternately, the pipe component may be left inside the S300 package during loading. Remove all twelve of the 7/8-9 UNC lid attachment bolts and remove the pipe component lid. Using the wire bail, remove the shield insert lid. Remove the upper two-inch thick polyethylene shielding plug. Ensure the lower two-inch thick polyethylene shielding plug is in place at the bottom of the shield insert cavity. Inspect all parts for damage and replace or repair as necessary. Ensure that the pipe component O-ring is in good condition.

7.1.2 Loading of Contents

The radioactive contents of the S300 package must be contained inside a SFC before placement into the package. The maximum loading of the SFC shall comply with the limits given in Table 1-2 for surface transport modes or Table 1-3 for air transport. Inspect, load, close, and evaluate the closure of the SFC according to an approved procedure. When complete, lower the SFC into the shield insert cavity. Ensure that no more than one SFC (of any authorized type) is placed within the cavity. Place the upper two-inch thick polyethylene shielding plug on top of the SFC, and replace the shield insert lid. Ensure that the shield insert lid contacts the shield insert body, and that the lid is not supported by the contents.

7.1.3 Preparation for Transport

Optionally coat the pipe component O-ring with a light coat of vacuum grease, and replace the pipe component lid. Using a light coating of an approved thread lubricant, install the twelve 7/8-9 UNC lid attachment bolts hand tight. Optionally, a thread locking compound may be used on the bolt threads. Using a star pattern, tighten the bolts to a torque of 65 ± 5 ft-lb. After completion of the star pattern, check the tightness of each bolt sequentially.

If the pipe component was removed from the S300 package, use the lifting ring(s) to lift the pipe component and replace it into the S300 package. Ensure it is seated properly in the cavity provided. Replace the top spacer and shims, ensuring that the side of the top spacer having the recesses is facing down, and that the top spacer is properly seated over the bolt heads and lift ring(s). Using the inner liner lid, measure the distance between the top spacer (or shim, if present) and the underside of the inner liner lid. If the distance is greater than 1/2 inch, add shims as necessary to achieve a clearance of less than 1/2 inch. Then replace the inner liner lid.

Replace the drum lid and ensure it is seated properly on the drum. Ensure that a locknut is present on the bolt between the two clamping ring lugs. Tighten the drum clamping ring bolt to a final torque of 40 ± 5 ft-lb, tapping around the clamping ring using a soft-headed hammer while tightening the bolt. When fully tight, spin the locknut towards the unthreaded clamping ring lug and tighten. Optionally, if inadequate bolt threads exist to tighten the locknut against the unthreaded lug, the locknut may be tightened against the threaded lug.

Install the tamper indicating wire and seal through the cross-drilled hole in the drum clamping ring bolt. If the S300 is to be shipped by exclusive use, ensure that the package is secured to a pallet or skid at least four inches thick. Determine the surface contamination level of each package per 49 CFR §173.443.[1] Monitor the external radiation level of each package per 49 CFR §173.441. For an exclusive use shipment, the shipper shall provide written instructions to the carrier per 10 CFR §§71.47(c) and (d).

The S300 package is now ready for transport.

7.2 Package Unloading

Upon receipt of the S300 package from the carrier, it may be immediately unloaded or optionally stored indefinitely in a safe and secure manner. Note that, due to the purpose for which the S300 package is intended, unloading of a package is not typically performed. Most S300 packages are stored with the payload intact and not reused, except as payload containers within a certified Type B package.

7.2.1 Opening the Package

The S300 package should be unloaded in a clean area that is protected from inclement weather. Provisions should be made for personnel protection and ALARA. After recording the condition of the tamper indicating device, remove the device.

After placing the S300 package in position and securing the work area, loosen the drum clamping ring bolt and remove the drum lid, inner liner lid, and the top spacer and shims, exposing the lid of the pipe component.

Using the lifting ring(s) on the top of the pipe component, lift the pipe component from the S300 package. Alternately, the pipe component may be left inside the S300 package during unloading. Remove all twelve of the 7/8-9 UNC lid attachment bolts and remove the pipe component lid. Using the wire bail, remove the shield insert lid. Remove the upper two-inch thick polyethylene shielding plug.

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[1] Title 49, Code of Federal Regulations Part 173 (10 CFR 173), *Shippers – General Requirements for Shipments and Packagings*, 01-01-06 Edition.

7.2.2 Removal of Contents

After removal of the two-inch thick upper polyethylene shielding plug, the SFC is exposed. Remove the SFC and place in safe storage.

7.3 Preparation of Empty Package for Transport

If the S300 package is to be transported empty after an initial use, the following procedure shall be employed. Ensure that the SFC has been removed from the shield insert cavity. Place the upper two-inch thick polyethylene shield plug into the cavity, and replace the shield cavity lid. Replace the pipe component lid and thread in the twelve 7/8-9 UNC lid attachment bolts hand tight. Using a star pattern, tighten the bolts to a torque of 65 ± 5 ft-lb. After completion of the star pattern, check the tightness of each bolt sequentially.

If the pipe component was removed from the S300 package, use the lifting ring(s) to lift the pipe component and replace it into the S300 package. Ensure it is seated properly in the cavity provided. Replace the top spacer and shims, ensuring that the side of the top spacer having the recesses is facing down, and that the top spacer is properly seated over the bolt heads and lift ring(s). Replace all of the shims that were removed (if any). Then replace the inner liner lid.

Replace the drum lid and ensure it is seated properly on the drum. Ensure that a locknut is present on the bolt between the two clamping ring lugs. Tighten the drum clamping ring bolt to a final torque of 40 ± 5 ft-lb, tapping around the clamping ring using a soft-headed hammer while tightening the bolt. When fully tight, spin the locknut towards the unthreaded clamping ring lug and tighten. Optionally, if inadequate bolt threads exist to tighten the locknut against the unthreaded lug, the locknut may be tightened against the threaded lug. Finally, remove or render non-visible any shipping labels required to be displayed on loaded packages.

The S300 package is now ready for empty transport or indefinite storage.

8. ACCEPTANCE TESTS AND MAINTENANCE PROGRAM

8.1 Acceptance Tests

8.1.1 Visual Inspections and Measurements

The S300 packaging is subject to the conventional visual inspections and measurements normally incident to fabrication and purchase of components.

8.1.2 Weld Examinations

Pipe component flange and bottom end welds are examined in accordance with the ASME B&PV Code, Section III, Division 1, Subsection NG, Articles NG-5230 and NG-5260, and accepted in accordance with Articles NG-5350 and NG-5360.

8.1.3 Structural and Pressure Tests

No structural or pressure tests are applicable to the S300 package.

8.1.4 Leakage Tests

Because the pipe component is designed only to retain the shielding insert and SFC under NCT, a leakage test is not required.

8.1.5 Component and Material Tests

No acceptance tests are performed on S300 packaging materials or components.

8.1.6 Shielding Tests

Due to the simple design and construction of the shield insert as a right circular cylinder machined from a single billet of HDPE material, no shielding tests are needed for the S300 package.

8.1.7 Thermal Tests

Since the heat generation of the payload is negligible, thermal tests are not applicable to the S300 package.

8.2 Maintenance Program

For purposes of ALARA, the S300 Package is loaded and closed once, then sealed with a tamper-indicating device. The multifunction S300 is used as a transport package, a storage container (if required), and a final disposal container. The S300 may be transported more than once and stored if necessary before final disposal at the Waste Isolation Pilot Plant (WIPP). If it is required to inspect the contents of the S300 or open it for any reason, that activity shall be performed according to the procedures in Section 7.0, *Package Operations*.

To ensure that the S300 is in unimpaired condition, it shall be visually inspected before loading and prior to each transport. The visual inspection shall provide assurance that:

- The drum closure lid is properly installed and the clamping ring is intact and tight.
- The tamper-indicating device is intact.
- The drum has not experienced corrosion to the extent that its structural integrity would be impaired. Note: Loss of paint or surface corrosion that does not impair the structural integrity of the drum is acceptable.
- There are no penetrations through the drum or closure lid (except for the vent filter), there are no gross deformations of the drum or closure lid that could significantly affect structural integrity, and no evidence of water entry into the drum.
- There are no other indications which could prevent the S300 package from meeting the requirements of 10 CFR 71.

If a S300 package fails visual inspection prior to any transport, it shall be removed from service, and repaired and recertified, or replaced as necessary. Any replacement components shall comply with the drawings provided in Appendix 1.3.1, *Packaging General Arrangement Drawings*.

9. QUALITY ASSURANCE

This chapter defines the Quality Assurance (QA) requirements and methods of compliance applicable to the S300 package. The S300 package described in this SAR is identical to the S300 pipe overpack currently used as a payload container within the TRUPACT-II package; and has been used as a qualified DOT 7A Type A transportation package by OSRP for a number of years.

The QA requirements for packaging established by the NRC are described in Subpart H of 10 CFR Part 71 (10 CFR 71). Subpart H is an 18-criteria QA program based on ANSI/ASME NQA-1. Guidance for QA programs for packaging is provided by NRC Regulatory Guide 7.10[1]. The QA requirements of DOE for the use of NRC certified packaging are described in DOE Order 460.1B[2].

The S300 packaging is designed and built for, and used by DOE; and must be approved by the NRC for the shipment of radioactive material in accordance with the applicable provisions of the DOT, described in 49 CFR 173, Subpart I. Procurement, design, fabrication, assembly, testing, maintenance, repair, modification, and use of the S300 package are all done under QA programs that meet all applicable NRC and DOE QA requirements.

The DOE Field Offices for shipping and receiving sites inspect and approve the respective shipper's and receiver's QA programs for equivalency to the NRC's QA program requirements in Subpart H of 10 CFR 71. Non-DOE users of the S300 package may only use it when approved to do so by the NRC.

QA requirements for the S300 package are discussed in the *Contact-Handled Transuranic Waste Authorized Methods for Payload Control* (CH-TRAMPAC). QA programs applicable to procurement, design, fabrication, assembly, testing, use, maintenance, and repair of the TRUPACT-II are also noted in Chapter 9.0 of the TRUPACT-II SAR. The certification and packaging QA requirements are based on the Carlsbad Field Office (CBFO) Quality Assurance Program Document (QAPD) and 10 CFR 71, Subpart H, *Packaging and Transportation of Radioactive Material, Quality Assurance.*

The Central Characterization Project (CCP) was established by the Department of Energy/Carlsbad Field Office (DOE-CBFO) to provide more efficient and cost effective characterization and certification of transuranic (TRU) waste using the resources of multiple corporate and national laboratory entities.

The CCP is the first centralized TRU waste characterization and certification project in the DOE complex. The Waste Isolation Pilot Plant (WIPP) Management and Operations contractor, Washington TRU Solutions, LLC (WTS), manages the project, with technical support from Los Alamos National Laboratory (LANL) and Sandia National Laboratory (SNL). These two primary subcontractors provide operational support for CCP characterization operations in the

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[1] U.S. Nuclear Regulatory Commission, Regulatory Guide 7.10, *Establishing Quality Assurance Programs for Packaging Used in transport of Radioactive Material, Revision 2,* March 2005.

[2] U.S. Department of Energy Order 460.1B, *Packaging and Transportation Safety,* 4-4-03.

field. Collectively, the subcontractors, WTS, LANL, and SNL personnel are all members of the CCP team.

The CCP is tasked with characterizing and certifying all aspects of TRU waste (e.g., Pu/Be sources) for disposal at WIPP. Accordingly, the CCP team must comply with DOE/WIPP 02-3122, *Contact-Handled Transuranic Waste Acceptance Criteria for the Waste Isolation Pilot Plant* (CH-WAC).

The CH-WAC establishes the specific physical, chemical, radiological, and packaging criteria for acceptance of defense TRU waste shipments to WIPP in S300 packages. The CH-WAC also requires that the CCP produce documents, including a certification plan that addresses the applicable requirements and criteria specific to packaging, characterization, certification, and shipping of TRU waste, such as Pu/Be special form sources, to WIPP for disposal.

To accommodate the aforementioned requirement to develop a certification plan, the CCP has produced document CCP-PO-002, *Transuranic Waste Certification Plan* as well as CCP-PO-003, *CCP Transuranic Authorized Methods for Payload Control*. Within these documents reside requirements for effective application of a QA program founded on the CBFO QAPD and 10 CFR 71, Subpart H.

The CCP team implements the Quality Assurance Plan (QAP) established in Section 4.0 of CCP-PO-002. This QAP establishes the overall QA program requirements as well as establishes measures for design, procurement, fabrication, testing, use, inspection, examination, maintenance, repair, modification, handling, storage, shipping, and cleaning. The DOE-CBFO approves the QAP before transuranic material is packaged and transported to the WIPP or other sites.

Compliance methods are documented in DOE-CBFO approved programmatic Transuranic Waste Authorized Methods for Payload Control (TRAMPACs) and/or waste-specific data TRAMPACs. The DOE-CBFO managing and operating contractor performs surveillance of users' payload compliance procedures or data package to ensure the requirements of this CH-TRAMPAC are met. The DOE-CBFO periodically audits users' payload compliance QA programs.

In addition to CCP QA requirements, OSRP must also comply with the extensive Quality Assurance Program (QuAP) at Los Alamos National Laboratory (LANL). The QuAP is the approved institutional description of the overall management system at LANL that provides a level of confidence that both its business management and technical processes are effective and efficient.

The LANL QuAP is issued under the authority of the Laboratory Director and reflects the values of LANL senior management. It is consistent with requirements of the prime contract and LANL Governing Policies on performance, safety, and safeguards and security, and it promotes compliance with federal, state, and local regulations and codes.

This QuAP establishes the LANL quality assurance program requirements for site-wide implementation and is to serve as the basis for LANL quality assurance program acceptability. It is designed such that implementation of the full scope of requirements as stated in DOE Order 414.1, Quality Assurance (current contractual version), constitutes compliance to nuclear safety quality assurance criteria required by 10 CFR 830, Subpart A, *Nuclear Safety Management Quality Assurance Requirements*.

In the interests of ALARA, OSRP recovery team members handle recovered radioactive sources as little as possible. Therefore, when sources are packaged by OSRP at the recovery site for transport, they are actually ready for final disposition at WIPP (or interim storage at LANL if necessary). Since the multi-function S300 must be able to serve as transport packaging, storage container, and disposal container, OSRP is required to comply with all aspects of CCP QA and LANL QA program descriptions whenever packaging Pu/Be sources into an S300 container.

A detailed discussion of the LANL/CCP QA program which governs OSRP packaging operations is presented on the following pages to demonstrate compliance with 10 CFR 71, Subpart H.

9.1 Organization

9.1.1 LANL/Central Characterization Project Organization

The responsibilities for transuranic (TRU) source management of the LANL/CCP are distributed within various organizations. This section identifies the organizations involved and describes the responsibilities of and interactions between these organizations.

9.1.1.1 Central Characterization Project Management

CCP management has overall responsibility for successfully accomplishing activities. Management provides the necessary planning, organization, direction, control, resources, and support to achieve their defined objectives. Management is responsible for planning, performing, assessing, and improving the work.

CCP management is responsible for establishing and implementing policies, plans, and procedures that control the quality of work, consistent with requirements.

CCP QA management responsibilities include:

- Ensuring that adequate technical and QA training is provided for personnel performing activities.
- Ensuring compliance with all applicable regulations, DOE orders and requirements, and applicable federal, state, and local laws.
- Ensuring that personnel adhere to procedures for the generation, identification, control, and protection of QA records.
- Exercising the authority and responsibility to STOP unsatisfactory work such that cost and schedule do not override environmental, safety, or health considerations.
- Developing, implementing, and maintaining plans, policies, and procedures that implement the QAPD.
- Identifying, investigating, reporting, and correcting quality problems.
- Members of the CCP management are responsible for achieving and maintaining quality in their area. Quality achievement is the responsibility of those performing the work.

Quality achievement is verified by persons or organizations not directly responsible for performing the work.

- CCP management empowers employees by delegating authority and decision making to the lowest appropriate level in the organization.
- Figure 9.1-1, *LANL/CCP Organization,* is a functional organization chart pertaining to TRU characterization and certification activities of LANL/CCP. The following subsections identify the organizations that oversee LANL/CCP and describe the roles and responsibilities of key positions charged with implementing the requirements defined in the QA plan.

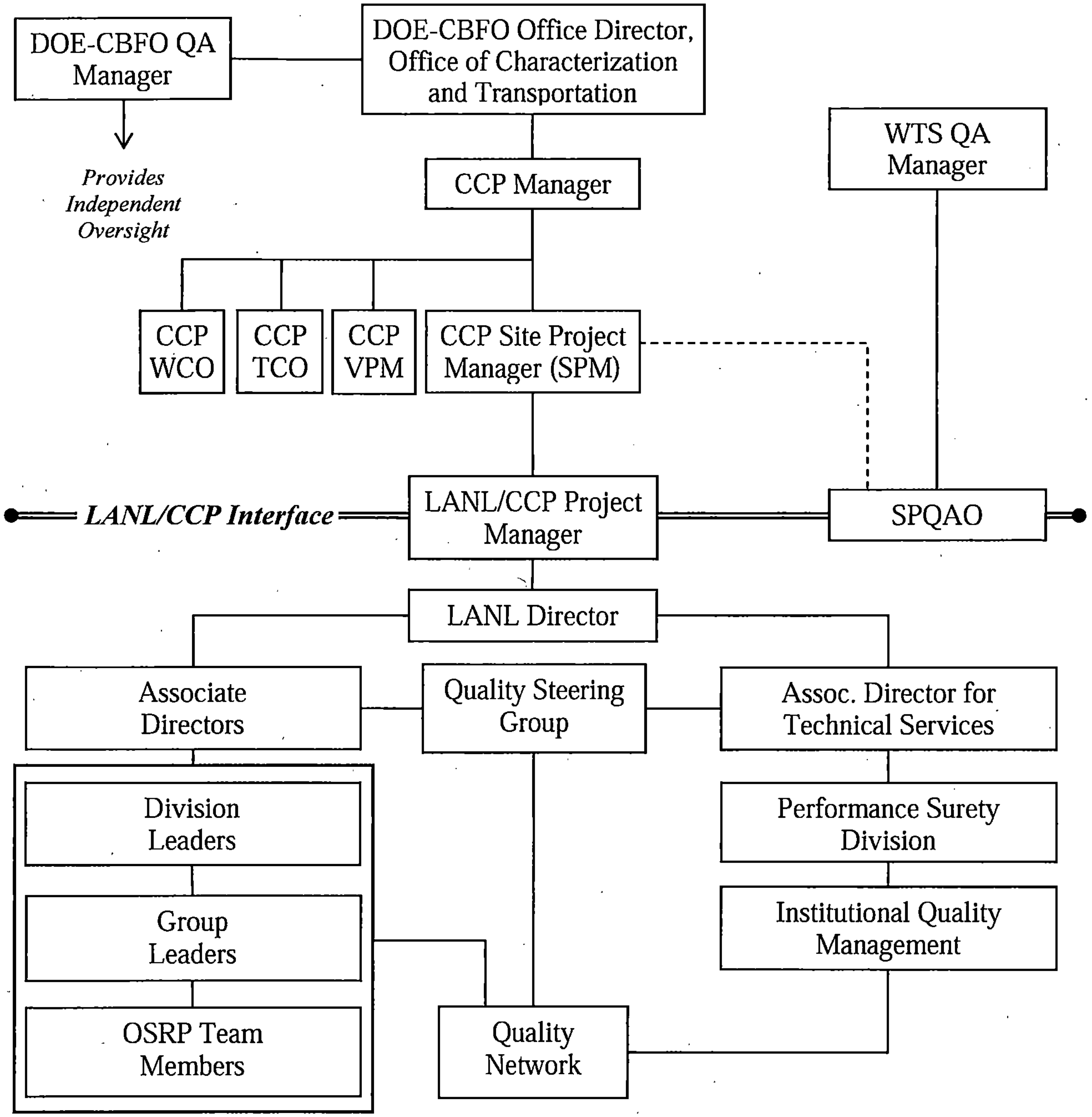

Figure 9.1-1 - LANL/CCP Organization

9.1.1.2 DOE-CBFO Quality Assurance Manager

The DOE-CBFO QA Manager provides independent oversight of QA activities of the CCP.

9.1.1.3 DOE-CBFO Office Director, Office of Characterization and Transportation

The DOE-CBFO Office Director, Office of Characterization and Transportation, provides overall policy direction and oversees CCP characterization and certification activities and approves the QA plan.

9.1.1.4 CCP Manager

The CCP Manager is responsible for the day-to-day management and direction of CCP activities. The CCP Manager is responsible for:

- Ensuring successful CCP/site interface.
- Ensuring CCP plans and operations are coordinated, integrated, and consistent with DOE-CBFO programs, policies, and guidance.
- Coordinating CCP activities and functioning as principal point-of-contact (POC) with DOE-CBFO and other regulating agencies.
- Reviewing and approving the QA plan.

9.1.1.5 CCP Site Project Manager (SPM)

The Site Project Manager (SPM) is the principal POC with DOE [including CBFO and National TRU Program (NTP)] for technical activities associated with TRU. The SPM coordinates with the CCP Waste Certification Official (WCO) and Transportation Certification Official (TCO) and oversees CCP activities to ensure that TRU is characterized and certified compliant with WIPP requirements. Specific responsibilities assigned to the SPM include the following:

- Developing, maintaining, reviewing, approving, and implementing CCP procedures and plans. Development, approval, and implementation of procedures and plans will occur at the earliest time consistent with the schedule for accomplishing the activities.
- Scheduling revisions and distributing CCP procedures and plans and forwarding these documents (if significantly revised) to DOE-CBFO for review and approval before implementation. The term "significantly revised" means non-editorial changes in accordance with the QAPD, Section 1.4.3.
- Ensuring CCP personnel receive appropriate training and are properly qualified, so that suitable proficiency is achieved and maintained.
- Obtaining Acceptable Knowledge (AK) information from waste generators regarding U.S. Environmental Protection Agency (EPA) hazardous waste codes.
- Assigning additional EPA hazardous waste codes to TRU waste based on analytical results, as applicable.
- Reviewing and approving interface documents.
- Waste selection and tracking.

- Halting characterization or certification activities if problems affecting the quality of certification processes or work products exist.
- Validating and verifying characterization data.
- Reconciling verified data with data quality objectives.
- Evaluating and reconciling AK information with characterization data.
- Preparing and submitting SPM Data Validation Summaries, Waste Stream Profile forms, Characterization Information Summaries, Waste Stream Characterization Packages, and QA/Quality Control (QC) reports to DOE-CBFO.

The SPM may delegate any of these activities to another individual; however, the SPM retains ultimate responsibility for ensuring that CCP certification requirements are met.

9.1.1.6 CCP Site Project Quality Assurance Officer (SPQAO)

The SPQAO provides QA oversight and planning for TRU characterization and certification, verifies the implementation of QA requirements, and provides day-to-day guidance on quality-related matters. The SPQAO has the authority to stop CCP work activities if quality is not assured or controlled. The SPQAO has no responsibilities unrelated to the QA Program that would prevent appropriate attention to QA matters. The SPQAO is responsible for verifying the achievement of quality by those performing the work. As shown in Figure 9.1-1, *LANL/CCP Organization*, the CCP SPQAO reports directly to the WTS QA Manager, so that required authority and organizational freedom are provided, including sufficient independence from cost and schedule considerations. The SPQAO's specific responsibilities include:

- Reviewing and approving CCP procedures and plans; including the QA plan.
- Interfacing with WTS QA for activities in CCP-PO-008, *CCP Quality Assurance Interface with WTS QA Program.*
- Coordinating and participating in internal and external audits and assessments to verify compliance.
- Tracking compliance and evaluating trends in compliance with QA objectives.
- Performing assessments of testing, sampling, and analytical facilities.
- Tracking and trending CCP nonconformances and corrective action reports.
- Verifying CCP corrective actions.
- Validating and verifying data at the project level.
- Submitting semi-annual and other QA/QC reports to the SPM and DOE-CBFO.
- Coordinating responses to CCP nonconformance reports (NCRs) generated by DOE-CBFO or other external assessment organizations.
- Reviewing and approving supplier and subcontractor QA Plans.
- Reviewing interface documents.

- Providing guidance to all CCP organizations concerning identification, control, and protection of QA records.
- Comparing Visual Examination (VE) and radiography data, and calculating miscertification rates.
- Stopping work if quality is not assured or controlled.
- Providing day-to-day guidance on quality-related matters.
- Maintaining liaison with participant QA organizations and other affected organizations.
- Developing, establishing, and interpreting QA policy and ensuring effective implementation.
- Interfacing, as appropriate, with the DOE-CBFO staff, participants, and other stakeholders on QA matters.
- Assisting subordinate organizations with quality planning, documentation, quality measurement, and problem identification and resolution.
- Initiating, recommending, or providing solutions to quality problems through designated channels.
- Ensuring that further processing, delivery, installation, or use is controlled until proper disposition of a nonconformance, deficiency, or unsatisfactory condition has occurred.
- Coordinating with responsible management on resolution of differences of opinion involving the definition and implementation of QA Program requirements. If not resolved, progressively elevating the issues to successively higher levels of management as necessary.
- Ensuring that a graded approach is used to exercise control over activities affecting quality to an extent consistent with their importance.
- Interfacing with the CCP WCO and TCO on matters related to waste characterization, certification, and transportation.

The SPQAO may delegate one or more individuals to perform the above functional responsibilities; however, the SPQAO retains ultimate responsibility for ensuring compliance with CCP QA requirements.

9.1.1.7 CCP Waste Certification Official (WCO)

The CCP WCO is responsible for reviewing data and information necessary to document TRU payload containers prepared for shipment to WIPP meet specified criteria. The WCO coordinates activities related to waste certification. Specific duties and responsibilities of the WCO include the following:

- Certifying that packages and shipments meet CH-WAC requirements.
- Interfacing with the CCP SPM, TCO, and SPQAO on matters related to characterization and certification.

- Stopping certification activities if problems affecting the quality of certification processes or work products exist.
- Ensuring that certification data entered into the WIPP Waste Information System (WWIS) are accurate and demonstrate the acceptability of the material for transport to and disposal at the WIPP.
- Reviewing the applicable CCP plans and procedures and any other waste certification-related documents.
- Reviewing the QA plan.
- Preparing responses to deficiency reports.

The WCO may delegate one or more individuals to perform the above responsibilities; however, the WCO retains ultimate responsibility for ensuring compliance with CH-WAC requirements.

9.1.1.8 CCP Transportation Certification Official (TCO)

The CCP TCO documents and certifies that payload containers and assemblies to be transported meet the requirements of CCP-PO-003. Specific responsibilities of the TCO include:

- Reviewing the applicable CCP transportation plans and transportation procedures.
- Interfacing with the CCP SPM, WCO, and SPQAO on matters associated with transportation.
- Reviewing and maintaining CCP-PO-003.
- Ensuring that data used in completion of the transportation documents are accurate and demonstrate that the waste is acceptable for transportation.
- Preparing and signing Payload Container Transportation Certification Documents and Overpack Payload Container Transportation Certification Documents.
- Preparing and signing Payload Assembly Transportation Certification documents.
- Assisting the SPQAO with preparation of responses to deficiency reports in transportation matters.
- Ensuring that the transportation data entered into the WWIS are accurate and demonstrate that waste is acceptable for disposal at WIPP.
- Reviewing interface documents.
- Halting transportation certification activities if problems affecting the certification or work process exist.

9.1.1.9 WTS Quality Assurance Manager

The WTS QA Manager is responsible for specific activities that relate to the CCP scope of work. These include:

- Performing independent assessments of CCP activities, in accordance with the CBFO-approved WTS QA Program and implementing procedures.

- Providing inspection services support for procurement, including source inspections.
- Providing vendor qualification and maintenance of the WTS Qualified Suppliers List for vendors used by CCP.

9.1.1.10 CCP Vendor Project Manager (VPM)

- Monitors the List of Qualified Individuals to confirm that only qualified personnel perform waste characterization activities.
- Ensures that in-process documents and the documents are transmitted to the CCP Site Project Office as soon as practicable per CCP-QP-008, *CCP Records Management*.
- Ensures applicable Material Safety Data Sheets are maintained and available to support operations.
- Notifies the CCP Project Manager of any abnormal events associated with safe operation of CCP characterization activities for reporting purposes.

9.1.1.11 LANL/CCP Project Manager

The LANL/CCP Project Manager is the primary liaison between LANL and CCP for successful implementation of the QA plan. Specific responsibilities include:

- Confirming that characterization activities are conducted at LANL per the Statement of Work requirements, the Interface Document, and the CCP schedule.
- Providing primary oversight responsibility for project safety and compliance for CCP personnel at LANL.
- Providing CCP personnel and equipment to support characterization, certification, and transportation, as required.
- Providing support to the CCP Site Project Manager (SPM).
- Receiving documentation of required LANL site-specific training.
- Providing weekly production reports to the DOE-CBFO and LANL Production Control as required.
- Receiving reports of LANL oversight activities and formally responding, as required.
- Interfacing with DOE-CBFO and DOE/Los Alamos Site Office (LASO) upon request.

9.1.1.12 LANL Director

- Retains the ultimate authority and accountability for the QuAP and its implementation at LANL.
- Ensures that overall institutional vision, values, standards, and management systems that define the QuAP are established and documented in policies and procedures.
- Ensures that resources necessary for effective implementation of the QuAP are provided.

- Fosters an environment that promotes and supports the identification of issues and resolution for continuous quality improvement.
- Appoints the Quality Steering Group Chair to administer the QuAP.
- Approves the QuAP and supports its implementation.

9.1.1.13 LANL Quality Steering Group

- Oversees and guides the development and implementation of the QuAP.
- Endorses the QuAP institutional support documents.
- Reviews and interprets quality documents and policy issues.
- Provides recommendations regarding quality assurance policy issues to support the Quality Steering Group Chair key decisions.

9.1.1.14 LANL Associate Directors

- Account for directorate compliance with quality assurance requirements [e.g., 10 CFR 830, Subpart A, DOE O 414.1 (current contractual version), and DOE/NNSA QC-1].
- Determine and provide resources (e.g., budget, personnel, materials) to accomplish required work activities.
- Serve as the directorate representative on the Quality Steering Group.
- Appoint directorate and/or division representatives to serve on the Quality Network.
- Ensure the flow down and effective implementation and enforcement of quality assurance requirements within their directorates.
- Ensure that applicable quality standards and quality requirements are identified for the work to be performed.
- Develop/approve directorate/division and program quality assurance supplemental documents (where applicable) and QuAP implementation plans within their directorates.
- Ensure that LANL customer and programmatic requirements are integrated into the scopes of work activities (e.g., ISM, Integrated Safeguards and Security Management, Conduct of Operations).
- Foster an environment that promotes identification and comprehensive correction of quality issues that support continuous quality improvement.
- Support the identification and recommendation for policy, process, or procedure changes that improve quality and efficiency within their directorates and/or throughout LANL.
- Perform and provide a summary management assessment report to the Quality Steering Group Chair and Laboratory Director annually that evaluates the adequacy, effectiveness, and implementation of management systems performance within their directorates.

9.1.1.15 LANL Performance Surety Division

- Provides formal operations and oversight for interdivisional and inter-directorate services.
- Develops and implements integrated management systems that document performance indicators, measure performance status through investigations, and regularly report results to LANL senior management (e.g., issues management, authorization basis).

9.1.1.16 LANL Division Leaders/Program, Project, and Office Directors

- Determine quality assurance program requirements based on work scopes and develop and/or approve quality assurance program documents and implementation plans within their divisions/programs/projects/offices.
- Approve quality assurance supplemental documents and implementation plans within their divisions/programs/projects/offices (where applicable).

9.1.1.17 LANL Institutional Quality Management Group

- Provides procedures, processes, tools, and quality training to assist organizations in implementation of the QuAP.
- Serves as a resource to systematically manage potential quality concerns, issues, and problems.
- Provides inspection, quality assurance compliance and performance assessments, and program development support services to LANL.
- Reviews directorate and/or division quality assurance supplemental documents and QuAP implementation plans for compliance with the QuAP requirements.
- Coordinates and chairs the Quality Network and disseminates quality-related information to Quality Network members.
- Independently assesses the QuAP implementation utilizing a risk-based process to determine assessment scope.

9.1.1.18 LANL Quality Network

- Assist in the development and implementation of the QuAP.
- Share quality-related information (e.g., defective items, product recalls) among workers within directorates, divisions, programs, and offices and identifies and helps to resolve multi-organizational quality issues.

9.1.1.19 Members of the LANL Workforce (at all levels)

- Implement their organization's procedures to meet QA requirements.
- Comply with administrative and technical work control requirements.

- Identify and report issues to the responsible manager for resolution and continuous improvement for the work being performed.
- Seek, identify, and recommend work methods or procedural changes that would improve quality and efficiency.

9.2 Quality Assurance Program

9.2.1 General

The CBFO QAPD establishes the QA program requirements for programs, projects, and activities sponsored by the CBFO. CCP-PO-002, *Transuranic Waste Certification Plan*, Section 4.0, *Quality Assurance Plan* describes and implements the CBFO QAPD requirements for LANL/CCP. CCP-PO-002 is based on the CBFO QAPD as it applies to the characterization, certification, and transportation of TRU material and therefore incorporates the applicable requirements from the regulatory and committed QA source documents identified in the CBFO QAPD. Section 4.0 of CCP-PO-002, *Transuranic Waste Certification Plan*, fulfills the requirements for a transportation QA plan as required by 10 CFR 71, Subpart H for the S300 packaging.

The scope of the integrated Quality Assurance Program Requirements for Nuclear Facilities (NQA-1) Program is to ensure that all items and activities that are important to the safe containment of TRU Waste at WIPP comply with program objectives. Applicable criteria are identified in the individual element descriptions contained within the CCP-PO-002, *Transuranic Waste Certification Plan*, Section 4.0.

The LANL/CCP QA program is developed and maintained through an ongoing process that selectively applies QA criteria as appropriate to the function or work activity being performed. Applicable QA criteria consist of the following:

- Title 10 CFR Subpart 71, Packaging and Transportation of Radioactive Material
- Title 10 CFR Part 194, Criteria for the Certification and Re-Certification of Radioactive Material
- Title 10 CFR 830.120, Quality Assurance Requirements
- ASME NQA-1, Quality Assurance Requirements for Nuclear Facility Application
- DOE O 414.1, Quality Assurance
- USDOE DOE-CBFO-94-1012, Quality Assurance Program Document

The LANL/CCP QAP is inclusive of applicable requirements from criteria noted above and addresses the following as applicable for this SAR:

- Organization
- Quality Assurance Program
- Implementation of the QA Program
- Personnel Qualification and Training
- Records
- Work Process
- Procurement
- Inspection and Testing

- Quality Improvement
- Documents
- Management Assessments
- Independent Assessment

Table 9.2-1 depicts how the requirements of 10 CFR 71, Subpart H are addressed within the LANL/CCP QA program.

The CCP Manager is responsible for ensuring implementation of requirements as defined within the QA program as well as the requirements of this SAR including design, procurement, fabrication, inspection, testing, maintenance, and modifications. Procurement documents are to reflect applicable requirements from 10 CFR 71, Subpart H, ASME NQA-1 and the QA program.

LANL and CCP management assesses the adequacy and effectiveness of the QA program to ensure effective implementation inclusive of objective evidence and independent verification, where appropriate, to demonstrate that specific project and regulatory objectives are achieved.

All LANL/CCP personnel and contactors are responsible for effective implementation of the QA program within the scope of their responsibilities. Personnel responsible for inspection and testing are to be qualified, as appropriate, through minimum education and/or experience, formal training, written examination and/or other demonstration of skill and proficiency. Objective evidence of qualifications and capabilities are to be maintained as required. As appropriate, the initial employee training should consist of the following:

- General employee indoctrination
- Program indoctrination
- Radiation/industrial training
- QA program training

Table 9.2-1 - QA Program Requirement Cross-mapping

10 CFR 71 Subpart H Requirement	Title	CCP QA Plan Section	Description	Application to CCP Implementation
1 (71.103)	QA Organization	4.1	Identifies organizations and their relationships in performance of activities affecting quality.	Applicable
2 (71.105)	QA Program	4.1	Describes basic methods for establishing a documented QA program that implements requirements of 10 CFR 71, Subpart H.	Applicable
3 (71.107)	Package Design Control	4.1	Describes design control measures established for structures, systems, and components.	Not Applicable
4 (71.109)	Procurement Document Control	4.7	Describes procedures for ensuring that applicable regulatory requirements, design bases, and other requirements necessary to ensure adequate quality are suitably included or referenced in documents for procurement of material and services.	Applicable
5 (71.111)	Instructions, Procedures, and Drawings	4.5	Describes documentation of instructions, procedures, or drawings to ensure that safety criteria have been met. Also describes QA review and concurrent processes.	Applicable
6 (71.113)	Document Control	4.4	Describes documents to be maintained by the QA program and how those documents may be changed, reviewed, approved, and issued.	Applicable
7 (71.115)	Control of Purchased Material, Equipment, and Services	4.7	Describes procurement planning, sources, bids, evaluations, awards, performance control, verification activities, control of nonconformances, and records.	Applicable

10 CFR 71 Subpart H Requirement	Title	CCP QA Plan Section	Description	Application to CCP Implementation
8 (71.117)	Identification and Control of Materials, Parts, and Components	4.6	Describes procedures to track materials to prevent the use of incorrect or defective items.	Applicable
9 (71.119)	Control of Special Processes	4.6	Describes procedures to monitor special processes such as welding, radiography, and heat-treating.	Applicable
10 (71.121)	Internal Inspection	4.8	Describes the planning and use of inspection procedures, instructions, and checklists.	Applicable
11 (71.123)	Test Control	4.8	Describes requirements and procedures for testing materials in accordance with original design and testing requirements. Also ensures that the test results are documented and evaluated by qualified individuals.	Applicable
12 (71.125)	Control of Measuring and Test Equipment	4.8	Describes procedures for ensuring that measuring and test equipment is properly calibrated and appropriate actions should the equipment be out of calibration.	Applicable
13 (71.127)	Handling, Storage, and Shipping Control	4.8	Describes procedures for ensuring that containers and packaging are preserved, prepared, released, and delivered in good condition.	Applicable
14 (71.129)	Inspection, Test, and Operating Status	4.8	Describes methods for the identification of the inspection, test, and operating status of items including the application/removal of tags, markings, or stamps.	Applicable
15 (71-131)	Inspection, Test, and Nonconforming Materials, Parts, or Components	4.7	Describes the identification, segregation, disposition, and evaluation of items that do not conform to design and construction criteria.	Applicable

10 CFR 71 Subpart H Requirement	Title	CCP QA Plan Section	Description	Application to CCP Implementation
16 (71-133)	Corrective Action	4.7	Described procedures for identifying, reporting, and obtaining corrective actions from suppliers for defective material.	Applicable
17 (71-135)	Quality Assurance Records	4.5	Describes the establishment of quality assurance records, content, indexing and classification, and appropriate methods for storage, preservation, and safekeeping.	Applicable
18 (71.137)	Audits	4.9	Describes internal and external audit programs applicable to both in-house and major suppliers.	Applicable

9.2.2 S300-Specific Program

The S300 was designed and tested as described in Chapter 2, *Structural Evaluation,* of this SAR. QA requirements are invoked in the design, procurement, fabrication, assembly, testing, maintenance, and use of the packaging to ensure established standards are maintained. Items and activities to be controlled and documented are described in this chapter.

9.2.3 QA Levels

Materials and components of the S300 are designed, procured, fabricated, assembled, and tested using a graded approach under a 10 CFR 71, Subpart H equivalent QA Program. Under that program, the categories critical to safety are established for all S300 packaging components. These defined quality categories consider the impact to safety if the component were to fail or perform outside design parameters.

Graded Quality Category A Items:

These items and services are critical to safe operation and include structures, components, and systems whose failure could directly result in a condition adversely affecting public health and safety. The failure of a single item could cause loss of primary containment leading to a release of radioactive material beyond regulatory requirements, loss of shielding beyond regulatory requirements, or unsafe geometry compromising criticality control.

Graded Quality Category B Items:

These items and services have a major impact on safety and include structures, components, and systems whose failure or malfunction could indirectly result in a condition adversely affecting public health and safety. The failure of a Category B item, in conjunction with the failure of an additional item, could result in an unsafe condition.

Graded Quality Category C Items:

These items and services have a minor impact on safety and include structures, components, and systems whose failure or malfunction would not significantly reduce the packaging effectiveness and would not be likely to create a situation adversely affecting public health and safety.

The CCP QAPD graded assessment results for the S300 are shown in Table 9.2-2. Table 9.2-3 identifies the level of effort for package activities appropriate for each quality category element.

Table 9.2-2 - QA Categories for Design and Procurement of S300 Subcomponents

Component	Subcomponent	Category
Shells and Heads	Pipe Flange	A
	Cylindrical Shell	A
	Pipe End Cap	A
Vessel Closure	Lid	A
	Closure Bolts	A
Seals	Containment O-Ring Seal	A
Pressure Relief Devices	Filter Vent	A
Neutron Shielding	Shield Insert Body	B
	Shield Insert Lid	B
Drum	55-Gallon Drum and Lid	B
Dunnage	Fiber board	B
	Plywood	B
Lifting Devices	Lifting Device	B
Package Hardware	Outer Rigid Polyethylene Drum Liner	C
Pressure Relief Devices	Drum Filter Vent	A
Miscellaneous	Weld Filler Metal	A
	Thread Locking Compound (optional)	C
	Vacuum Grease (optional)	C

Table 9.2-3 - Level of Quality Assurance Effort per QA Element

QA Element	Level of QA Effort	QA Category		
		A	B	C
1	QA Organization			
	• Organizational structure and authorities defined	X	X	X
	• Responsibilities defined	X	X	X
	• Reporting levels established	X	X	X
	• Management endorsement	X	X	X
2	QA Program			
	• Implementing procedures in place	X	X	
	• Trained personnel	X	X	
	• Activities controlled	X	X	
3	Design			
	• Control of design process and inputs	X	X	X
	• Control of design input	X	X	X
	• Software validated and verified	X	X	X
	• Design verification controlled	X	X	X
	• Quality category assessment performed	X	X	X
	• Definition of commercial or generic item (off-the-shelf) not related to A or B component			X
4	Procurement Document control			
	• Complete traceability	X	X	
	• Qualified suppliers list	X	X	
	• Commercial grade dedicated items acceptable	X	X	
	• Off-the-shelf item			X
5	Instructions, Procedures, and Drawings			
	• Must be written and controlled	X	X	
	• Qualitative or quantitative acceptance criteria	X	X	
6	Document Control			
	• Controlled issuance	X	X	
	• Controlled changes	X	X	
	• Procurement documents	X	X	X

QA Element	Level of QA Effort	QA Category A	QA Category B	QA Category C
7	Control of Purchased Material, Equipment, and Services			
	• Source evaluation and selection plans	X	X	
	• Evidence of QA at supplier	X	X	
	• Inspections at supplier, as applicable	X	X	
	• Receiving inspection	X	X	
	• Objective proof that all specifications are met	X	X	
	• Audits/surveillances at supplier facility, as applicable	X	X	
	• Incoming inspection for damage only			X
8	Identification and Control of Material, Parts, and Components			
	• Positive identification and traceability of each item	X	X	
	• Identification and traceable to heats, lots, or other groupings	X	X	
	• Identification to end use drawings, etc.			X
9	Control of Special Processes			
	• All welding, heat treating, and nondestructive testing done by qualified personnel	X	X	
	• Qualification records and training of personnel	X	X	
	• No special processes			X
10	Inspection			
	• Documented inspection to all specifications required	X	X	
	• Examination, measurement, or test of material or processed product to assure quality	X	X	
	• Process monitoring if quality requires it	X	X	
	• Inspectors must be independent of those performing operations	X	X	X
	• Qualified inspectors only	X	X	X
	• Receiving inspection	X	X	X
11	Test Control			
	• Written test program	X	X	
	• Written test procedures for requirements in the package approval	X	X	
	• Documentation of all testing and evaluation	X	X	
	• Representative of buyer observes all supplier acceptance tests if specified in procurement documents	X		
	• No physical tests required			X

QA Element	Level of QA Effort	QA Category		
		A	B	C
12	Control of Measuring and Test Equipment			
	• Tools, gauges, and instruments to be in a formal calibration program	X	X	
	• Only qualified inspectors	X	X	
	• No test required			X
13	Handling, Storage, and Shipping			
	• Written plans and procedures required	X	X	
	• Routine handling			X
14	Inspection, Test, and Operating Status			
	• Individual items identified as to status or condition	X	X	
	• Stamps, tags, labels, etc., must clearly show status	X	X	X
	• Visual examination only			X
15	Nonconforming Materials, Parts, or Components			
	• Written program to prevent inadvertent use	X	X	X
	• Nonconformance to be documented and closed	X	X	X
	• Disposal without records			X
16	Corrective Action			
	• Objective evidence of closure for conditions adverse to quality	X	X	X
17	QA Records			
	• Design and use records	X	X	
	• Results of reviews, inspections, test, audits, surveillance, and materials analysis	X	X	
	• Personnel qualifications	X	X	
	• Records of fabrication, acceptance, and maintenance retained throughout the life of package	X	X	X
	• Record of package use kept for three years after shipment	X	X	
	• All records managed by written plans for retention and disposal	X	X	
	• Procurement records	X	X	X
18	Audits			
	• Written plan of periodic audits	X	X	X
	• Lead auditor certified	X	X	

Upon custodianship of the S300 packages by LANL, functional classifications will be used for site operations and activities related to the S300. The method of classification is documented as follows.

The package-specific safety documents identify systems, structures, and components (SSCs) that are important to the safety functions for transportation. As appropriate, the hazard analysis and accident scenarios in the safety basis documents help identify SSCs that must function in order to prevent or mitigate these events. These SSCs are then identified using the classification system found in the NRC QA Category system provided in NRC Regulatory Guide (RG) 7.10. The categories as defined in RG 7.10, and listed below, are analogous to Safety Class, Safety Significant, and General Service that are identified for facility SSCs.

> **Quality Category A:**
>
> Critical impact on safety and associated functional requirements – items or components whose single failure or malfunction could directly result in an unacceptable condition of containment, shielding, or nuclear criticality control. This is functionally equivalent to "safety class" designation used for nuclear facility safety.
>
> **Quality Category B**:
>
> Impact on safety and associated functional requirement – components whose failure or malfunction in conjunction with one other independent failure or malfunction could result in an unacceptable condition of containment, shielding, or nuclear criticality control. This is functionally equivalent to "safety significant" designation used for nuclear facility safety.
>
> **Quality Category C:**
>
> Minor impact on safety and associated functional requirements – components whose failure or malfunction would not result in an unacceptable condition of containment, shielding, or nuclear criticality control regardless of other single failures. This is functionally equivalent to designations given to components that do not meet "safety class or safety significant" criteria used for nuclear facility safety.

The CCP shall assign a Design Authority (DA) who shall identify critical characteristics when they identify design attributes necessary to preserve the safety support function. As necessary, the DA also ensures critical characteristics are included in this SAR by the identification of SSCs and their QA Category designations. Additionally, this SAR shall include the safety function, design, and operational attributes necessary for reliable performance. The DA applies design criteria to the design, operation, and maintenance of each critical SSC including recommended codes and standards, as required by RG 7.10. QA requirements shall be applied as necessary to assure the SSCs can perform their function.

9.3 Package Design Control

As required by CCP-PO-002, *Transuranic Waste Certification Plan*, design processes shall be established and implemented to satisfy the requirements of CCP-PO-002, Section 4.0. These requirements are to be in accordance with:

- 10 CFR 830.122(f), *Criterion 6 – Performance/Design*[1]
- DOE Order 414C, CRD, Attachment 1, 2.b.(2), *Criterion 6 – Design*

Requirements are implemented to ensure processes and procedures are in place to ensure design features of packaging systems are appropriately translated into specifications, drawings, procedures, and instructions. Design control measures are established for criticality, shielding, thermal, and structural analyses under both normal and accident condition analyses as defined in DOT and NRC regulations.

The LANL/CCP will be responsible for maintaining the package and this SAR. The design documents (e.g., drawings and specifications) are controlled by incorporation into this SAR, which will be reviewed and approved by the U.S. Department of Energy – Packaging Certification Office and the NRC.

The design of the S300 will be performed under an NRC-approved QA Program as required by CCP, but is not applicable to this QA plan. Design inputs will consist of a CCP statement of work, applicable DOE orders, national standards, specifications, and drawings.

Procedures are established to control design activities to ensure that the following occur:

- Design activities will be planned, controlled, and documented.
- Regulatory requirements, design requirements, and appropriate quality standards will be correctly translated into specifications, drawings, and procedures.
- Competent engineering personnel, independent of design activities, perform design verification. Verification may include design reviews, alternate calculations, or qualification testing. Qualification tests are conducted in accordance with approved test programs or procedures.
- Design interface controls will be established and adequate.
- Design, specification, and procedure changes will be reviewed and approved in the same manner as the original issue. In a case where a proposed design change potentially affects licensed conditions, the Quality Assurance Program shall provide for ensuring that licensing considerations have been reviewed and are complied with or otherwise reconciled by amending the license.
- Design errors and deficiencies will be documented, corrected and corrective action to prevent recurrence is taken.
- Design organization(s) and their responsibilities and authorities will be delineated and controlled through written procedures.

Materials, parts, equipment, and processes essential to the function of items that are important to safety will be selected and reviewed for suitability of application.

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[1] DOE, Code of Federal Regulations, 10 CFR 830.122, *Quality Assurance Criteria*, U.S. Department of Energy, Washington, D.C., 2006.

Computer programs used for design analysis or verification will be controlled in accordance with approved procedures. These procedures will provide for verification of the accuracy of computer results and for the assessment and resolution of reported computer program errors.

9.4 Procurement Document Control

As required by the CCP-PO-002, *Transuranic Waste Certification Plan*, procurement/acquisition processes and related document control activities shall be established and implemented to satisfy the requirements of CCP-PO-002, Section 4.0. These requirements are to be in accordance with:

- 10 CFR 830.122(d), Criterion 4 – Management/Documents and Records
- 10 CFR 830.122(g), Criterion 7 – Performance/Procurement
- DOE Order 414C, CRD, Attachment 1, 2.a.(4), Criterion 4 – Documents and Records
- DOE Order 414C, CRD, Attachment 1, 2.b.(3), Criterion 7 – Procurement

Requirements are implemented to ensure processes and procedures are in place to ensure appropriate levels of quality are achieved in the procurement of material, equipment, and services. Quality Level and Quality Category designations assigned by the Design Authority are used to grade the application of QA requirements of procurements based on radiological material at risk, mission importance, safety of workers, public, environment, and equipment, and other differentiating criteria. Implementing procedures will provide the logic process for determining Quality Levels used in procurement of equipment and subcontracting of services. Procedures shall be in place to ensure processes address document preparation and document control, and management of records meeting regulatory requirements. Procurement records must be kept in a manner that satisfies regulatory requirements.

LANL/CCP will be responsible for initiating procurement actions for packaging and spare parts from a supplier with a 10 CFR 71, Subpart H QA Program.

Implementing procedures shall ensure that procurement documents are prepared to clearly define applicable technical and quality assurance requirements including codes, standards, regulatory requirements and commitments, and contractual requirements. These documents serve as the principal documents for the procurement of structures, systems and components, and related services for use in the design, fabrication, maintenance and operation, inspection and testing of storage and/or transportation systems. Procedures shall ensure that purchased material, components, equipment, and services adhere to the applicable requirements. Furthermore:

- The assignment of quality requirements through procurement documents is administered and controlled.
- Procurement activities are performed in accordance with approved procedures delineating requirements for preparation, review, approval, and control of procurement documents. Revisions to procurement documents are reviewed and approved by the same cognizant groups as the original document.
- Quality requirements are included in quality-related purchase orders as applicable to the scope of the procurement referencing 10 CFR 71, Subpart H or other codes and standards, as appropriate.

- LANL/CCP procurement documents will require suppliers to convey appropriate quality assurance program requirements to sub-tier suppliers.
- LANL/CCP procurement documents will include provisions that suppliers either maintain or supply those QA records which provide evidence of conformance to the procurement documents. Additionally, procurement documents shall designate the supplier documents required for submittal to LANL/CCP for review and/or approval.
- LANL/CCP shall maintain the right of access to supplier facilities and performance of source surveillance and/or audit activities, as applicable. A statement to this effect is to be included in procurement documents.

Procurement documents shall also address the applicability of the provisions of 10 CFR 21 for the Reporting of Defects and Noncompliances.

9.5 Instructions, Procedures, And Drawings

As required by the CCP-PO-002, *Transuranic Waste Certification Plan,* instructions, procedures, and drawing work processes and applicable quality improvement activities shall be established and implemented to satisfy the requirements of Section 4.0. These requirements are to be in accordance with:

- 10 CFR 830.122(c), Criterion 3 – Management/Quality Improvement
- 10 CFR 830.122(e), Criterion 5 – Performance/Work Processes
- DOE Order 414C, CRD, Attachment 1, 2.a.(3), Criterion 3 – Quality Improvement
- DOE Order 414C, CRD, Attachment 1, 2.b.(1), Criterion 5 – Work Processes

Requirements are implemented to ensure processes and procedures are in place that achieve quality objectives and ensure appropriate levels of quality and safety are applied to critical components of packaging and transportation systems utilizing a graded approach. The program shall ensure processes and procedures in place to identify and correct problems associated with transportation and packaging activities.

Implementing procedures shall be established to ensure that methods for complying with each of the applicable criteria of 10 CFR 71, Subpart H; 10 CFR 72, Subpart G; 10 CFR 50, Appendix B, or ASME Section III, as applicable, for activities affecting quality during design, fabrication, inspection, testing, use and maintenance are specified in instructions, procedures, and/or drawings. In addition:

- Instructions, procedures, and drawings shall be developed, reviewed, approved, utilized, and controlled in accordance with the requirements of approved procedures. These instructions, procedures, and drawings shall include appropriate quantitative and qualitative acceptance criteria.
- Changes to instructions, procedures and drawings, are developed, reviewed, approved, utilized and controlled using the same requirements and controls as applied to the original documents.
- Compliance with these approved instructions, procedures and drawings is mandatory for LANL/CCP personnel while performing activities affecting quality.

Specific activities by LANL/CCP regarding preparation of packaging for use, repair, rework, maintenance, loading contents, unloading contents, and transport, must be accomplished in accordance with written and approved instructions, procedures, specifications, and/or drawings. These documents must identify appropriate inspection and hold points and emphasize those characteristics that are important to safety and quality. Transportation package procedures are to be developed and reviewed by technical and quality staff and shall be approved by appropriate levels of management.

9.5.1 Preparation and Use

Activities concerning loading and shipping are performed in accordance with written operating procedures developed by the user and approved by the package custodian. Packaging first-time usage tests, sequential loading and unloading operations, technical constraints, acceptance limits, and references are specified in the procedures. A pre-planned and documented inspection will be conducted to ensure that each loaded package is ready for delivery to the carrier.

9.5.2 Operating Procedure Changes

Changes in operating procedures that affect the process must be approved at the same supervisory level as the initial issue.

9.5.3 Drawings

Controlled drawings are shown in Appendix 1.3.1, *Packaging General Arrangement Drawings*, of this SAR. Implementation of design revisions is discussed in SAR Section 9.3, *Package Design Control*.

9.6 Document Control

As required by the CCP-PO-002, *Transuranic Waste Certification Plan*, document control activities shall be established and implemented to satisfy the requirements of Section 4.0. These requirements are to be in accordance with:

- 10 CFR 830.122(d), Criterion 4 – Management/Documents and Records
- DOE Order 414C, CRD, Attachment 1, 2.a.(4), Criterion 4 – Documents and Records

Requirements are implemented to ensure processes and procedures are in place to address document, document control, and for the management of records. Records (engineering, test reports, user instructions, etc.) must be maintained in a manner that conforms to regulatory requirements.

Document control activities related to the design, procurement, fabrication, and testing of S300 components; and SAR preparation shall be controlled.

Implementing procedures shall be established to control the issuance of documents that prescribe activities affecting quality and to assure adequate review, approval, release, distribution, use of documents and their revisions. Controlled documents may include, but are not limited to:

- Design specifications

- Design and fabrication drawings
- Special process specifications and procedures
- QA Program Manuals/Plans, etc.
- Implementing procedures
- Test procedures
- Operational test procedures and data.

Requirements shall ensure changes to documents, which prescribe activities affecting quality, are reviewed and approved by the same organization that performed the initial review and approval, or by qualified responsible organizations. Documents that prescribe activities affecting quality are to be reviewed and approved for technical adequacy and inclusion of appropriate quality requirements prior to approval and issuance. Measures are taken to ensure that only current documents are available at the locations where activities affecting quality are performed prior to commencing the work.

Package users are responsible for establishment, development, review, approval, distribution, revision, and retention of their documents. Documents requiring control, the level of control, and the personnel responsibilities and training requirements are to be identified.

Packaging documents to be controlled include as a minimum:

- Operating procedures
- Maintenance procedures
- Inspection and test procedures
- Loading and unloading procedures
- Preparation for transport procedures
- Repair procedures
- Specifications
- Fabrication records
- Drawings of packaging and components
- SAR and occurring supplements

Revisions are handled in a like manner as the original issue. Only the latest revisions must be available for use.

Documentation received from the supplier for each package must be filed by package serial number. These documents are to be retained in the user's facility.

9.7 Control Of Purchased Material, Equipment And Services

As required by the CCP-PO-002, *Transuranic Waste Certification Plan*, the control of purchased material, equipment and services and applicable quality improvement activities shall be established and implemented to satisfy the requirements of Section 4.0. These requirements are to be in accordance with:

- 10 CFR 830.122(c), Criterion 3 – Management/Quality Improvement
- 10 CFR 830.122(g), Criterion 7 – Performance/Procurement
- 10 CFR 830.122(h), Criterion 8 – Performance/Inspection and Acceptance Testing
- DOE Order 414C, CRD, Attachment 1, 2.b.(3), Criterion 3 – Quality Improvement
- DOE Order 414C, CRD, Attachment 1, 2.b.(3), Criterion 7 – Procurement
- DOE Order 414C, CRD, Attachment 1, 2.b.(4), Criterion 8 – Inspection and Acceptance Testing

Requirements are implemented to ensure processes and procedures are in place to ensure appropriate inspections and tests are applied prior to acceptance or use of the packaging or component, and to identify the status of packaging items, components, etc. Requirements shall ensure processes and procedures are in place such that appropriate levels of quality are achieved in the procurement of material, equipment, and services. Quality Level and Quality Category designations by the Design Authority are used to grade the application of QA requirements of procurements based on radiological material at risk, mission importance, safety of workers, public, environment, and equipment, and other differentiating criteria. Requirements shall ensure processes and procedures in place to identify and correct problems associated with transportation and packaging activities.

Activities related to the control of purchased material, equipment and services shall be controlled. Control of purchased material, equipment, and services consist of the following elements:

- Implementing procedures shall be established to assure that purchased material, equipment and services conform to procurement documents.
- Procurement documents shall be reviewed and approved by authorized personnel for acceptability of proposed suppliers based on the quality requirements of the item/activity being purchased.
- As required, audits and/or surveys are conducted to determine supplier acceptability. These audits/surveys are based on one or all of the following criteria: the supplier's capability to comply with the requirements of 10 CFR 71, Subpart H; 10 CFR 50, Appendix B, or ASME Section III that are applicable to the scope of work to be performed; a review of previous records to establish the past performance of the supplier; and/or a survey of the supplier's facilities and review of the supplier's QA Program to assess adequacy and verify implementation of quality controls consistent with the requirements being invoked.

- Qualified personnel shall conduct audits and surveys. Audit/survey results are to be documented and retained as Quality Assurance Records. Suppliers are re-audited and/or re-evaluated at planned intervals to verify that they continue to comply with quality requirements and to assess the continued effectiveness of their QA Program. Additionally, interim periodic evaluations are to be performed of supplier quality activities to verify implementation of their QA Program.
- Suppliers are required to provide objective evidence that items or services provided meet the requirements specified in procurement documents. Items are properly identified to appropriate records that are available to permit verification of conformance with procurement documents. Any procurement requirements not met by suppliers shall be reported to LANL/CCP for assessment of the condition. These conditions are reviewed by technical and quality personnel to assure that they have not compromised the quality or service of the item.
- Periodic surveillance of supplier in-process activities is performed as necessary, to verify supplier compliance with the procurement documents. When deemed necessary, the need for surveillance is noted in approved quality or project planning documents. Surveillances are to be performed and documented in accordance with approved procedures. Personnel performing surveillance of supplier activities are to be trained and qualified in accordance with approved procedures.
- Quality planning for the performance of source surveillance, test, shipping and/or receiving inspection activities to verify compliance with approved design and licensing requirements, applicable 10 CFR 71, 10 CFR 50 criteria, procurement document requirements, or contract specifications is to be performed in accordance with approved procedures.
- For commercial "off-the-shelf" items, where specific quality controls appropriate for nuclear applications cannot be imposed in a practical manner, additional quality verification shall be performed to the extent necessary to verify the acceptability and conformance of an item to procurement document requirements. When dedication of a commercial grade item is required for use in a quality-related application, such dedication shall be performed in accordance with approved procedures.

To ensure compliance with procurement requirements, control measures shall include verification of supplier capability and verification of item or service quality. Procurements of S300 components are required to be placed with pre-qualified and selected vendors. The vendor's QA Plan must address the requirements of 10 CFR 71, Subpart H and defined requirements. A graded approach is used based on the QA Levels established in Table 9.2-2.

The approach used to control the procurement of items and services must include the following:

- Source evaluation and selection
- Evaluation of objective evidence of quality furnished by the supplier
- Source inspection
- Audit
- Examination of items or services upon delivery or completion.

9.8 Identification And Control Of Material, Parts And Components

As required by the CCP-PO-002, *Transuranic Waste Certification Plan*, activities concerning the identification and control of material, parts, and components shall be established and implemented to satisfy the requirements of Section 4.0. These requirements are to be in accordance with:

- 10 CFR 830.122(e), Criterion 5 – Performance/Work Processes
- 10 CFR 830.122(g), Criterion 7 – Performance/Procurement
- 10 CFR 830.122(h), Criterion 8 – Performance/Inspection and Acceptance Testing
- DOE Order 414C, CRD, Attachment 1, 2.b.(1), Criterion 5 – Work Processes
- DOE Order 414C, CRD, Attachment 1, 2.b.(3), Criterion 7 – Procurement
- DOE Order 414C, CRD, Attachment 1, 2.b.(4), Criterion 8 – Inspection and Acceptance Testing

Requirements are implemented to ensure processes and procedures are in place that achieve quality objectives and ensure appropriate levels of quality and safety are applied to critical components of packaging and transportation systems utilizing a graded approach. The program also ensures processes and procedures are in place such that appropriate inspections and tests are applied prior to acceptance or use of the packaging or component, and to identify the status of packaging items, and components. The program shall ensure processes and procedures are in place to ensure appropriate levels of quality are achieved in the procurement of material, equipment, and services.

Activities related to the identification and control of material, parts and components shall be controlled. The requirements for identification and control of material, parts, and components consist of the following elements:

- Implementing procedures are established to identify and control materials, parts, and components. These procedures assure identification of items by appropriate means during fabrication, installation, and use of the items and prevent the inadvertent use of incorrect or defective items.
- Requirements for identification are established during the preparation of procedures and specifications.
- Methods and location of identification are selected to not adversely affect the quality of the item(s) being identified.
- Items having limited shelf or operating life are controlled to prevent their inappropriate use.

Control and identification must be maintained either directly on the item or within documents traceable to the item to ensure that only correct and acceptable items are used. When physical identification is not practical, other appropriate means of control must be established such as bagging, physical separation, or procedural control. Each packaging unit shall be assigned a unique serial number after fabrication or purchase. All documentation associated with subsequent storage, use, maintenance, inspection, acceptance, etc., must refer to the assigned serial number. Verification of acceptance status is required prior to use. Items that are not acceptable must be controlled accordingly. Control of nonconforming items is addressed in SAR Section 9.15, *Nonconforming Parts, Materials, or Components.*

Each S300 package will be conspicuously and durably marked with information identifying the package owner, model number, unique serial number, and package gross weight, in accordance with 10 CFR 71.85(c).

Replacement parts must be identified to ensure correct application. Minute items must be individually packaged and marked with material certification, size, cure date, and shelf life, as appropriate. Replacement bolts must be source traceable, certified, marked to reflect their American Society for Testing and Materials (ASTM) or ASME designation, and segregated from other materials and fasteners to prevent misuse or installation of unacceptable bolts. Items that have limited calendar-life cycles, operating-life cycles, or shelf life must be controlled to preclude the use of expired items. Processes shall be in place to replace aging items before failure or expiration.

Assessment of the S300 packaging parts according to safety significance is shown in Table 9.2-2.

9.9 Control Of Special Processes

As required by the CCP-PO-002, *Transuranic Waste Certification Plan,* activities for the control of special processes shall be established and implemented to satisfy the requirements of Section 4.0. These requirements are to be in accordance with:

- 10 CRF 830.122(b), Criterion 2 – Management/Personnel Training and Qualifications
- 10 CFR 830.122(e), Criterion 5 – Performance/Work Processes
- 10 CFR 830.122(g), Criterion 7 – Performance/Procurement
- DOE Order 414C, CRD, Attachment 1, 2.a.(2), Criterion 2 - Personnel Training and Qualifications
- DOE Order 414C, CRD, Attachment 1, 2.b.(1), Criterion 5 – Work Processes
- DOE Order 414C, CRD, Attachment 1, 2.b.(3), Criterion 7 – Procurement

Requirements will be implemented to ensure only trained and qualified personnel perform transportation and packaging activities. The program shall ensure processes and procedures are in place that achieve quality objectives and ensure appropriate levels of quality and safety are applied to critical components of packaging and transportation systems utilizing a graded approach.

Activities related to the control of special processes shall be controlled. The requirements for control of special processes consist of the following elements:

- Implementing procedures shall be established to control special processes used in the fabrication and inspection of storage/transport systems. These processes may include welding, non-destructive examination, or other special processes as identified in procurement documents.

- Special processes are performed in accordance with approved procedures.
- Personnel who perform special processes are to be trained and qualified in accordance with applicable codes, standards, specifications, and/or other special requirements. Records of qualified procedures and personnel are to be maintained and kept current by the organization that performs the special processes.

Package users are responsible to ensure special processes for welding and nondestructive examination of the S300 during fabrication, use, and maintenance are controlled. Equipment used in conduct of special processes must be qualified in accordance with applicable codes, standards, and specifications. Special process operations must be performed by qualified personnel and accomplished in accordance with written process sheets or procedures with recorded evidence of verification when applicable. Qualification records of special process procedures, equipment, and personnel must be maintained.

Welders, weld procedures, and examination personnel are to be qualified in accordance with the appropriate articles of ASME BPVC, Section III,[2] Subsections NB (for containment components) and NG (for criticality control components); ASME BPVC, Section IX, "Welding and Brazing Qualifications";[3] and ASME BPVC, Section V, "Nondestructive Examination."[4]

Containment vessel and criticality control component structural welds must be examined by nondestructive methods using radiography and dye penetrant techniques and must meet the requirements of the ASME BPVC as cited on the design drawings.

Special processes for QA Level A and B items must be performed by qualified personnel in accordance with documented and approved procedures. Applicable special processes performed by an outside supplier such as welding, plating, anodizing, and heat treating, which are controlled by the suppliers' quality program, are reviewed and/or witnessed in accordance with procurement requirements.

9.10 Internal Inspection

As required by the CCP-PO-002, *Transuranic Waste Certification Plan*, internal inspection activities shall be established to satisfy the requirements of Section 4.0. These requirements are to be in accordance with:

- 10 CRF 830.122(b), *Criterion 2 – Management/Personnel Training and Qualifications*
- 10 CFR 830.122(h), *Criterion 8 – Performance/Inspection and Acceptance Testing*
- DOE Order 414C, CRD, Attachment 1, 2.a.(2), *Criterion 2 - Personnel Training and Qualifications*

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[2] ASME, 2004, American Society of Mechanical Engineers Boiler and Pressure Vessel Code, Section III, *Rules for Construction of Nuclear Power Plant Components*, American Society of Mechanical Engineers, New York, NY

[3] ASME, 2004, American Society of Mechanical Engineers Boiler and Pressure Vessel Code, Section IX, *Welding and Brazing Qualifications*, American Society of Mechanical Engineers, New York, NY

[4] ASME, 2004, American Society of Mechanical Engineers Boiler and Pressure Vessel Code, Section V, *Nondestructive Examination*, American Society of Mechanical Engineers, New York, NY

- DOE Order 414C, CRD, Attachment 1, 2.b.(4), *Criterion 8 – Inspection and Acceptance Testing*

Requirements are implemented to ensure only trained and qualified personnel perform transportation and packaging activities. The program shall ensure processes and procedures are in place to ensure appropriate inspections and tests are applied prior to acceptance or use of the packaging or component, and to identify the status of packaging items, components, etc.

Activities related to internal inspection shall be controlled. The program requirements for control of internal inspection consist of the following elements:

- Implementing procedures shall be established to assure that inspection or surveillance is performed to verify that materials, parts, processes, or other activities affecting quality conform to documented instructions, procedures, specifications, drawings, and/or procurement documents.
- Personnel performing inspection and surveillance activities shall be trained and qualified in accordance with written approved procedures.
- Inspections and surveillances are to be performed by individuals other than those who performed or supervised the subject activities.
- Inspection or surveillance and process monitoring are both required where either one, by itself, will not provide assurance of quality.
- Modifications and/or repairs to and replacements of safety-related and important-to-safety structures, systems, and components are inspected in accordance with the original design and inspection requirements or acceptable alternatives.
- Mandatory hold points, inspection equipment requirements, acceptance criteria, personnel qualification requirements, performance characteristics, variable and/or attribute recording instructions, reference documents, and other requirements are considered and included, as applicable, during inspection and surveillance planning.

9.10.1 Inspections During Fabrication

Specific inspection criteria are incorporated into the drawings (see Appendix 1.3.1, *Packaging General Arrangement Drawings* of this SAR) for the S300 packaging. Inspection requirements for fabrication are divided into two responsible areas that document that an accepted S300 package conforms to tested and certified design criteria. These two areas are:

- In-process inspections performed by the fabricator.
- Independent surveillance of fabrication activities performed by individuals acting on behalf of the purchaser.

The vendor (fabricator) is required to submit a Manufacturing/Fabrication Plan prior to the start of fabrication for approval by the customer. This plan shall be used as a tool for establishing witness and hold points. A review for compliance with procurement documents is normally performed as part of the surveillance function at the vendor's facility. The plan shall define how fabrications and inspections are to be performed, processes to be engaged, and qualification requirements for personnel. Inspections must be documented and records delivered in individual data packages accompanying the package in accordance with the procurement specification.

Independent surveillance activities will be performed by qualified personnel selected with approval of the customer.

9.10.2 Inspections During Initial Acceptance and During Service Life

Independent inspections are performed upon receipt of the S300 packaging prior to first usage (implemented by package user procedures) and before loading and prior to each transport. Post-loading inspections are also performed prior to shipment. Inspection to be implemented by the package user (by qualified independent inspection personnel) must include the following:

- Acceptance – Ensure compliance with procurement documents. Per Chapter 8, *Acceptance Tests and Maintenance Program* of this SAR, perform (as applicable) first-time-usage inspections, weld examinations, pressure tests, structural tests, foam tests, and leakage rate tests with the use of approved procedures that implement the requirements of ANSI N14.5-1997, *American National Standard for Radioactive Materials – Leakage Tests on Packages for Shipment.*[5]
- Operation – Verify proper assembly and verify that post-load leak testing (if applicable) is carried out as discussed in Chapter 7, *Package Operations*, of this SAR.
- Maintenance – Ensure adequate packaging maintenance to ensure that performance is not impaired as discussed in Chapter 8, *Acceptance Tests and Maintenance Program* of this SAR.
- Final – Verify proper contents, assembly, marking, shipping papers, and implementation of any special instructions.

9.11 Test Control

As required by the CCP-PO-002, *Transuranic Waste Certification Plan*, test control activities shall be established and implemented to satisfy the requirements of Section 4.0. These requirements are to be in accordance with:

- 10 CFR 830.122(e), *Criterion 5 – Performance/Work Processes*
- DOE Order 414C, CRD, Attachment 1, 2.b.(1), *Criterion 5 – Work Processes*

Requirements are implemented to ensure processes and procedures are in place that achieve quality objectives and ensure appropriate levels of quality and safety are applied to critical components of packaging and transportation systems utilizing a graded approach.

Activities related to test control shall be controlled. The requirements for test control consist of the following elements:

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[5] ANSI, ANSI N14.5-1997, *American National Standard for Radioactive Materials – Leakage Tests on Packages for Shipment*, American National Standard Institute, Inc., New York, NY, 1998.

- Implementing procedures shall be established to assure that required proof, acceptance, and operational tests, as identified in design or procurement documents, are performed and appropriately controlled.
- Test personnel shall have appropriate training and shall be qualified for the level of testing which they are performing. Personnel shall be qualified in accordance with approved, written instructions, procedures, and/or checklists.
- Tests are performed by qualified personnel in accordance with approved, written instructions, procedures, and/or checklists. Test procedures are to contain or reference the following information, as applicable:
    - Acceptance criteria contained in the applicable test specifications, or design and procurement documents.
    - Instructions for performance of tests, including environmental conditions.
    - Test prerequisites such as test equipment, instrumentation requirements, personnel qualification requirements, fabrication, or operational status of the items to be tested.
    - Provisions for data recording and records retention.
- Test results are to be documented and evaluated to ensure that acceptance criteria have been satisfied.
- Tests to be conducted after modifications, repairs, or replacements of safety-related and important-to-safety structures, systems, or components are to be performed in accordance with the original design and testing requirements or acceptable alternatives.

Tests are required when it is necessary to demonstrate that an item or process will perform satisfactorily. Test procedures must specify the objectives of the tests, testing methods, required documentation, and acceptance criteria. Tests to be conducted by vendors at vendor facilities must be specified in procurement documents. Personnel conducting tests, test equipment, and procedures must be qualified and records attesting to qualification retained.

9.11.1 Acceptance and Periodic Tests

- The fabricator must supply QA documentation for the fabrication of each S300 packaging in accordance with applicable drawings, specifications, and/or other written requirements.
- The package user must ensure required S300 packaging pressure tests, structural tests, foam tests, or leakage rate tests, as applicable, are performed prior to first usage.
- Periodic testing, as applicable, will be performed to ensure the S300 packaging performance has not deteriorated with time and usage. The requirements for the periodic tests are given in the Chapter 8, *Acceptance Tests and Maintenance Program* of this SAR. The results of these tests are required to be documented and maintained with the specific packaging records by the package user.

9.11.2 Packaging Nonconformance

Packaging that does not meet the inspection criteria shall be marked or tagged as nonconforming, isolated, and documented in accordance with Section 9.15, *Nonconforming Parts, Materials, or Components*. The packaging must not be used for shipment until the nonconformance report has been properly dispositioned in accordance with Section 9.15.

9.12 Control Of Measuring And Test Equipment

As required by the CCP-PO-002, *Transuranic Waste Certification Plan*, activities pertaining to the control of measuring and test equipment shall be established and implemented to satisfy the requirements of Section 4.0. These requirements are to be in accordance with:

- 10 CFR 830.122(h), *Criterion 8 – Performance/Inspection and Acceptance Testing*
- DOE Order 414C, CRD, Attachment 1, 2.b.(4), *Criterion 8 – Inspection and Acceptance Testing*

Requirements are implemented to ensure processes and procedures are in place to ensure appropriate inspections and tests are applied prior to acceptance or use of the packaging or component, and to identify the status of packaging items, components, etc.

Activities pertaining to the control of measuring and test equipment shall be controlled. The requirements for control of measuring and test equipment shall consist of the following elements:

- Implementing procedures shall be established to assure that tools, gages, instruments and other measuring and testing devices (M&TE) used in activities affecting quality are properly controlled, calibrated and adjusted to maintain accuracy within required limits.
- M&TE are calibrated at scheduled intervals against certified standards having known valid relationships to national standards. If no national standards exist, the basis for calibration shall be documented. Calibration intervals are based on required accuracy, precision, purpose, amount of use, stability characteristics and other conditions that could affect the measurements.
- Calibrations are to be performed in accordance with approved written procedures. Inspection, measuring and test equipment are to be marked to indicate calibration status.
- M&TE are to be identified, labeled or tagged indicating the next required calibration due date, and traceable to calibration records.
- If M&TE is found to be out of calibration, an evaluation shall be performed and documented regarding the validity of inspections or tests performed and the acceptability of items inspected or tested since the previous acceptable calibration. The current status of M&TE is to be recorded and maintained. Any M&TE that is consistently found to be out of calibration shall be repaired or replaced.

Special calibration and control measures on rules, tape measures, levels and other such devices are not required where normal commercial practices provide adequate accuracy.

9.13 Handling, Storage, And Shipping Control

As required by the CCP-PO-002, *Transuranic Waste Certification Plan*, handling, storage, and shipping control activities shall be established and implemented to satisfy the requirements of Section 4.0. These requirements are to be in accordance with:

- 10 CFR 830.122(e), Criterion 5 – Performance/Work Processes
- DOE Order 414C, CRD, Attachment 1, 2.b.(1), Criterion 5 – Work Processes

Requirements are implemented to ensure processes and procedures are in place that achieve quality objectives and ensure appropriate levels of quality and safety are applied to critical components of packaging and transportation systems utilizing a graded approach.

Activities pertaining to handling, storage, and shipping shall be controlled. The requirements for handling, storage, and shipping control consist of the following elements:

- Implementing procedures shall be established to assure that materials, parts, assemblies, spare parts, special tools, and equipment are handled, stored, packaged, and shipped in a manner to prevent damage, loss, loss of identity, or deterioration.
- When necessary, storage procedures address special requirements for environmental protection such as inert gas atmospheres, moisture control, temperature levels, etc.

Package users shall ensure that components associated with the S300 are controlled to prevent damage or loss, protected against damage or deterioration, and provide adequate safety of personnel involved in handling, storage, and shipment (outgoing and incoming) operations. Handling, storage, and shipping must be accomplished in accordance with written and approved instructions, procedures, specifications, and/or drawings. These documents must identify appropriate information regarding shelf life, environment, temperature, cleaning, handling, and preservation, as applicable, to meet design, regulatory, and/or DOE shipping requirements.

Preparation for loading, handling, and shipment will be done accordance with approved procedures to ensure that all requirements have been met prior to delivery to a carrier. A package ready for shipment must conform to its shipping paper. Specific handling precautions for the S300 are given in Chapter 7, *Package Operations* of this SAR.

Empty packages, following usage, must be checked and decontaminated if required. Each package must be inspected, reconditioned, or repaired, as appropriate, in accordance with approved written procedures before storing or loading. Empty S300 packagings are to be tagged with "EMPTY" labels and stored in designated protected areas in order to minimize environmental effects on the containers. New and unused S300 packagings do not require an "EMPTY" label.

Routine maintenance on the S300 packaging may be performed as deemed necessary by package users and is limited to cleaning, rust removal, painting, light metal working to restore the original contours and replacement of damaged, worn, or malfunctioning components. Spare components, such as bolts, will be placed in segregated storage to maintain proper identification and to avoid misuse. Specific maintenance precautions for the S300 are given in Chapter 8, *Acceptance Tests and Maintenance Program* of this SAR.

9.14 Inspection, Test, And Operating Status

As required by the CCP-PO-002, *Transuranic Waste Certification Plan*, inspection, test, and operating status activities shall be established and implemented to satisfy the requirements of Section 4.0. These requirements are to be in accordance with:

- 10 CFR 830.122(e), *Criterion 5 – Performance/Work Processes*
- 10 CFR 830.122(h), *Criterion 8 – Performance/Inspection and Acceptance Testing*
- DOE Order 414C, CRD, Attachment 1, 2.b.(1), *Criterion 5 – Work Processes*
- DOE Order 414C, CRD, Attachment 1, 2.b.(4), *Criterion 8 – Inspection and Acceptance Testing*

Requirements are implemented to ensure processes and procedures are in place that achieve quality objectives and ensure appropriate levels of quality and safety are applied to critical components of packaging and transportation systems utilizing a graded approach. In addition, processes and procedures shall be in place to ensure appropriate inspections and tests are applied prior to acceptance or use of the packaging or component, and to identify the status of packaging items, components, etc.

Activities pertaining to inspection, test, and operating status activities shall be controlled. The requirements for inspection, test, and operating status consist of the following elements:

- Implementing procedures shall be established to assure that the inspection and test status of materials, items, structures, systems, and components throughout fabrication, installation, operation, and test are clearly indicated by suitable means, (e.g., tags, labels, cards, form sheets, check lists, etc.).
- Bypassing of required inspections, tests, or other critical operations is prevented through the use of approved instructions or procedures
- As appropriate, the operating status of nonconforming, inoperative or malfunctioning components of a storage/transport system (e.g., valves, switches, etc.) is indicated to prevent inadvertent operation. The application and removal of status indicators is performed in accordance with approved instructions and procedures.
- Any nonconforming items are identified and controlled in accordance with Section 9.15, *Nonconforming Parts, Materials, or Components*, of this SAR.

Package users shall ensure that the status of inspection and test activities are identified on the item or in documents traceable to the item to ensure that proper inspections or tests have been performed and that those items that do not pass inspection are not used. The status of fabrication, inspection, test, assembly, and refurbishment activities must be identified in documents traceable to the package components.

Measures established in specifications, procedures, and other instructions shall ensure that the following objectives are met:

- QA personnel responsible for oversight of packaging inspections can readily ascertain the status of inspections, tests, and/or operating conditions.
- No controlled items are overlooked.

- Inadvertent use or installation of unqualified items is prevented.
- Documentation is complete.

9.15 Nonconforming Materials, Parts, Or Components

As required by the CCP-PO-002, *Transuranic Waste Certification Plan*, control of nonconforming materials, parts, or components shall be established and implemented to satisfy the requirements of Section 4.0. These requirements are to be in accordance with:

- 10 CFR 830.122(c), Criterion 3 – Management/Quality Improvement
- DOE Order 414C, CRD, Attachment 1, 2.b.(3), Criterion 3 – Quality Improvement

Requirements are implemented to ensure that processes and procedures are in place to identify and correct problems associated with transportation and packaging activities.

Activities pertaining to the control of nonconforming materials, parts, or components shall be controlled. The requirements for nonconforming materials, parts, or components consist of the following elements:

- Implementing procedures shall be established to control materials, parts, and components that do not conform to requirements to prevent their inadvertent use during fabrication or during service.
- Nonconforming items include those items that do not meet specification or drawing requirements. Additionally, nonconforming items include items not fabricated or tested (1) in accordance with approved written procedures, (2) by qualified processes, or (3) by qualified personnel; where use of such procedures, processes, or personnel is required by the fabrication, test, inspection, or quality assurance requirements.
- Nonconforming items are identified and/or segregated to prevent their inadvertent use until properly dispositioned. The identification of nonconforming items is by marking, tagging, or other methods that do not adversely affect the end use of the item. The identification shall be legible and easily recognizable. When identification of each nonconforming item is not practical, the container, package, or segregated storage area, as appropriate, is identified.
- Nonconforming conditions are documented in NCRs and affected organizations are to be notified. The nonconformance report shall include a description of the nonconforming condition. Nonconforming items are dispositioned as use-as-is, reject, repair, or rework.
- Inspection or surveillance requirements for nonconforming items following rework, repair, or modification are detailed in the nonconformance reports and approved following completion of the disposition.
- Acceptability of rework or repair of nonconforming materials, parts, and components is verified by re-inspecting and/or re-testing the item to the original requirements or equivalent inspection/testing methods. Inspection, testing, rework, and repair methods are to be documented and controlled.

- The disposition of nonconforming items as use-as-is or repair shall include technical justification and independent verification to assure compliance with design, regulatory, and contractual requirements.
- Items dispositioned as rework or repair are reinspected and retested in accordance with the original inspection and test requirements or acceptable alternatives that comply with the specified acceptance criteria.
- When specified by contract requirements, nonconformances that result in a violation of client contract or specification requirements are to be submitted for client approval.
- Nonconformance reports are made part of the inspection records and are periodically reviewed to identify quality trends. Unsatisfactory quality trends are documented on a Corrective Action Report (CAR) as detailed in Section 9.16, *Corrective Action*, of this SAR. The results of these reviews are to be reported to management.
- Nonconformance reports relating to internal activities are issued to management of the affected organization. The appropriate Quality Assurance Manager shall approve the disposition and performs follow-up activities to assure proper closure.
- Compliance with the evaluation and reporting requirements of 10 CFR 21 related to defects and noncompliances are to be controlled by approved procedures.

9.16 Corrective Action

As required by the CCP-PO-002, *Transuranic Waste Certification Plan*, requirements for corrective action shall be established and implemented to satisfy the requirements Section 4.0. These requirements are to be in accordance with:

- 10 CFR 830.122(c), Criterion 3 – Management/Quality Improvement
- DOE Order 414C, CRD, Attachment 1, 2.b.(3), Criterion 3 – Quality Improvement

Requirements are implemented to ensure that processes and procedures are in place to identify and correct problems associated with transportation and packaging activities.

Activities pertaining to corrective actions shall be controlled. The requirements for corrective action consist of the following elements:

- Implementing procedures shall be established to identify significant conditions adverse to quality. Significant and/or repetitive failures, malfunctions and deficiencies in material, components, equipment, and operations are to be promptly identified and documented on a Corrective Action Reports (CARs) and reported to appropriate management. The cause of the condition and corrective action necessary to prevent recurrence are identified, implemented, and followed up to verify corrective action is complete and effective.
- The SPQAO is responsible for ensuring implementation of the corrective action program, including follow up and closeout actions. The SPQAO may delegate certain activities in the Corrective Action process to others.

9.17 Quality Assurance Records

As required by the CCP-PO-002, *Transuranic Waste Certification Plan,* activities associated with QA records shall be established and implemented to satisfy the requirements of Section 4.0. These requirements are to be in accordance with:

- 10 CRF 830.122(b), Criterion 2 – Management/Personnel Training and Qualifications
- 10 CFR 830.122(d), Criterion 4 – Management/Documents and Records
- 10 CFR 830.122(e), Criterion 5 – Performance/Work Processes
- 10 CFR 830.122(h), Criterion 8 – Performance/Inspection and Acceptance Testing
- DOE Order 414C, CRD, Attachment 1, 2.a.(2), Criterion 2 - Personnel Training and Qualifications
- DOE Order 414C, CRD, Attachment 1, 2.a.(4), Criterion 4 – Documents and Records
- DOE Order 414C, CRD, Attachment 1, 2.b.(1), Criterion 5 – Work Processes
- DOE Order 414C, CRD, Attachment 1, 2.b.(4), Criterion 8 – Inspection and Acceptance Testing

Requirements are implemented to ensure that only trained and qualified personnel perform transportation and packaging activities. The program shall ensure processes and procedures are in place to address document preparation, document control, and management of records. In addition, the program ensures processes and procedures are in place which achieves quality objectives and appropriate levels of quality and safety are applied to critical components of packaging and transportation systems utilizing a graded approach. Finally, the program ensures processes and procedures are in place to identify appropriate inspections and tests are applied prior to acceptance or use of the package or component, and to identify the status of packaging items, components, etc.

Quality assurance records shall be controlled. The requirements for quality assurance records consist of the following elements:

- Implementing procedures shall be established to assure control of quality records. The purpose of the Quality Assurance Records system is to assure that documented evidence relative to quality related activities is maintained and available for use by LANL/CCP, its customers, and/or regulatory agencies, as applicable.
- Approved procedures identify the types of documents to be retained as QA records, as well as those to be retained by the originating organization. Lifetime and Non-Permanent records are retained by CCP or its customers, as appropriate. Records are identified, indexed, and stored in accessible locations.
- QA Records are maintained for periods specified to furnish evidence of activities affecting the quality of structures, systems, and components that are safety-related or important-to-safety. These records include records of design, procurement, fabrication, assembly, inspection, and testing.
- Maintenance, records shall include the use of operating logs; results of reviews, inspections, tests, and audits; results from monitoring of work performance and material

analyses; results of maintenance, modification, and repair activities; qualification of personnel, procedures, and equipment; records of calibration of measuring and test equipment; and related instructions, procedures, and drawings.

- Requirements for indexing, record retention period, storage method(s) and location(s), classification, preservation measures, disposition of nonpermanent records, and responsibility for safekeeping are specified in approved procedures. Record storage facilities are established to prevent destruction of records by fire, flood, theft, and deterioration due to environmental conditions (such as temperature, humidity, or vermin). As an alternative, two identical sets of records (dual storage) may be maintained at separate locations.
- LANL/CCP shall retain required records for at least three (3) years beyond the date of last engagement of activities.

9.17.1 General

Sufficient records must be maintained by package users to furnish evidence of quality of items and of activities affecting quality. QA records that must be retained for the lifetime of the packaging include:

- Appropriate production-related records that are generated throughout the package manufacturing and fabrication process
- Records demonstrating evidence of operational capability; e.g., completed acceptance tests and inspections
- Records verifying repair, rework, and replacement
- Audit reports, and corrective actions
- Records that are used as a baseline for maintenance
- Records showing evidence of delivery of packages to a carrier and proof that all DOT requirements were satisfied.

9.17.2 Generating Records

Package user documents designated as QA records must be:

- Legible
- Completed to reflect the work accomplished and relevant results or conclusions
- Signed and dated or otherwise authenticated by authorized personnel.

QA records should be placed in a records storage area as soon as is feasible to avoid loss or damage. Individual package QA records must be generated and maintained for each package by the package serial number.

9.17.3 Receipt, Retrieval, and Disposition of Records

The CCP has overall responsibility for records management for the S300. Package users are responsible for maintaining records while they are in process and for providing completed records to the CCP Document Control. A receipt control system shall be established, and records maintained in-house or at other locations are to be identifiable and retrievable and not disposed of until prescribed conditions are satisfied.

Records are to be available for inspection upon request.

Table 9.17-1 - Quality Assurance Records

Quality Assurance Record	Retention period
Design and Fabrication Drawings	LOP+
Test Reports	LOP+
Independent Design Review Comments	LOP+
Safety Analysis Report for Packaging	LOP+
Vendor Manufacturing and Inspection Plan	LOP+
Material Test Report of Certification of Materials	LOP+
Welding Specifications and Procedures	LOP+
Procedure Qualification Record	LOP+
Welder or Welding Operator Qualification Tests	LOP+
Record of Qualification of Personnel Performing Radiographic and PT Reports	LOP+
Weld Radiographs	LOP+
Liquid Penetrant Reports	LOP+
Dimensional Inspection Report for All Features	LOP+
Structural Test Reports (by Vendor)	LOP+
Leakage Test Reports (by Vendor and annual)	LOP+
Leakage Test Reports (Acceptance)	LOP+
Visual and Dimensional Inspection upon Receipt of Packaging	LOP+
Leak Testing Personnel Qualification Records	S+
Package Loading Procedure	S+
Leak Test Results (post loading)	S+
Unloading Procedure	S+
Preparation of Empty Package for Transport	S+
Maintenance Procedures	LOP+
Repair Procedures	LOP+
Procurement Specifications	LOP+
Audit Reports	LOP+
Personnel Training and Qualification Documentation	LOP+
Maintenance Log	LOP+

Corrective Action Reports	LOP+
Nonconformance Reports (and resolutions)	LOP+
Incident Reports per 10 CFR 71.95	LOP+
Preliminary Determinations per 10 CFR 71.85	S+
Routine Determinations per 10 CFR 71.87	S+
Shipment Records per 10 CFR 71.91(a), (b), (c), (d)	S+
LOP+ Lifetime of packaging plus 3 years S+ Shipping date plus 3 years	

9.18 Audits

As required by the CCP-PO-002, *Transuranic Waste Certification Plan*, audit requirements shall be established and implemented to satisfy the requirements of Section 4.0. These requirements are to be in accordance with:

- 10 CFR 830.122(i), Criterion 9 – Assessment/Management Assessment
- 10 CFR 830.122(j), Criterion 10 – Assessment/Independent Assessment
- DOE Order 414C, CRD, Attachment 1, 2.c.(1), Criterion 9 – Management Assessment
- DOE Order 414C, CRD, Attachment 1, 2.c.(2), Criterion 10 – Independent Assessment

Requirements are implemented to ensure management assessments are performed on a regular basis. Management assessments are planned and conducted in accordance with written procedures. In addition, the program will be independently assessed periodically in accordance with procedures.

Activities pertaining to audits and assessments shall be controlled. The requirements for audits and assessments consist of the following elements:

- Implementing procedures shall be established to assure that periodic audits verify compliance with all aspects of the Quality Assurance Program and determine its effectiveness. Areas and activities to be audited, such as design, procurement, fabrication, inspection, and testing of storage/transportation systems, are to be identified as part of audit planning.
- CCP audits supplier Quality Assurance Programs, procedures, and implementation activities to evaluate and verify that procedures and activities are adequate and comply with applicable requirements.
- Audits are planned and scheduled in a manner to provide coverage and coordination with ongoing Quality Assurance Program activities commensurate with the status and importance of the activities.
- Audits are performed by trained and qualified personnel not having direct responsibilities in the areas being audited and are conducted in accordance with written plans and checklists. Audit results are documented and reviewed by management having responsibility for the area audited. Corrective actions and schedules for implementation

are established and recorded. Audit reports include an objective evaluation of the quality-related practices, procedures, and instructions for the areas or activities being audited and the effectiveness of implementation.

- Responsible management shall undertake corrective actions as a follow-up to audit reports when appropriate. The SPQAO shall evaluate audit results for indications of adverse trends that could affect quality. When results of such assessments so indicate, appropriate corrective action will be implemented.

The SPQAO shall follow up on audit findings to assure that appropriate corrective actions have been implemented and directs the performance of re-audits when deemed necessary.