ATTACHMENT 2

SAR PAGE CHANGES

RESPONSES TO RAI, ES-3100 Revision 10

GUIDE TO PAGE CHANGES
Y/LF-717, Rev 3, page change # 3

SAR SECTION	PAGE CHANGES
Volume 1, front section	Replace pages i, vi, xiv, and xxvi
Volume 1, Section 2	Replace pages 2-6, 2-11, 2-36, 2-37, 2-41 through 2-43, 2-53, 2-78, and 2-80
Volume 2, front section	Replace pages i, vi, xiv, and xxvi
Volume 2, Section 3	Replace or add pages, as applicable 3-16 through 3-18, 3-23, 3-27, 3-27a through 3-27d, 3-28, 3-30, 3-39, 3-147, 3-153 through 3-157, and 3-160 through 3-164
Volume 2, Section 4	Replace pages 4-7, 4-9, 4-23, and 4-25 through 4-34
Volume 2, Section 7	Replace pages 7-2, 7-6, 7-7, and 7-11

Y/LF-717, Rev. 3,
Volume 1

SAFETY ANALYSIS REPORT, Y-12 NATIONAL SECURITY COMPLEX, MODEL ES-3100 PACKAGE WITH BULK HEU CONTENTS

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REVISION LOG

Date	SAR Revision No.	Description	Affected Pages
5/6/09	3	This revision was issued to match Amendment 9 of the COC. -Remove the following contents for ground transport that were not reviewed by NRC: • HEU oxides (U_3O_8-Al and UO_2-Mg) • Research reactor fuel elements or components (clad U-Al, U_3O_8-Al, UO_2, or UO_2-Mg) -Remove the following contents for air transport that were not reviewed by NRC: • HEU oxides (UO_2, UO_2-Mg, U_3O_8, and U_3O_8-Al) • Broken HEU bulk metal and uranium-aluminum alloy of unspecified geometric form • Research reactor fuel elements or components (clad U-Al, U_3O_8-Al, UO_2, or UO_2-Mg)	All
4/14/10	3, Page Change 1	Revised SAR to • add uranium oxide loading with a CSI value of 0.4 • remove the 8-lb minimum payload weight • add stainless-steel option for can spacers • revise allowable weight changes for drum body and top plug • revise Drawing M2E801580A005 to clarify marking requirements on drum hex nuts • allow methods other than sieving for establishing minimum content sizes for pyrophoric purposes • revise the purity of the cover gas used for pyrophoric material	i, x, xxv, 1-13, 1-16, 1-22, 1-23, 1-24, 1-27, 1-89 through 1-126, 1-126a, 1-126b, 1-135, 1-147, 1-178a, 1-178b, 1-221, 2-1, 2-14, 2-24, 6-1, 6-3, 6-4, 6-31, 6-35, 6-57, 6-67 through 6-69, 6-104, 6-105, 6-195, 6-717 through 6-892, 7-3, 7-4, 8-9, 8-10

REVISION LOG

Date	SAR Revision No.	Description	Affected Pages
		Note: The NRC performed an acceptance review of Page Change 1 and generated several Requests for Supplemental Information (RSIs). Therefore, Page Change 1 will be superceded by Page Change 2, which incorporates the responses to the RSIs.	
7/22/10	3, Page Change 2	Reissue of Page Change 1 with RSI responses incorporated	i, x, xiv, xxv, xxvi 1-13, 1-16, 1-22, 1-23, 1-24, 1-27, 1-89 through 1-126, 1-126a, 1-126b, 1-135, 1-147, 1-178a, 1-178b, 1-221, 2-1, 2-6, 2-14, 2-24, 2-26, 3-8a, 3-8b, 3-9, 3-10, 3-12, 3-13, 3-18, 3-23, 3-27, 3-27a, 3-27b, 3-100, 3-104, 3-105, 3-115, 3-116, 3-140, 6-1, 6-3, 6-4, 6-31, 6-35, 6-57, 6-67 through 6-69, 6-104, 6-105, 6-195, 6-717 through 6-892, 7-3, 7-4, 8-9, 8-10
1/27/11	3, Page Change 3	Revised SAR in response to RAIs dated October 12, 2010, for review of CoC 9315, Revision 10	i, vi, xiv, xxvi, 2-6, 2-11, 2-36, 2-37, 2-41 through 2-43, 2-53, 2-78, 2-80, 3-16 through 3-18, 3-23, 3-27, 3-27a through 3-27d, 3-28, 3-30, 3-39, 3-147, 3-153 through 3-157, 3-160 through 3-164, 4-7, 4-9, 4-23, 4-25 through 4-34, 7-2, 7-6, 7-7, 7-11

contain any materials that off gas at the temperatures associated with NCT or HAC. When space is available inside the containment vessel, stainless-steel metal scrubbers will be placed on the top and bottom of this partially canned assembly or an empty convenience can will be placed on top of this assembly inside the containment vessel. The polyethylene bottles have a diameter of ~12.54 cm (4.94 in.) and a height of ~22.1 cm (8.7 in.). A total of three polyethylene bottles may be loaded into the containment vessel. The Teflon FEP bottles have a diameter of ~ 11.91 cm (4.69 in.) and a height of ~23.88 cm (9.4 in.). A total of three Teflon FEP bottles may be loaded into the containment vessel. Polyethylene bags may be used inside or outside any convenience can or bottle. In some packing arrangements, silicone rubber pads will be used between convenience cans. Also, some arrangements will require spacers between cans. These spacers are thin stainless-steel cans filled with the noncombustible cast neutron poison. Each convenience can and spacer is equipped with a stainless-steel band clamp and nylon coated wire for loading and unloading operations. The spacers are ~10.11 cm (3.98-in.) in diameter by 4.45 cm (1.75 in.) in height and a maximum weight ~0.58 kg (1.27 lb). In order to minimize displacement of convenience containers during transport, stainless-steel scrubbers or polyethylene bags may be added on top of the last can or bottle in the containment vessel. If partial loading configurations are employed and empty cans or bottles are used, these empty cans or bottles will be loaded last and will require a minimum 0.32 cm (⅛ in.) diameter hole to be placed through the lid.

2.1.2 Design Criteria

2.1.2.1 General standards for all packages

The general design standards for all packages in accordance with 10 CFR 71.43(a) through (e), (g) and (h) are addressed in the following paragraphs.

10 CFR 71.43(a)

Requirement: The smallest overall dimension of a package shall not be <10 cm (4 in.).

Compliance: The drums' outside diameter over the rolled rings is 49.20 cm (19.37 in.), and the outside height including the lid is 110.49 cm (43.50 in.). The minimum outside diameter of the ES-3100 containment vessel is 13.36 cm (5.26 in.), and the overall height is 82.30 cm (32.40 in.). Therefore, the packaging meets this requirement.

10 CFR 71.43(b)

Requirement: The outside of the package must incorporate a feature, such as a seal, that is not readily breakable and that, while intact, would be evidence that the package has not been opened by unauthorized persons.

Compliance: The removable drum head is attached to the body by eight ⅝-11-UNC-2B silicon bronze nuts and ⅝-in. nominal washers. Two 0.51-cm (0.20-in.)-thick lugs with 0.953-cm (0.38-in.)-diam holes (Drawing M2E801580A005, Appendix 1.4.8) project through slots in the drum lid and provide attachment for tamper-indicating devices (TIDs). These TIDs consist of a stainless-steel cable with an aluminum crimp closure or equivalent. The requirement is satisfied by the TIDs, which are installed as specified in Sect. 7.1.2.2. The TID is only required when the containment vessel has HEU in the package. It is not required for empty shipments.

10 CFR 71.43(c)

Requirement: Each package must include a containment system securely closed by a positive fastening device that cannot be opened unintentionally or by pressure that may arise within the package.

Compliance: The fastened lid on the drum with tamper-indicating features provides assurance that the drum assembly will not be unintentionally breached. The containment boundary is sealed using the lid assembly and closure nut to ensure that this boundary will be breached only through a deliberate effort, and then only after the drum assembly is breached. The design of the containment boundary is analyzed in Appendix 2.10.1 for a differential pressure of 699.82 kPa (101.5 psi) internal and 150 kPa (21.7 psi) external. The internal design pressure exceeds the maximum differential pressure of 173.98 kPa (25.233 psi) and 494.64 kPa (71.741 psi) attained during NCT (Sect. 2.6.2) and HAC (Sect. 3.5.3), respectively. In addition, calculation results are provided in Sects. 2.6.1 and 2.7.4.3 to demonstrate that the stresses in the containment boundary and closure nut threads do not exceed the stress limits established by the ASME code for NCT and HAC. Therefore, the containment boundary will not be breached during any mode of transport due to pressurization of the containment boundary.

10 CFR 71.43(d)

Requirements: A package must be made of materials and construction that assure that there will be no significant chemical, galvanic, or other reaction among the packaging components, among package contents, or between the packaging components and the package contents including possible reaction resulting from inleakage of water, to the maximum credible extent. Account must be taken of the behavior of materials under irradiation.

Compliance: Compliance with the regulatory requirements are discussed in Sect. 2.2.2.

10 CFR 71.43(e)

Requirement: A package valve or other device, the failure of which would allow radioactive contents to escape, must be protected against unauthorized operation and, except for a pressure relief device, must be provided with an enclosure to retain any leakage.

Compliance: No penetrations, connections, or fittings into the containment vessels exist; therefore, the requirements of 10 CFR 71.43(e) are not applicable.

10 CFR 71.43(g)

Requirement: A package must be designed, constructed, and prepared for transport so that in still air at 38°C (100°F) and in the shade, no accessible surface of a package would have a temperature exceeding 50°C (122°F) in a nonexclusive use shipment or 85°C (185°F) in an exclusive use shipment.

Compliance: Since the components to be shipped have a calculated maximum decay heat load of 0.4 W, thermal analyses were conducted for the ES-3100 package; results are summarized in Appendix 3.6.2. The predicted temperatures, while the package is stored at 38°C (100°F) in the shade, for the drum lid center, and the containment vessel flange, are approximately 38.3°C (101°F). The analysis shows that no accessible surface of the package would have a temperature exceeding 50°C maximum normal operating pressure). As shown in Table 2.6, the containment vessel design stresses are well below the allowable stresses (see Fig. 2.1 for stress locations). Therefore, this ES-3100 containment vessel is capable of shipping at a higher internal pressure. The external pressure requirement from 10 CFR 71.73(c)(6) is 150 kPa (21.7 psi) gauge. These design and operating pressures were used to calculate the stresses (Appendix 2.10.1) in all components of the containment boundary, which are well below the allowable limits at all operating conditions. The maximum normal operating pressure calculated for NCT in accordance with 10 CFR 71.4 and 10 CFR 71.71(c)(1) for the bounding load case is 198.98 kPa (28.859 psia). The maximum internal gauge pressure calculated for NCT is 173.98 kPa (25.233 psi), which is the maximum normal operating pressure minus the reduced external pressure condition of 10 CFR 71.71(c)(3) [198.98 − 25.00 kPa (28.859 − 3.626 psia)] (Sect. 2.6.3). A summary of the package's design, NCT, and HAC pressures and temperatures is presented in Appendices 3.6.4 and 3.6.5. Allowable stress intensity limits and calculated stresses at the design evaluation conditions for the containment vessel are summarized in Tables 2.4 through 2.6. The stresses used in the design of all metal containment vessel components are in the elastic range of the material properties.

For conditions addressed by analysis, the margin of safety is calculated. The margin of safety (M.S.) is defined as:

Margin of Safety = Allowable Stress/ Actual Stress − 1.

In Regulatory Guide 7.11, below Table 1, the following quote is found: "Although NUREG/CR-1815 (Ref. 2) addresses the use of ferritic steels only, it does not preclude the use of austenitic stainless steels. Since austenitic stainless steels are not susceptible to brittle failure at temperatures encountered in transport, their use in containment vessels is acceptable to the staff and no tests are needed to demonstrate resistance to brittle failure." According to Regulatory Guide 7.11, because the containment vessel is manufactured from type 304L stainless steel (which is an austenitic stainless steel), "no tests are needed to demonstrate resistance to brittle failure." Therefore, brittle or fatigue failures are not anticipated under any design, transport, accident, or storage condition (Sects. 2.6 and 2.7). Material specifications for the ES-3100 packaging components are listed in Table 2.7.

Table 2.5. Allowable stress intensity (S_m) for the containment boundary construction materials of construction [a]

Description	Specification	S_m
Pipe body (Method 1)	ASME SA-312 welded or seamless pipe, type TP304L stainless steel	8.825×10^4 kPa (12,800 psi)[b]
Formed body, end cap and flange (Method 2)	ASME SA-182, F304L stainless steel	8.825×10^4 kPa (12,800 psi)[b]
Flange and end cap (Method 1)	ASME SA-182 Forging, F304L stainless steel	8.825×10^4 kPa (12,800 psi)[b]
Containment vessel sealing lid	ASME SA-479, stainless steel 304	8.825×10^4 kPa (12,800 psi)[b]
Containment vessel closure nut	ASME SA-479, UNS-S21800, Nitronic 60 SST	1.524×10^5 kPa (22,100 psi)

[a] *ASME Boiler and Pressure Vessel Code*, Sect. II, Part D, Table 2A at 148.89°C (300°F).
[b] Lower of two allowable values was chosen to limit deflection of the flange and lid attachment in accordance with note G7 in Table 2A of Part D.

Table 2.6. ES-3100 containment boundary design evaluation allowable stress comparisons[a]

Stress locations shown in Fig. 2.1	Internal pressure design evaluation containment boundary stress @ 699.82 kPa (101.5 psi) gauge		External pressure design evaluation containment boundary stress @ −149.62 kPa (−21.7 psi) gauge		Allowable stress or shear capacity (AS)
	kPa (psi) or kg (lb)	M.S.	kPa (psi) or kg (lb)	M.S.	kPa (psi) or kg (lb)
Top flat portion of sealing lid (center of lid)	6.895×10^3 (1000)	18.2	1.474×10^3 (213.8)	88.8	1.727×10^5 (19,200)[b]
Closure nut ring (Away from threaded portion)	8.621×10^4 (12,504)	4.3	4.246×10^4 [f] (6158)	9.8	4.571×10^5 (66,300)[c]
Top flat head (sealing surface region)	2.717×10^4 (3941)	8.74	1.665×10^4 [f] (2415)	14.9	1.324×10^5 (38,400)[c]
Cylindrical section (middle)	1.999×10^4 (2899)	3.41	4.273×10^3 (619.8)	19.7	8.825×10^4 (12,800)[d]
Cylindrical section (shell to flange interface)	3.016×10^4 (4374)	7.78	1.236×10^4 (1793)	20.4	1.324×10^5 (38,400)[c]
Cylindrical section (shell to bottom interface)	5.127×10^4 (7436)	4.16	1.096×10^4 (1589.8)	23.2	1.324×10^5 (38,400)[c]
Body flange threads load, kg (lb)	2.051×10^3 (4521)	9.01	9.072×10^2 [f] (2000)	21.6	2.053×10^4 (45266)[e]
Body flange thread region (under cut region)	5.926×10^4 (8595)	3.47	2.397×10^4 [f] (3476)	10	2.648×10^5 (38,400)[c]
Flat bottom head (center)	4.826×10^4 (7000)	1.74	1.032×104 (1496.6)	11.8	1.727×10^5 (19,200)[b]
Closure nut thread load, kg (lb)	2.051×10^3 (4521)	16.29	9.072×10^2 [f] (2000)	38.1	3.545×10^4 (78154)[e]

[a] Stresses are calculated using pressures, gasket and closure nut preload, and nominal dimensions for all containment boundary components in Appendix 2.10.1. Calculated stresses for external pressure were determined by multiplying the stress at the design conditions by a factor equal to the ratio of external pressure to design pressure and adding in contribution from preload. Allowable stress values are taken from Table 2.5.

[b] Stress interpreted as the sum of $P_l + P_b$; allowable stress intensity value is $1.5 \times S_m$.

[c] Stress interpreted as the sum of $P_l + P_b + Q$; allowable stress intensity value is $3.0 \times S_m$.

[d] Stress interpreted as the primary membrane stress (P_m); allowable stress intensity value is S_m.

[e] Allowable shear capacity is defined as $0.6 \times S_m \times$ thread shear area. Thread shear area = 38.026 cm² (5.894 in.²).

[f] Stress and shear load in these areas are dominated by the 162.7 ± 6.8 N·m (120 ± 5 ft-lb) preload.

can handles, and tungsten grit was ~3.6 kg (8 lb). In the heavy-weight configurations, the surrogate payload consists of three steel cylindrical shaped components with handles, two can spacers filled with BoroBond4 and handles, and 6 silicone rubber pads. The can spacers, handles and silicone rubber pads are identical to those proposed for transport. These components weighed a total of approximately 50 kg (110.2 lb). These different weight assemblies bound the range of possible content configurations and structural deformation resulting from compliance testing. Since the decay heat of the proposed contents is ~0.4 W, little or no impact on the pressure or temperature of the package components will result during NCT. Differences in thermal capacitance of these surrogate payloads from the proposed HEU contents during HAC thermal testing are evaluated in Sect. 3.5.3.

2.5.2 Evaluation by Analysis

Although physical testing of the ES-3100 containers was performed generally at or near room temperature except for Test Unit-2, the effectiveness of the Kaolite insulating material at various temperature extremes was examined through the use of laboratory testing and structural analysis of a similar package, the ES-2LM (Handy 1997). For low-temperature service, Kaolite specimens were tested at -28.89 and -40°C (-20 and -40°F). These tests showed little change in the response of the material as compared to room temperature. Furthermore, structural analyses for bounding soft and stiff material cases were run. The Kaolite 1600 data used in these bounding analyses were from laboratory experiments that used a heavily cured sample (stiff) and a sample to which borax had been added (soft) [Oaks 1997]. Following the production run for the ES-2100 and DPP-2 shipping containers, new casting specimens were available for compression testing. In order to reduce the total cost of Kaolite testing, specimens were tested to approximately -40°C (-40°F) to cover both the cold conditions stipulated in 10 CFR 71.71(c)(2) and the -29°C (-20°F) temperature stipulated in 10 CFR 71.71(b)(1) and at 38°C (100°F). The results of Kaolite specimen testing are documented in Y/DW-1890 (Smith and Byington, Appendix 2.10.3) and Y/DW-1972 (Smith, Appendix 2.10.3). Upon further review of the data, the new test data was somewhat stiffer in the cold/high-density specimens than the data previously used in Y/DW-1972 (Smith, Appendix 2.10.3). Therefore, in order to encompass the extremes of all existing data, an additional drop simulation sequence using the new bounding curves has been conducted on the ES-3100 package as documented in Appendix 2.10.2. In addition to the analytical effort, the ES-3100 Test Unit-2 was pre-chilled to a nominal temperature of -40°C (-40°F). This was accomplished by placing the unit in an environmental chamber in Bldg. 5800 at ORNL and initially setting the chamber control to -56.7°C (-70°F) for 24 hours. After this initial period, the control on the environmental chamber was set to -42.8°C (-45° F) for at least 48 hours. Prior to the initiation of structural testing of this unit, it was removed from the environmental chamber and placed in an insulated box and transported to the NTRC. High-temperature [up to 38°C (100°F)] behavior was not addressed. However, in light of the fact that the insulation material is typically used as a cast refractory insulation in furnace applications, and that structural tests were performed in the range of 20.8 to 30.6°C (69.4 to 87°F) or just 7.4 to 17.2°C (13 to 30°F) below the high-temperature limit, it is not anticipated that any decline in impact absorption would be detrimental at 38°C (100°F).

2.6 NORMAL CONDITIONS OF TRANSPORT

This section demonstrates compliance with 10 CFR 71.43(f) and with 10 CFR 71.51(a)(1) and (b) following the tests and NCT conditions stipulated in 10 CFR 71.71. It is shown that the package will not experience any loss in shielding effectiveness or spacing and will not release any radioactive content or undergo leakage of water into the containment vessel during exposure to NCT. The four tests (water spray, free drop, compression, and penetration) made on Test Unit-4 were conducted in the 20.8 to 22.4°C (69.4 to 72.4°F) range, with the 1.2-m drop test conducted at 22.4°C (72.4°F). The maximum regulatory reference air leakage rate is ≤2.2976 × 10^{-3} ref-cm^3/s. Compliance with this permitted activity release limit is not dependent on filters or mechanical cooling systems. Following NCT compliance testing, the package was subjected to the sequential HAC test battery.

Title 10 CFR 71.71(b) specifies that the tests for NCT be conducted at the most unfavorable ambient temperature within the range of −28.89 to 38°C (−20 to 100°F). The drum is fabricated from type 304 stainless steel, and the containment boundary is fabricated from type 304L stainless steel, which is particularly suitable for low-temperature service. The Izod impact strength for the stainless steel used in the package components remains constant over a large range [specifically, from 21.11 to −195.5°C (70 to −320°F)] (*Stainless Steel Handbook*). Tensile strength increases from a minimum of 4.826 × 10^5 to 1.696 × 10^6 kPa (70,000 to 246,000 psi), and the yield strength increases about 10% over the same temperature range. The O-rings in the containment vessel have a normal service temperature range of −40 to 150°C [−40 to 302°F (Table 2.15)]. The normal service temperature range of the drum and containment vessel is −40 to 426.7°C (−40 to 800°F) [ASME, B&PV Code, Sect. II, Part D]. At −28.89°C (−20°F), the impact limiting material has been shown by tests to be stiffer than at 22.4°C (72.4°F). This condition has been evaluated by the compliance testing conducted on Test Unit-2. The reduction in tensile strength of the stainless steel from 22.4 to 38°C (73 to 100°F) is only approximately 2%, and the impact-limiting material test trends show that the impact-limiting material may become slightly softer. However, these slight reductions in tensile strength and absorption characteristics should not affect the results significantly compared to those conducted at 38°C (100°F).

Title 10 CFR 71.71(b) also states that the initial internal pressure within the containment system during NCT drop testing shall be considered as the maximum normal operating pressure. The maximum normal operating pressure is defined in 10 CFR 71.4 as the maximum gauge pressure that would develop in the containment system in a period of 1 year under the heat conditions specified in 10 CFR 71.71(c)(1). The internal pressure developed under these conditions in the ES-3100 containment vessel is calculated in Appendix 3.6.4 and discussed in Sects. 2.6.1.1 and 3.4.2. As noted in these sections, the internal pressure is calculated to be 198.98 kPa (28.859 psia). As shown in Appendix 2.10.1, the design absolute pressure of the containment vessel is 801.17 kPa (116.2 psia), and the hydrostatic test pressure stipulated in JS-YMN3-801580-A001 is 1135.57 kPa (164.7 psia). Thus, increasing the internal pressure of the containment vessel to a maximum of 198.98 kPa (28.859 psia) during NCT would have no detrimental effect. Table 2.20 provides a summary of the pressures and temperatures in the various shipping configurations. As discussed in Sect. 2.6.1.4, the containment vessel and the closure nut stresses for this pressure condition are well below the allowable stress values.

Title 10 CFR 71.71(c) specifies that the package service temperature must extend from −40 to 38°C (−40 to 100°F) with solar insolation. As shown in Sect. 3.4.1 and calculated in Appendix 3.6.2, the upper service temperature with solar insolation is calculated to be 87.81°C (190.06°F) for an empty ES-3100 containment vessel. Thermal cycling of the packages over the above temperature range from −40°C (−40°F) is considered an unlikely event, and the change would occur over a long period of time. In any event, the 127.81°C (230.06°F) thermal cycle would not result in brittle fracture or fatigue failure in the packaging. The acceptability of the packaging against brittle fracture is discussed in Sect. 2.6.2. The only concern for fatigue or endurance failure is related to the containment boundary cyclic pressure changes as the temperature varies from low to high. A 25°C (77°F) ambient temperature normally exists for the containment boundary during assembly. The containment boundary is sealed at an absolute pressure of ~101.35 kPa (14.70 psi). The internal absolute pressure at an average gas temperature of 87.81°C (190.06°F) is 198.98 kPa (28.859 psi) for the ES-3100 containment vessel (Table 2.20). The absolute internal pressure at −40°C or −40°F is 76.74 kPa (11.13 psi) for the containment vessel. Therefore, the maximum cyclic pressure differential for the containment vessel from low to high temperatures is (198.98 – 76.74) kPa or 122.24 kPa (17.729 psi). This cyclic pressure is insignificant when considering the integrity of the containment boundary as shown by the stress levels discussed in Sect. 2.6.1.3.

The ES-3100 package has been tested to determine the effectiveness of the package following a sequential NCT 1.2-m (4-ft) drop test and an HAC test battery. Testing conducted on Test Unit-4 showed that there would be no loss or dispersal of radioactive contents and no significant increase in external surface radiation levels if the actual contents had been subjected to these tests, and no substantial reduction in the effectiveness of the packaging to survive the HAC testing. Thus, the requirements of 10 CFR 71.43(f) are satisfied.

Table 2.20. Summary of temperatures and pressures for NCT

Average gas evaluation temperature °C (°F)	Containment vessel absolute internal pressure kPa (psia)
–40 (–40) [a]	76.74 (11.13)
25.0 (77) [b]	101.35 (14.70)
87.81 (190.06) [c]	198.98 (28.859)

[a] Analysis conducted with no decay heat load in accordance with 10 CFR 71.71(c)(2).
[b] Assembly temperature and pressure.
[c] Due to the lack of measurable off-gassing, all ES-3100 containment vessel configurations with solar insolation, and 0.4 W decay heat produce the same internal pressure (Appendix 3.6.4).

2.6.1 Heat

Requirement. Exposure to an ambient temperature of 38 °C (100 °F) in still air and insolation as stated in 10 CFR 71.71(c)(1).

Analysis. An increase in ambient temperature to 38 °C (100 °F) with insolation will have no effect on the ability of the containment boundary to provide containment.

The maximum normal operating pressure is defined in 10 CFR 71.4 as the maximum gauge pressure that would develop in the containment system in a period of 1 year under the heat conditions specified in 10 CFR 71.71(c)(1). The internal pressure developed under these conditions in the ES-3100 containment vessel is calculated in Appendix 3.6.4 and discussed in Sects. 2.6.1.1 and 3.4.2. As noted in these sections, the internal pressure varies with temperature. Based on the isotopic determination of the proposed contents, a decay heat of 0.4W was calculated and used for the maximum internal heat load in evaluating the package for NCT (Sect. 3.1.2). The maximum calculated internal absolute pressure in the containment vessel with solar insolation and using the bounding case parameters is 198.98 kPa (28.859 psia). The design absolute pressure of the containment vessel is 801.17 kPa (116.20 psia), and the hydrostatic test pressure is 113.55 kPa (164.7 psia). Thus, increasing the internal pressure of the containment vessel to a maximum of 198.98 kPa (28.859 psia) during NCT would have no detrimental effect. Table 2.20 provides a summary of the pressures and temperatures for the various shipping configurations. As discussed in Sect. 2.6.1.4, the containment vessel and closure nut stresses for these pressure conditions are well below the allowable stress values. If the package is exposed to solar radiation at 38 °C (100 °F) in still air, the conservatively calculated temperatures at the top of the drum, on the surface of the containment vessel, and on the containment vessel near the O-ring sealing surfaces are 117.72 °C (243.89 °F), 87.81 °C (190.06 °F), and 87.72 °C (189.9 °F), respectively (Sect. 3.4.1). Nevertheless, these temperatures are within the service limits of all packaging components, including the O-rings. The normal service temperature range of the O-rings used in the containment boundary is −40 to 150 °C (−40 to 302 °F) as shown in Table 2.15.

2.6.1.1 Summary of pressures and temperatures

An ambient temperature of 25 °C (77 °F) is assumed for the packaging at assembly. Since there are four ventilation holes near the top of the drum, and holes in the liner encapsulating the neutron poison material that are not hermetically sealed, the drum assembly will not become pressurized as the temperature increases. The containment boundary is sealed; thus, the internal pressure will change with temperature. Maximum calculated pressures at various temperatures (Sect. 3.4.1) are listed in Table 2.20.

2.6.1.2 Differential thermal expansion

The drum, inner liners, and containment vessel are all constructed of type 304 or 304L stainless steel. Radial and vertical expansion among these components will not cause any interferences or thermally induced stresses due to design clearances at assembly. Due to similarities of the coefficient of thermal expansion between type 304/304L and the containment vessel closure nut material (ASME SA-479), the compression of the O-rings does not change appreciably during the temperature excursion from 25 °C (77 °F) to the maximum temperature of 87.81 °C (190.06 °F).

The Kaolite 1600 insulation and Cat 277-4 material is poured and cast in place during the fabrication of the drum weldment (Drawing M2E801508A002, Appendix 1.4.8). Although some contraction of these materials may occur during curing, it is assumed for analysis purpose that a zero gap will exist between the Kaolite and the bounding drum and mid liner and a zero gap exists between the Cat 277-4 and the two liners. Due to differences in coefficients of thermal expansion, some radial and axial interferences are expected due to thermal growth of the inner liners. These radial and axial interferences and induced stresses are calculated in Appendix 3.6.3. A maximum von Mises stress of 6.693×10^4 kPa (9708 psi) was calculated for the inner liners. This stress value is well below the allowable yield strength of 1.324×10^5 kPa (19200 psi) at 148.9°C (300 °F). A maximum von Mises stress of 1.379×10^3 kPa (200 psi) and 1.034×10^3 kPa (150 psi) occurs in the Cat 277-4 and Kaolite 1600 materials, respectively. Based on tabulated data and curves presented in Y/DW-1987 (Smith and Byington, Appendix 2.10.4) and the curves presented in Y/DW-1972 (Smith, Appendix 2.10.3) at 38 °C (100 °F), these compressive stresses are well below the failure limit of ~4.826×10^3 kPa (700 psi) and 5.171×10^3 kPa (750 psi) for the Cat 277-4 and Kaolite 1600 materials, respectively. Therefore, these thermally induced stresses will not reduce the effectiveness of the drum assembly.

The effects of differences in coefficient of thermal expansion between the HEU contents and their associated convenience cans, polyethylene or Teflon FEP bottles are not addressed. No credit is taken for the ability of the convenience can or bottle to maintain it structural integrity during transport. Section 4 of this document assumes the HEU content is in the form of an aerosol and all is available for release; therefore, no credit for the convenience can or bottle is taken. Based on assembly clearances and the flexibility of the polyethylene or Teflon FEP bottles, no radial or vertical interferences will develop during NCT. Based on assembly clearances and insignificant differences in the coefficient of thermal expansion between the stainless-steel, tin-plated carbon steel, or nickel-alloy convenience cans and the stainless-steel containment vessel, no radial or vertical interferences will develop during NCT testing.

Table 2.21. ES-3100 containment boundary evaluation for both hot and cold conditions [a]

Stress locations shown in Fig. 2.1	Hot conditions [10 CFR 71.71(c)(1)] containment boundary stress @ 97.62 kPa 14.159 psi) gauge		Cold conditions [10 CFR 71(c)(2)] containment boundary stress @ −24.61 kPa (−3.57 psi) gauge		Allowable stress or shear capacity (AS)
	kPa (psi) or kg (lb)	M.S.	kPa (psi) or kg (lb)	M.S.	kPa (psi) or kg (lb)
Top flat portion of sealing lid (center of lid)	9.618×10^2 (139.5)	137	2.425×10^2 (35.17)	545	1.324×10^5 (19,200) [b]
Closure nut ring (away from threaded portion)	5.031×10^4 (7,297)	8.1	4.246×10^4 [f] (6,158)	9.8	4.571×10^5 (66,300) [c]
Top flat head (sealing surface region)	1.899×10^4 (2,754.4)	12.9	1.665×10^4 [f] (2,415)	14.9	2.648×10^5 (38,400) [c]
Cylindrical section (middle)	2.788×10^3 (404.4)	30.7	7.030×10^2 (102)	124.5	8.825×10^4 (12,800) [d]
Cylindrical section (shell to flange interface)	1.056×10^4 (1,532)	24.1	8.034×10^3 (1,165.2)	32	2.648×10^5 (38,400) [c]
Cylindrical section (shell to bottom interface)	7.152×10^3 (1,037.3)	36.0	1.803×10^3 (261.5)	145.8	2.648×10^5 (38,400) [c]
Body flange threads load, kg (lb)	1.067×10^3 (2,351.7)	18.2	9.072×10^2 [f] (2,000)	21.6	2.053×10^4 (45,266) [e]
Body flange thread region (under cut region)	2.954×10^4 (4,284.9)	8	2.256×10^4 [f] (3,272)	10	2.648×10^5 (38,400) [c]
Flat bottom head (center)	6.733×10^3 (976.5)	18.7	1.698×10^3 (246.2)	77	1.324×10^5 (19,200) [b]
Closure nut thread load, kg (lb)	2.351×10^3 (1,066.7)	32.2	9.072×10^2 [f] (2,000)	38.1	3.545×10^4 (78,154) [e]

[a] Calculated stresses were determined by multiplying the stress at the design conditions (Appendix 2.10.1) by a factor equal to the ratio of operating pressures to design pressures (independent of pressure direction) plus contribution from preload. Allowable stress values are taken from Table 2.5.

[b] Stress interpreted as the sum of $P_l + P_b$; allowable stress intensity value is $1.5 \times S_m$.

[c] Stress interpreted as the sum of $P_l + P_b + Q$; allowable stress intensity value is $3.0 \times S_m$.

[d] Stress interpreted as the primary membrane stress (P_m); allowable stress intensity value is S_m.

[e] Allowable shear capacity is defined as $0.6 \times S_m \times$ thread shear area. Thread shear area = 38.026 cm^2 (5.894 in.^{2}).

[f] Stress and shear load in these areas are dominated by the 162.7 ± 6.8 N·m (120 ± 5 ft-lb) preload.

2.6.3 Reduced External Pressure

Requirement. An absolute external pressure of 25 kPa (3.5 psi) is required by 10 CFR 71.71(c)(3).

Analysis. Reducing the absolute external pressure from ambient pressure to 25 kPa (3.626 psi) will have no effect on the drum assembly because the plastic plugs and aluminum tape covering the ventilation holes for the Cat 277-4 will allow the internal pressure of the drum assembly to equalize. This reduced pressure and a maximum internal pressure produces the maximum pressure differential across the containment boundary of 173.98 kPa (25.233 psi) [198.98 - 25 (28.859 - 3.626)]. The containment boundary is designed and fabricated in accordance with Sects. III and IX of the *ASME Boiler and Pressure Vessel Code* for an internal pressure differential of 699.82 kPa (101.5 psi) as shown in Appendix 2.10.1. A summary of the resulting stress intensities at various locations identified in Fig. 2.1 on the containment vessel in comparison with the ASME code allowable limits for this condition is shown in Table 2.22. These tabulated stresses were determined by multiplying the stress at the design conditions (Appendix 2.10.1 and Table 2.6) by a factor equal to the ratio of operating pressures to design pressures and adding any contribution from the closure nut preload. This methodology is based on linear elastic material behavior. As shown in Table 2.22, all stresses in the containment boundary components are well below the *ASME Boiler and Pressure Vessel Code* allowable stress intensity limits. Therefore, the ES-3100 packaging is acceptable for NCT at an absolute external pressure of 25 kPa (3.626 psi).

2.6.4 Increased External Pressure

Requirement. An absolute external pressure of 140 kPa (20 psi) is required by 10 CFR 71.71(c)(4).

Analysis. Increasing the absolute external pressure from ambient pressure to 140 kPa (20.31 psi) would have no effect on the drum assembly because the plastic plugs and aluminum tape covering the ventilation holes for the Cat 277-4 will allow the internal pressure of the drum assembly to equalize. At this increased external pressure, the maximum pressure differential across the containment boundary would be −63.26 kPa (−9.18 psi) [76.74 − 140 (11.13 − 20.31)], assuming the vessel's absolute pressure and temperature to be 76.74 kPa (11.13 psi) and −40°C (−40°F), respectively. Each containment boundary is designed and fabricated in accordance with Sects. III and IX of the *ASME Boiler and Pressure Vessel Code* for a minimum external pressure of 150 kPa (21.7 psi) gauge. A comparison of the resulting stress intensities at various locations on the containment vessel (Fig. 2.1) with the ASME code allowable limits for this condition is shown in Table 2.22. These tabulated stresses were determined by multiplying the stress at the design conditions (Appendix 2.10.1 and Table 2.6) by a factor equal to the ratio of operating pressures to design pressures and adding any contribution from the closure nut preload. This methodology is based on linear elastic material behavior. As shown in Table 2.22, all stresses in the containment boundary components are well below the *ASME Boiler and Pressure Vessel Code* allowable stress intensity limits. Therefore, the ES-3100 packaging is acceptable for NCT at an external absolute pressure of 140 kPa (20.31 psi).

Table 2.22. NCT ES-3100 containment boundary stress compared to the allowable stress at reduced and increased external pressures [a]

Stress locations shown in Fig. 2.1	Reduced external pressure [10 CFR 71.71(c)(3)] containment boundary stress @ 173.98 kPa (25.233 psi) gauge kPa (psi)		Increased external pressure [10 CFR 71.71(c)(4)] containment boundary stress @ −63.26 kPa (−9.18 psi) gauge kPa (psi)		Allowable stress or shear capacity (AS)
	kPa (psi) or kg (lb)	M.S.	kPa (psi) or kg (lb)	M.S.	kPa (psi) or kg (lb)
Top flat portion of sealing lid (center of lid)	1.714×10^3 (248.6)	76.2	6.236×10^2 (90.4)	211.3	1.324×10^5 (19,200) [b]
Closure nut ring (away from threaded region)	5.526×10^4 (8,014.1)	7.3	4.246×10^4 [f] (6,158)	9.8	4.571×10^5 (66,300) [c]
Top flat head (sealing surface region)	2.019×10^4 (2,928.9)	12.1	1.665×10^4 [f] (2415)	14.9	2.648×10^5 (38,400) [c]
Cylindrical section (middle)	4.969×10^3 (720.7)	16.8	1.808×10^3 (262.2)	47.8	8.825×10^4 (12,800) [d]
Cylindrical section (shell-to-flange interface)	1.321×10^4 (1,915.5)	19.0	9.374×10^3 (1,359.6)	27.2	2.648×10^5 (38,400) [c]
Cylindrical section (shell-to-bottom interface)	1.275×10^4 (1,848.6)	19.8	4.637×10^3 (672.5)	56.1	2.648×10^5 (38,400) [c]
Body flange threads load, kg (lb)	1.192×10^3 (2,626.7)	16.2	9.072×10^2 [f] (2,000)	21.6	2.053×10^4 (45,266)
Body flange thread region (under cut region)	3.348×10^4 (4,856)	6.9	2.397×10^4 [f] (3,476)	10	2.648×10^5 (38,400) [c]
Flat bottom head (center)	1.200×10^4 (1,740.2)	10	4.365×10^3 (633)	29.3	1.324×10^5 (19,200) [b]
Closure nut thread load, kg (lb)	1.192×10^3 (2,626.7)	28.8	9.072×10^2 [f] (2,000)	38.1	3.545×10^4 [e] (78,154)

[a] Calculated stresses were determined by multiplying the stress at the design conditions (Appendix 2.10.1) by a factor equal to the ratio of operating pressures to design pressures (independent of pressure direction) plus contribution from preload. Allowable stress values are taken from Table 2.5.
[b] Stress interpreted as the sum of $P_l + P_b$; allowable stress intensity value is $1.5 \times S_m$.
[c] Stress interpreted as the sum of $P_l + P_b + Q$; allowable stress intensity value is $3.0 \times S_m$.
[d] Stress interpreted as the primary membrane stress (P_m); allowable stress intensity value is S_m.
[e] Allowable shear capacity is defined as $0.6 \times S_m \times$ thread shear area. Thread shear area = 38.026 cm^2 (5.894 in.^{2}).
[f] Stress and shear load in these areas are dominated by the 162.7 ± 6.8 N·m (120 ± 5 ft-lb) preload.

2.6.5 Vibration

Requirement. Vibration normally incident to transportation is required by 10 CFR 71.71(c)(5).

Analysis. Vibration testing on a prototypical ES-3100 package (Test Unit-4) was conducted in accordance with the ES-3100 test plan (Appendix 2.10.8) and documented in the test report (Appendix 2.10.7). Testing was conducted with the package restrained as shown in Fig. 2.3. The containment vessel was assembled with the mock-up content weighing 49.90 kg (110 lb). The total weight of the test unit was 201.8 kg (445 lb). The unit was subjected to an endurance test with random vibrations modeled after the power spectral density plot for the Safe-Secure Trailer/Safeguards Transporter (SST/SGT) vibration envelope in the vertical axis (Cap, Appendix 2.10.6). At this level of vibration intensity, the test unit compares with MIL-STD-810F. MIL-STD-810F is a standard random vibration test for basic transportation vibrations generated by a large truck or tractor-trailer combination. MIL-STD-810F defines 60 min of testing as equal to 1609 km (1000 miles) of common carrier transportation. Assuming that the two random vibration tests are similar in intensity, Test Unit-4 had about 6436 km (4000 miles) of simulated random vibration testing. Based on a nominal shipping distance of 3218 km (2000 miles), Test Unit-4 was subjected to a test that was approximately two times more severe than that required by 10 CFR 71.71(c)(5). As shown by the following paragraphs, containment, shielding effectiveness, and subcriticality were maintained even when the package was subjected to such an arduous environment.

The test was run at ~22.8 °C (73 °F) rather than at the high or low temperatures specified for NCT. This was reasonable because the thermal coefficients of expansion of the flange and closure nut materials are very close. Therefore, the temperature extremes would not have a significant effect on the closure tightness.

Summarizing 10 CFR 71.43(f), the tests and conditions of NCT shall not substantially reduce the effectiveness of the packaging to withstand HAC sequential testing. The effectiveness of the ES-3100 to withstand HAC sequential testing is not diminished through application of the tests and conditions stipulated in 10 CFR 71.71. The justification for this statement is provided by physical testing of both the ES-2M (Byington 1997) and ES-3100 test packages. Due to the similarities in design, fabrication, and construction materials of the ES-2M and the ES-3100 packages, the physical characteristics of the Kaolite 1600 will hold true for both designs. The integrity of the Kaolite 1600 is not significantly affected by the NCT vibration and 1.2-m drop tests. Prior to testing the ES-2M design, each test unit was radiographed to determine the integrity of the Kaolite 1600 impact and insulation material. Following casting of the material inside the drum, some three-dimensional curving cracks were seen in some packages near the thinner top sections from the bottom of the liner to the bottom drum edge. After vibration testing, radiography of the ES-2M Test Unit-4 showed that the lower half of the impact limiter was broken into small pieces. In order to evaluate these findings, Test Unit-4 was reassembled and subjected to HAC sequential testing. After vibration and impact testing, many three-dimensional curving cracks were seen around the impact areas, and the inner liner was visibly deformed. Nevertheless, Test Unit-4 maintained the adequate spacing required for shielding effectiveness and subcriticality. Temperatures at the containment boundary were also similar to other packages not subjected to vibration testing prior to HAC testing. No inleakage of water was recorded following immersion. Additionally, Test Unit-4 of the ES-3100 test series was subjected to tests and conditions stipulated in 10 CFR 71.71(c)(5) through (c)(10), excluding (c)(8). Following completion of both the NCT and HAC tests, the containment vessel was removed, and a full-body helium leak test was conducted to the leaktight criterion ($\leq 2 \times 10^{-7}$ cm^3/s) in accordance with ANSI N14.5-1997.

Title 10 CFR 71.73(b) requires that the HAC tests, except for the water immersion tests, be conducted at the most unfavorable ambient temperature within the range of −29 to 38°C (−20 to 100°F). This requirement was previously discussed in Sect. 2.6 for NCT, in which it was concluded that the tests performed at 70 to 90°F ambient temperatures should provide essentially the same results, except for thermal, as those made at any ambient temperature between −29 to 38°C (−20 to 100°F). Buckling failures are not anticipated for this package design. This assumption is based on the fact that no evidence of buckling occurred when the package was subjected to the compression test in accordance with 10 CFR 71.71(c)(9); the water immersion tests in accordance with 10 CFR 71.73(c)(5) and 71.73(c)(6); and the 1.2-m and 9-m drop test conducted on Test Unit-4. Code calculations further substantiate that buckling failures of the containment vessel are not anticipated for this package design (Appendix 2.10.1).

Title 10 CFR 71.73(b) states that the HAC initial pressure within the containment boundary vessel during testing shall be considered as the maximum internal normal operating pressure. The internal pressures in the ES-3100 containment vessel at various temperatures for NCT are discussed in Sects. 3.4.1 and 3.4.2 and tabulated in Table 2.20. The maximum normal absolute operating pressure due to insolation and the bounding case parameters is 198.98 kPa (28.859 psia) for the containment vessel. This pressure is well below the design internal gauge pressure of 699.82 kPa (101.5 psi). Increasing the internal pressure in the containment boundary to the value noted above before a free drop (Sect. 2.7.1), crush (Sect. 2.7.2), puncture (Sect. 2.7.3), or water immersion (Sect. 2.7.5) testing would have no detrimental effect on the containment boundary's structural integrity due to the low stresses shown in Table 2.21. Temperature and pressure increases in the containment boundary due to the compliance thermal tests are discussed and evaluated in Sects. 2.7.4 and 3.5.3. A summary of these pressures is presented in Appendix 3.6.5.

Summarizing 10 CFR 71.43(f) and 71.55(d)(4), the tests and conditions of NCT will not substantially reduce the effectiveness of the packaging to withstand HAC sequential testing. The effectiveness of the ES-3100 to withstand HAC sequential testing is not diminished through application of the tests and conditions stipulated in 10 CFR 71.71. The justification for this statement is provided by physical testing of both the ES-2M and ES-3100 test packages, and the analytical structural deformation predicted in Appendix 2.10.2 (summarized in Sect. 2.7.8). Due to the similarities in design, fabrication, and material used in construction of both the ES-2M and the ES-3100 package, the physical characteristics of the Kaolite 1600 will hold true for both designs. The integrity of the Kaolite 1600 is not significantly affected by the NCT vibration and 1.2-m (4-ft) drop tests. Prior to testing the ES-2M design, each test unit was radiographed to determine the integrity of the Kaolite 1600 impact and insulation material. Following casting of the material inside the drum, some three-dimensional curving cracks were seen in some packages near the thinner top sections from the bottom of the liner to the bottom drum edge. After vibration testing, radiography of the ES-2M Test Unit-4 showed that the lower half of the impact limiter was broken into small pieces. In order to evaluate these findings, Test Unit-4 was reassembled and subjected to HAC sequential testing. After vibration and impact testing, many three-dimensional curving cracks were seen around the impact areas, and the inner liner was visibly deformed. Nevertheless, the ES-2M Test Unit-4 maintained the adequate spacing required for shielding effectiveness and subcriticality. Temperatures at the containment boundary were also similar to other packages not subjected to vibration testing prior to HAC testing. No inleakage of water was recorded following immersion. Additionally, Test Unit-4 of the ES-3100 test series was subjected to tests and conditions stipulated in 10 CFR 71.71(c)(5) through (c)(10), excluding (c)(8). Following completion of these NCT tests, the test unit was subjected to the full HAC test battery. Following these tests, the containment vessel was removed and subjected to a full-body helium leak test. Criteria for a leaktight condition was achieved. Based on the success of these units, vibration normally incident to transport does not reduce the effectiveness of the packaging during HAC testing. Thus, the requirements of 10 CFR 71.43(f) and 71.55(d)(4) are satisfied.

2.7.1 Free Drop

Requirement. A free drop of 9 m (30 ft) onto a flat, unyielding, horizontal surface, striking the surface in a position for which maximum damage is expected is required by 10 CFR 71.73(c)(1).

Analysis. Five test packages were drop tested from 9 m (30 ft) in accordance with 10 CFR 71.73(c)(1) with the set up as shown in Fig. 2.8. A description of the drop pad is presented in Sect. 2.6.7. Four different drop positions were used in the testing based on the analytical results from LS-Dyna drop simulations. The ES-3100 test units were designated as Test Units-1, through -5. Test Unit-4 was subjected to the full NCT testing (water spray, 1.2-m (4-ft) drop, compression, penetration, and vibration) prior to HAC testing. The gross weight of the ES-3100 test units varied between 157.4 kg (347 lb) and 203.7 kg (449 lb). Mock-up components weighing between 3.6 kg (8 lb) [Test Unit-5] to 50.3 kg (111 lb) [Test Unit-3] were used during testing. Discussion of the damage to each test package resulting from the 9-m (30 ft) drop is given in subsequent paragraphs. Rationale for the four drop positions is included in the discussion for each test unit. Minor changes to the mid liner and the substitution of the neutron poison from BoroBond4 to Cat 277-4 are further evaluated in Sect. 2.7.8.

Fig. 2.8. 9-m drop test arrangement for all test units.

(Appendix 2.10.8) The drums were disassembled, and the damage was photographed. The post-thermal test weight of each loaded containment vessel was also recorded. Each package was visually inspected, and the condition of the package and any observations were recorded.

After the containment vessels were removed from Test Units 1 through 5, two different leak tests were performed on each containment vessel. An operational leak test was conducted between the O-rings using a CALT5 leak tester. Following this operational leak test, a full body helium leak test was conducted. Details of these leak tests are provided in the test report (Appendix 2.10.7) and the results are summarized in Table 2.23. All five containment vessels were then removed from the drum assembly and immersed under a head of water of at least 0.9 m (3 ft) in a horizontal position for a period of ≥8 h. Following the immersion test of 10 CFR 71.73(c)(6), the containment boundary of Test Units-1 through -5 were opened to remove the contents, gather available data and look for signs of water in-leakage. No water in-leakage was detected in any of the units.

The blackout temperatures on the surface of all five containment boundaries, inner liners, and mock-up components used in the test packages are given in the test report (Test Form 5 for each test unit). Maximum blackout temperatures recorded on the surface of all test units are tabulated in Table 2.50. These values and temperature adjustments are discussed in Sect. 3.5.3.

Conclusion. All five test packages were intact following the 30-min exposure to the high-temperature thermal environment as required in 10 CFR 71.73(c)(4). Examination during disassembly showed that the containment boundary surfaces, flanges, fasteners, sealing surfaces, and O-rings were not damaged by the thermal testing. All five containment boundary assemblies met the subsequent 0.9-m (3-ft) water immersion test and maintained a full-body helium leak rate $\leq 2.0 \times 10^{-7}$ cm^3/s. Following compliance testing, minor changes were made to the mid liner, and the neutron poison was changed from BoroBond4 to Cat 277-4. In order to evaluate the impact of these changes, extensive analytical drop simulations were utilized. A detailed description of the models, material properties, and drop orientations evaluated is shown in Appendix 2.10.2. Results comparing structural deformation and maximum strains in the various material of construction are shown in Sect. 2.7.8. Based on the HAC analytical structural deformation results shown in Sect. 2.7.8, similar compliance test results would be expected had testing been conducted on packages employing the new proposed Cat 277-4 neutron poison. Therefore, the requirements of 10 CFR 71.73(c)(4) were satisfied, and containment was maintained.

2.7.4.1 Summary of pressures and temperatures

The ES-3100 shipping packages will typically be loaded at an ambient temperature and absolute pressure of ~25 °C (77 °F) and 101.35 kPa (14.70 psi), respectively. If the temperature of the package increases during shipment due to external temperature or solar insolation, the drum will not pressurize because four ventilation holes are drilled near the top of the drum, and the drum is not sealed at the drum lid–flange interface. The containment boundary is sealed at assembly. The internal pressure will increase due to transport temperatures, solar insolation (Sect. 3.4.1), decay heating, and the temperatures during HAC (Sect. 3.5.3). Temperature and pressures are summarized in Tables 3.21 and 3.11.

Table 2.50. Maximum HAC temperatures recorded on the test packages' interior surfaces

Temperature patch location [a]	ES-3100 Test Unit				
	1	2	3	4	5
	°C (°F)	°C (°F)	°C (°F)	°C (°F)	°C (°F)
Top plug bottom	149 (300)	163 (325)	177 (350)	177 (350)	177 (350)
Inner liner					
Flange step wall	135 (275)	163 (325)	135 (275)	135 (275)	135 (275)
BoroBond4 step	107 (225)	135 (275)	107 (225)	177 (350)[b]	121 (250)
CV body wall high	99 (210)	99 (210)	99 (210)	99 (210)	104 (219)
CV body wall middle	99 (210)	93 (199)	116 (241)[b]	93 (199)	99 (210)
Bottom flat portion	104 (219)	99 (210)	99 (210)	127 (261)	110 (230)
Containment boundary					
Lid (external top)	116 (241)	110 (230)	116 (241)	127 (261)	127 (261)
Lid (internal)	104 (219)	104 (219)	110 (230)	110 (230)	116 (241)
Flange (external)	116 (241)	110 (230)	110 (230)	116 (241)	121 (250)
Flange (internal)	104 (219)	99 (210)	116 (241)[b]	104 (219)	116 (241)
Body wall mid height	99 (210)	88 (190)	99 (210)	82 (180)	93 (199)
Bottom end cap (center)	99 (210)	99 (210)	88 (190)	110 (230)	99 (210)
Mock-up					
Side top	82 (180)	77 (171)	77 (171)	77 (171)	99 (210)
Side middle	77 (171)	77 (171)	77 (171)	77 (171)	93 (199)
Side bottom	77 (171)	77 (171)	77 (171)	77 (171)	88 (190)

[a] Refer to figures for exact locations and to Test Form 5 in the test report for recorded values. (ORNL/NTRC-013)
[b] Temperature indicating patch may have been damaged due to impact with surrounding structure. See Test Form 5 in ORNL/NTRC-013 for additional information.

The maximum HAC internal absolute pressure in the containment boundary of the ES-3100 has been calculated to be 595.99 kPa (86.441 psia). This predicted pressure is based on a conservative maximum adjusted average gas temperature of 123.85°C (254.93°F) as shown in Sect. 3.5.3 and Appendix 3.6.5.

2.7.4.2 Differential thermal expansion

The drum, inner liner, and containment vessel are all constructed of type 304 or 304L stainless steel. Because of design clearances used during assembly, radial and vertical expansion among these components will not cause any interferences or thermally induced stresses. Due to similarities of the coefficient of thermal expansion between type 304/304L and the containment vessel closure nut (ASTM A-479 and ARMCO Nitronic 60), the compression of the O-rings and the closure nut and containment vessel thread load do not change appreciably during the temperature excursion from 25°C (77°F) to the maximum adjusted containment vessel temperature of 152.22°C (306.0°F) [Sect. 3.5.3].

The Kaolite 1600 insulation and Cat 277-4 neutron poison are poured and cast in place during the fabrication of the drum assembly weldment (Drawing M2E801580A002, Appendix 1.4.8). This process produces a zero gap between the insulation and the bounding drum and inner liner and zero gap between the neutron poison and the mid and inner liners. Because of differences in coefficients of thermal expansion, some radial and axial interferences are expected from thermal growth of the liners. These radial and axial interferences have been addressed by the HAC thermal test. The results show that the stresses induced are minimal and do not reduce the effectiveness of the drum assembly.

Since there are ample clearances between the various size convenience containers and HEU contents, no induced thermal stresses from differences in coefficient of thermal will exist.

2.7.4.3 Stress calculations

The temperature gradient on the containment boundary was essentially uniform from top to bottom during the thermal tests (Table 2.50). The gradient around the periphery of the six test units was also essentially uniform and similar to the vertical gradient. As noted in the ES-3100 test report, the temperatures recorded on the containment vessels of all the test units were fairly uniform, both vertically and circumferentially. The maximum temperature variation on the containment vessels was ~50°F (from the test temperatures reported in Table 2.50). No damage would be expected on the containment vessel from thermal stresses resulting from a temperature differential of this magnitude. This conclusion is based on the guidelines given in the *ASME Boiler and Pressure Vessel Code*, Sect. III, Div. 1. Thermal stress is defined as a self-balancing stress produced by a nonuniform distribution of temperature (ASME B&PVC, Sect. III, Paragraph NB-3213.13). This paragraph further states that there are two types of thermal stresses: general thermal stress and local thermal stress. An example of a general stress is that produced by an axial temperature distribution in a cylindrical shell (ASME B&PVC, Paragraph NB-3213.9). This general stress is further classified (Paragraph NB-3213.9) as a secondary stress (that is, a normal stress or a shear stress developed by the constraint of adjacent materials or by self-constraint of the structure) [ASME B&PVC, Paragraph NB-3213.9]. Paragraph NB-3213.9 further states that the basic characteristic of a secondary stress is that it is self-limiting. Local yielding and minor distortions can satisfy the conditions that cause the stress to occur, and failure from a single application would not be expected. An example of a local thermal stress is a small hot spot in the wall of a pressure vessel (ASME B&PVC, Paragraph NB-3213.13). Local thermal stress is associated with almost complete suppression of the differential expansion and thus produces no significant distortion. Such stresses are considered only from a fatigue standpoint. Fatigue will not result from a one-time cyclic event such as an accidental fire.

The principal effect of the elevated temperature on stress levels is caused by the increase in the internal pressure. The calculated stresses as shown in Table 2.51 were determined by multiplying the stress at the design conditions (Appendix 2.10.1) by a factor equal to the ratio of operating pressures to design pressures and adding any contribution from the closure nut preload. This methodology is based on the application of linear elastic material behavior. As shown in Sect. 2.7.4.4, all stresses in the containment boundary components (based on nominal dimensions for the components) are well below the *ASME Boiler and Pressure Vessel Code* allowable stress intensity limits.

2.7.4.4 Comparison with allowable stresses

As noted in Sect. 2.7.4.3, the differential stresses resulting from temperatures recorded during HAC are negligible. Also, as shown in Table 2.51, stresses of this low magnitude do not affect the adequacy of the packaging. Corresponding calculated stress regions are shown in Fig. 2.1.

Table 2.51. HAC ES-3100 containment boundary stress compared to the allowable stress [a]

Stress locations shown in Fig. 2.1	Thermal condition 10 CFR 71.73 (c)(4) containment boundary stress @494.64 kPa (71.741 psi) gauge & 123.85°C (254.93°F) kPa (psi)		Immersion condition 10 CFR 71.73 (c)(6) containment boundary stress @−150 kPa (−21.76 psi) gauge & −2.22°C (28°F) kPa (psi)		Allowable stress (AS)
	kPa (psi)	M.S.	kPa (psi)	M.S.	kPa (psi)
Top flat portion of sealing lid (center of head)	4.873×10^3 (706.8)	26.2	1.478×10^3 (214.4)	88.6	1.324×10^5 (19,200) [b]
Closure nut ring (away from threaded portion)	7.603×10^4 (11,027)	5.0	4.246×10^4 [f] (6,158)	9.8	4.571×10^5 (66,300) [c]
Top flat head (sealing surface region)	2.525×10^4 (3,661.8)	9.5	1.665×10^4 [f] (2,415)	14.9	2.648×10^5 (38,400) [c]
Cylindrical section (middle)	1.413×10^4 (2,049)	5.2	4.285×10^3 (621.5)	19.6	8.825×10^4 (12,800) [d]
Cylindrical section (shell-to-flange interface)	2.431×10^4 (3,526.5)	9.9	1.238×10^4 (1,795.3)	20.4	2.648×10^5 (38,400) [c]
Cylindrical section (shell-to-bottom interface)	3.624×10^4 (5,255.8)	6.3	1.099×10^4 (1,594.2)	23.1	2.648×10^5 (38,400) [c]
Body flange threads load, kg (lb)	1.715×10^3 (3,781.9)	11	9.072×10^2 [f] (2,000)	21.6	2.053×10^4 (45,266) [e]
Body flange thread region (under cut region)	5.002×10^4 (7,254.7)	4.3	2.397×10^4 [f] (3,476)	10	2.648×10^5 (38,400) [c]
Flat bottom head (center)	3.411×10^4 (4,947.7)	2.9	1.035×10^4 (1,500.7)	11.8	1.324×10^5 (19,200) [b]
Closure nut thread load, kg (lb)	1.715×10^3 (3,781.9)	19.7	9.072×10^2 [f] (2,000)	38.1	3.545×10^4 (78,154) [e]

[a] Calculated stresses were determined by multiplying the stress at the design conditions (Appendix 2.10.1) by a factor equal to the ratio of operating pressures to design pressures (independent of pressure direction) plus contribution from preload. Allowable stress values are taken from Table 2.5.
[b] Stress interpreted as the sum of $P_l + P_b$; allowable stress intensity value is $1.5 \times S_m$.
[c] Stress interpreted as the sum of $P_l + P_b + Q$; allowable stress intensity value is $3.0 \times S_m$.
[d] Stress interpreted as the primary membrane stress (P_m); allowable stress intensity value is S_m.
[e] Allowable shear capacity is defined as $0.6 \times S_m \times$ thread shear area. Thread shear area = 38.026 cm² (5.894 in.²).
[f] Stress and shear load in these areas are dominated by the 162.7 ± 6.8 N·m (120 ± 5 ft-lb) preload.

2.7.5 Immersion—Fissile Material

Requirement. In those cases for which water leakage into the containment boundary has not been assumed for criticality analysis, the specimen must be immersed under a 0.9-m (3-ft) head of water in an attitude for which maximum leakage is expected, as required by 10 CFR 71.73(c)(5).

Analysis. The containment vessels for the ES-3100 test packages (Units-1 through -5) were removed from their respective drum assemblies following the thermal tests described in Sect. 2.7.4.

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Volume 2

SAFETY ANALYSIS REPORT, Y-12 NATIONAL SECURITY COMPLEX, MODEL ES-3100 PACKAGE WITH BULK HEU CONTENTS

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REVISION LOG

Date	SAR Revision No.	Description	Affected Pages
5/6/09	3	This revision was issued to match Amendment 9 of the COC. -Remove the following contents for ground transport that were not reviewed by NRC: • HEU oxides (U_3O_8-Al and UO_2-Mg) • Research reactor fuel elements or components (clad U-Al, U_3O_8-Al, UO_2, or UO_2-Mg) -Remove the following contents for air transport that were not reviewed by NRC: • HEU oxides (UO_2, UO_2-Mg, U_3O_8, and U_3O_8-Al) • Broken HEU bulk metal and uranium-aluminum alloy of unspecified geometric form • Research reactor fuel elements or components (clad U-Al, U_3O_8-Al, UO_2, or UO_2-Mg)	All
4/14/10	3, Page Change 1	Revised SAR to • add uranium oxide loading with a CSI value of 0.4 • remove the 8-lb minimum payload weight • add stainless-steel option for can spacers • revise allowable weight changes for drum body and top plug • revise Drawing M2E801580A005 to clarify marking requirements on drum hex nuts • allow methods other than sieving for establishing minimum content sizes for pyrophoric purposes • revise the purity of the cover gas used for pyrophoric material	i, x, xxv, 1-13, 1-16, 1-22, 1-23, 1-24, 1-27, 1-89 through 1-126, 1-126a, 1-126b, 1-135, 1-147, 1-178a, 1-178b, 1-221, 2-1, 2-14, 2-24, 6-1, 6-3, 6-4, 6-31, 6-35, 6-57, 6-67 through 6-69, 6-104, 6-105, 6-195, 6-717 through 6-892, 7-3, 7-4, 8-9, 8-10

REVISION LOG

Date	SAR Revision No.	Description	Affected Pages
		Note: The NRC performed an acceptance review of Page Change 1 and generated several Requests for Supplemental Information (RSIs). Therefore, Page Change 1 will be superceded by Page Change 2, which incorporates the responses to the RSIs.	
7/22/10	3, Page Change 2	Reissue of Page Change 1 with RSI responses incorporated	i, x, xiv, xxv, xxvi 1-13, 1-16, 1-22, 1-23, 1-24, 1-27, 1-89 through 1-126, 1-126a, 1-126b, 1-135, 1-147, 1-178a, 1-178b, 1-221, 2-1, 2-6, 2-14, 2-24, 2-26, 3-8a, 3-8b, 3-9, 3-10, 3-12, 3-13, 3-18, 3-23, 3-27, 3-27a, 3-27b, 3-100, 3-104, 3-105, 3-115, 3-116, 3-140, 6-1, 6-3, 6-4, 6-31, 6-35, 6-57, 6-67 through 6-69, 6-104, 6-105, 6-195, 6-717 through 6-892, 7-3, 7-4, 8-9, 8-10
1/27/11	3, Page Change 3	Revised SAR in response to RAIs dated October 12, 2010, for review of CoC 9315, Revision 10	i, vi, xiv, xxvi, 2-6, 2-11, 2-36, 2-37, 2-41 through 2-43, 2-53, 2-78, 2-80, 3-16 through 3-18, 3-23, 3-27, 3-27a through 3-27d, 3-28, 3-30, 3-39, 3-147, 3-153 through 3-157, 3-160 through 3-164, 4-7, 4-9, 4-23, 4-25 through 4-34, 7-2, 7-6, 7-7, 7-11

3.1.4 Summary Tables of Maximum Pressures

3.1.4.1 Maximum NCT Pressures

Table 3.10 summarizes the results from Appendix 3.6.4 in which the pressure of the containment vessel when subjected to the tests and conditions of NCT per 10 CFR 71.71 has been determined for the most restrictive containment vessel arrangements (CVAs) shipped in the ES-3100. The most restrictive CVAs are those in which the void volume inside the containment vessel is minimized based on content volumes and those CVAs that carry the largest mass of items that offgas at the predicted temperatures during NCT. Several convenience container heights are proposed for shipment (Fig. 1.4). Shipping configurations will use these containers in any configuration as long as it does not exceed the HEU weight limit and form and does not exceed the height constraint of the containment vessel. However, in order to determine the worst-case shipping configuration, the arrangements that minimize the void volume inside the containment vessel are analyzed as follows:

1. one shipment will contain six cans with external dimensions of 10.8 cm (4.25 in.) diameter by 12.38 cm (4.875 in.) high cans;

2. one shipment will contain five cans with external dimensions of 10.8 cm (4.25 in.) diameter by 12.38 cm (4.875 in.) high cans and three can spacers;

3. one shipment will contain three cans with external dimensions of 10.8 cm (4.25 in.) diameter by 22.23 cm (8.75 in.) high and two can spacers;

4. one shipment will contain three cans with external dimensions of 10.8 cm (4.25 in.) diameter by 25.4 cm (10 in.) high;

5. one shipment will contain six nickel cans with external dimensions of 7.62 cm (3.00 in.) diameter by 12.07 cm (4.75 in.) high;

6. one shipment will contain three polyethylene bottles with external dimensions of 12.54 cm (4.94 in.) diameter by 22.1 cm (8.7 in.) high; and

7. one shipment will contain three teflon bottles with external dimensions of 11.91 cm (4.69 in.) diameter by 23.88 cm (9.4 in.) high.

Table 3.10. Total pressure inside the containment vessel at 87.81°C (190.06°F) [a]

CVA	n_a [b] (lb-mole)	n_v [b] (lb-mole)	n_{po} [b] (lb-mole)	n_{bo} [b] (lb-mole)	n_{tf} [b] (lb-mole)	n_{H2} [b] (lb-mole)	n_{O2} [b] (lb-mole)	n_T [b] (lb-mole)	P_T (psia)
2	5.7148E-04	1.8626E-05	0.0000E+00	0.0000E+00	0.0000E+00	3.1895E-05	1.5948E-05	6.3795E-04	19.238
7	4.5793E-04	2.4829E-04	0.0000E+00	0.0000E+00	2.2296E-05	2.5558E-05	1.2779E-05	7.6685E-04	28.859

[a] This assumes that the internal convenience cans, polyethylene or Teflon FEP bottles, and Cat 277-4 spacer cans are not sealed.

[b] n_a –molar quantity of dry air in the gas mixture;
n_v –molar quantity of water vapor in the gas mixture due primarily from efflorescence;
n_{po} –molar quantity of gas due to offgassing of the silicone rubber pads;
n_{bo} –molar quantity of gas due to offgassing of the polyethylene bags, bottles, and lifting sling;
n_{tf} –molar quantity of gas due to offgassing of the Teflon bottles;
n_{H2} –molar quantity of hydrogen gas due to radiolysis of water;
n_{O2} –molar quantity of oxygen gas due to radiolysis of water;
n_T –total molar quantity in the gas mixture.

These arrangements are shown in Fig. 1.4. To determine the ES-3100's maximum normal operating pressure, the following assumptions have been used in the calculations:

1. The HEU contents are loaded into convenience cans, and convenience cans are placed inside the containment vessel at standard temperature (T_{amb}) and pressure (P_t) [25°C (77°F) and 101.35 kPa (14.7 psia)] with air at a maximum relative humidity of 100%;

2. The convenience cans and bottles are assumed to not be sealed to maximize the void volume inside the containment vessel;

3. Convenience can and bottle geometry does not change during pressure increase inside containment vessel;

4. If metal convenience cans are used, the total amount of polyethylene bagging and lifting slings is limited to 500 g per containment vessel shipping arrangement;

5. The mass of offgassing material (polyethylene bagging or bottles, Teflon bottles, silicone pads, lifting slings) is assumed to be 1490 g for the offgassing evaluation of containment vessel arrangement #7 and 500 g for containment vessel arrangement #6; and

6. Containment vessel arrangements that utilize closed convenience cans with a diameter greater than 10.8 cm (4.25 in.) will not contain any materials that off gas at the temperatures associated with Normal Conditions of Transport (NCT).

The offgassing material limits identified in assumptions 4 and 5 have been established based on the needs of shippers. All configurations are limited to 500 g of polyethylene in the form of bags, slings, and/or bottles. When the requirement to ship material in Teflon bottles arose, the upper limit of 1490 g of offgassing material was established. This limit is a combination of three Teflon bottles (330 g per bottle) and the original 500 g allowance for polyethylene material. These offgassing material limits have been used in calculations pertaining to containment vessel pressure, radioactive material leakage criteria, and criticality control. Therefore, portion of the safety basis of this shipping package has been based on these material limits.

NUREG-1609, Sect. 4.5.2.3, requires the applicant to demonstrate that any combustible gases generated in the package during a period of one year do not exceed 5% (by volume) of the free gas volume in any confined region of the package. No credit should be taken for getters, catalysts, or other recombination devices. The analysis conducted in Appendix 3.6.7 evaluates the different packaging arrangements for the generation of hydrogen gas due to the radiolysis of water vapor, free water, interstitial water, polyurethane bags, and polyurethane or Teflon bottles. By limiting the mass and the material composition as shown in Appendix 3.6.7, the combustible gas concentration limit stated in NUREG-1609 is not exceeded. These limits are further discussed and shown in Tables 1.3 and 1.3a. Getters, catalysts, or other recombination devices are not employed in any of the containment vessel packaging arrangements. The analysis conducted in Appendix 3.6.4 predicts the maximum normal operating pressure inside the containment vessel for the various packaging arrangements and masses discussed previously. This appendix also includes the hydrogen gas generation predicted by Appendix 3.6.7.

3.1.4.2 Maximum HAC Pressures

Table 3.11 summarizes the results from Appendix 3.6.5 in which the pressure of the containment vessel when subjected to the tests and conditions of HAC per 10 CFR 71.73 has been determined for the most restrictive CVAs shipped in the ES-3100. The shipping configurations discussed in Sect. 3.1.4.1 are evaluated for HAC. To determine the maximum pressure generated inside the ES-3100's containment vessel due to HAC conditions, the following assumptions have been used in the calculations:

1. The initial pressure inside the containment vessel is the maximum normal operating pressure shown in Table 3.10 for each CVA at standard temperature [25°C (77°F)];

2. The convenience cans and bottles are assumed to not be sealed in order to maximize the void volume inside the containment vessel;

3. Convenience can and bottle geometry does not change during pressure increase inside containment vessel or because of damage from compliance testing;

4. If metal convenience cans are used, the total amount of polyethylene bagging and lifting slings is limited to 500 g per containment vessel shipping arrangement;

5. The mass of offgassing material (polyethylene bagging or bottles, Teflon bottles, silicone pads, lifting slings) is assumed to be 1490 g for the offgassing evaluation of containment vessel arrangement #7 and 500 g for containment vessel arrangement #6; and

6. Containment vessel arrangements that utilize closed convenience cans with a diameter greater than 10.8 cm (4.25 in.) will not contain any materials that off gas at the temperatures associated with Hypothetical Accident Conditions (HAC).

Table 3.11. Total pressure inside the containment vessel at 123.85°C (254.93°F) [a]

CVA	n_{MNOP} [b] (lb-mole)	n_{po} [b] (lb-mole)	n_{bo} [b] (lb-mole)	n_{tf} [b] (lb-mole)	n_{r-H2} (lb-mole)	n_{r-O2} (lb-mole)	n_{wv} [b] (lb-mole)	n_T [b] (lb-mole)	P_T (psia)
2	7.7228E-04	1.7302E-05	3.1529E-04	0.0000E+00	3.1895E-05	1.5948E-05	0.0000E+00	1.1527E-03	38.236
7	9.2831E-04	0.0000E+00	3.1529E-04	2.2296E-05	2.5558E-05	1.2779E-05	7.8428E-04	2.0885E-03	86.441

[a] This assumes that the internal convenience cans, polyethylene or Teflon FEP bottles, and Cat 277-4 spacer cans are not sealed.

[b] n_{MNOP} –molar quantity of the gas mixture at maximum normal operating pressure at standard temperature [25°C (77°F)];
n_{po} –molar quantity of gas due to offgassing of the silicone rubber pads;
n_{bo} –molar quantity of gas due to offgassing of the polyethylene bags, bottles, and lifting sling;
n_{tf} –molar quantity of gas due to offgassing of the Teflon bottles;
n_{r-H2} –molar quantity of hydrogen gas due to radiolysis of water;
n_{r-O2} –molar quantity of oxygen gas due to radiolysis of water;
n_{wv} –molar quantity of water vapor due to efflorescence of UNX crystals; and
n_T –total molar quantity in the gas mixture.

The offgassing material limits identified in assumptions 4 and 5 have been established based on the needs of shippers. All configurations are limited to 500 g of polyethylene in the form of bags, slings, and/or bottles. When the requirement to ship material in Teflon bottles arose, the upper limit of 1490 g of offgassing material was established. This limit is a combination of three Teflon bottles (330 g per bottle) and the original 500 g allowance for polyethylene material. These offgassing material limits have been used in calculations pertaining to containment vessel pressure, radioactive material leakage criteria, and criticality control. Therefore, portion of the safety basis of this shipping package has been based on these material limits.

3.2 SUMMARY OF THERMAL PROPERTIES OF MATERIALS

3.2.1 Material properties

Thermal properties at various temperatures for the stainless steel used in the fabrication of the drum, noncombustible cast refractory (Kaolite 1600), noncombustible neutron poison (BoroBond 4 or Cat 277-4), silicone rubber pads, and air are listed in Table 3.12. Properties used to evaluate thermal stresses due to differences in coefficient of thermal expansion are listed in Table 3.13.

3.2.2 Component Specifications

Component specifications are listed in Tables 3.14 and 3.15.

3.3 GENERAL CONSIDERATIONS

Thermal evaluation of the package design for NCT was performed by analysis. Evaluation of the package design for HAC was performed by a combination of testing and analysis.

3.3.1 Evaluation by Analysis

A description of the method and calculations used to perform the thermal and thermal stress analyses of the package for NCT and HAC is presented in detail in Appendices 3.6.1, 3.6.2 and 3.6.3.

Table 3.15. Component allowable service temperature and pressure

Component	Allowable service temperature range °C (°F)	Allowable pressure range kPa (psi) gauge
Drum assembly		
Stainless-steel drum and lid	−40 to 871 (−40 to 1600) [a]	48.3 (7)
Silicon bronze nuts	−40 to 871 (−40 to 1600) [a]	N/A
Stainless-steel washers	−40 to 871 (−40 to 1600) [a]	N/A
Stainless-steel mid liner	−40 to 871 (−40 to 1600) [a]	N/A
Stainless-steel inner liner	−40 to 871 (−40 to 1600) [e]	N/A
Stainless-steel top plug weldment	−40 to 871 (−40 to 1600) [a]	
Kaolite 1600	−40 to 871 (−40 to 1600) [a]	N/A
Cat 277-4	−40 to 150 (−40 to 302) [b] −40 to 161 (−40 to 320) [g]	N/A
Silicone rubber pads	−40 to 232 (−40 to 450) [f]	N/A
Containment vessel		
Stainless-steel body and sealing lid	−40 to 427 (−40 to 800) [c]	149.62 (21.7) external 699.82 (101.5) internal
Nitronic 60 closure nut	−40 to 427 (−40 to 800) [c]	149.62 (21.7) external 699.82 (101.5) internal
Stainless-steel retaining ring	−40 to 427 (−40 to 800) [c]	N/A
Dowel pins	−40 to 427 (−40 to 800) [c]	N/A
Brass VCO fitting (Viton O-rings)	−40 to 204 (−40 to 400) [d]	N/A
Ethylene propylene O-rings	−40 to 150 (−40 to 302) [d]	5.52×10^3 (800) with no backing rings
Containment vessel silicone pads	−40 to 232 (−40 to 450) [f]	N/A

[a] In accordance with *Kaolite SuperLightweight Insulating Castables* (Appendix 2.10.3), the recommended use limit temperature for Kaolite 1600 material is 871°C (1600°F). This temperature is the established limit for material in immediate contact with the Kaolite 1600 material and is based on continuous service.
[b] This limit is established based on criticality limits of moisture loss for NCT. It is based on continuous service.
[c] This limit is established by the *ASME Boiler and Pressure Vessel Code*.
[d] This limit is provided by the *Parker O-Ring Handbook* for each material's continuous service limit.
[e] This limit is established based on the fact that the inner liner material is identical to the drum material.
[f] This represents the allowable service temperature limit listed in the McMaster-Carr catalog description for this material.
[g] This limit is established based on criticality limits of moisture loss for HAC. It is based on four hours at this temperature.

3.3.2 Evaluation by Test

Full-scale testing of five ES-3100 test units was conducted in accordance with 10 CFR 71.73 for HAC. A single full-scale ES-3100 (TU-4) was assembled and subjected to both NCT testing and the sequential tests specified in 10 CFR 71.73(c). The furnace used for thermal testing was the No. 3 furnace at Timken Steel Company in Latrobe, Penn., which is a gas-fired furnace. This furnace employs "pulsed" fire burners, in which the natural gas flow rate is varied based on furnace controller demands, but the flow of air through the burners is constant, even when no gas is flowing. This ensures a very rich furnace atmosphere capable of supporting any combustion of package materials of construction.

Oxygen content was not monitored in stack gases of the furnace because it was not anticipated that any of the package's materials of construction were combustible. There was some burning of the silicone pads which are placed between the inner liner and the top plug of the package.

The most significant change to the definition of the HAC thermal test in the current 10 CFR 71 is the requirement for calculation purposes to base convective heat input on "that value which may be demonstrated to exist if the package was exposed to the fire specified." This is not especially significant for this package because it was tested in the gas-fired furnace with burners placed in an attitude which produced a strong convective swirl. Careful examination of the thermal test data indicates that the total heat imparted to the packages was significantly greater than the required total heat specified in 10 CFR 71.73(c)(4).

Compliance with ASTM E-2230-02, *Standard Practice for Thermal Qualification of Type B Packages for Radioactive Materials* (ASTM E-2230-02), was accomplished by the method described in Sect. 7.3 of this standard. This standard is in general agreement with Paragraph 2.2.1 ("Steady-state Method of Compliance") of SG 140.1 entitled *Combination Test Analysis/ Method Used to Demonstrate Compliance to DOE Type B Packaging Thermal Test Requirements (30 Minute Fire Test).* The data from each of the thermal tests, as shown in the test report, show that five of the six thermocouple-instrumented exterior surfaces of each package reached temperatures well in excess of 800°C (1475°F) during the 30-min thermal testing. Similarly, all other surfaces of the furnace, including the support stand, exceeded 800°C (1475°F) during the timed portion of the thermal test. For the test specified in the regulations, regardless of the amount of heat input by convection, radiation, or conduction, the maximum temperature the skin of the package could reach would be 800°C (1475°F). That is, the source of the heat in the regulatory-specified test is at 800°C (1475°F). Heat can only be transferred from a hotter source to a colder source. Thus, regardless of the mode of heat transfer, the greatest temperature a specimen exposed to the 10 CFR 71.73,(c)(4) thermal test can attain is 800°C (1475°F). The thermal performance of the packaging components as an assembled unit has been demonstrated through full-scale tests. Actual tests and procedures followed are described in Sect. 4.5 of ORNL/NTRC-013, Vol. 1. Figures 3.2 through 3.5 show the general testing arrangements.

Since full-scale testing in accordance with 10 CFR 71.73 for HAC was conducted on prototypical packages. No analyses were conducted to show compliance with the HAC thermal test. However, to determine the thermal impacts of (1) an internal heat source, (2) application of insolation during cool down, (3) thermal capacitance differences between test mock-ups and actual contents, and (4) the change in neutron absorbing material, analyses were conducted and are summarized in Appendices 3.6.1 and 3.6.2. Further discussion of these issues is found in Sect. 3.5.3.

3.3.3 Margins of Safety

Tables 3.16 and 3.17 summarize the results of thermal analysis and testing in accordance with NCT and HAC regulatory requirements. Margins of safety have not been calculated. However, the predicted or calculated results of individual components are compared with their allowable continuous service limit for NCT in Table 3.16 and for HAC in Table 3.17. For all components, the values calculated during NCT (Table 3.16) do not approach their allowable limits stated in Table 3.15. The temperature values predicted or calculated for the Kaolite 1600 material, the top plug stainless steel, the silicon bronze nuts, and the Cat 277-4 neutron poison do approach and/or exceed their allowable continuous service limits during HAC thermal testing. However, short-term excursions above these allowable limits as shown in ORNL/NTRC-013/V1 do not reduce the ability of the packaging components to provide their safety functions during HAC. Justification of this statement is provided by the following information:

1. As discussed in Sect. 3.5.2, the thermal tests were conducted in compliance with ASTM E 2230-02 and SG 140.1 using the steady state environmental method to comply with 10 CFR 71.73(c)(4). In order to maintain a 800 °C thermal environment at all locations inside the furnace and on all external surfaces of the shipping package, the set point of the furnace had to be adjusted upward to 871 °C (1600 °F). A direct result of this action was that some of the external thermocouples on the package surface exceeded 871 °C (1600 °F) for short periods of time during the timed thermal test.

2. In accordance with National Bronze & Metals, Inc., the silicon bronze nuts remain solid or crystalline in nature up to a temperature of 1032 °C (1890 °F). Their only safety function during and following the thermal test is to keep the lid attached to the drum assembly. By remaining solid during and following HAC testing, the silicon bronze nuts performed their safety function. All lids remained attached to the drum assembly following HAC thermal testing.

3. In accordance with ASM Aerospace Specification Metals Inc., Type 304/304L stainless steel has a continuous service temperature of 927 °C (1700 °F). During the thermal test, the safety function of the stainless steel in the top plug is to encapsulate the Kaolite 1600 insulating material. As shown in ORNL/NTRC-013/V1, the external temperature does intermittently exceed the continuous service limit of the Kaolite 1600 material. However, these short-term temperature excursions do not diminish the ability of the stainless steel to maintain the boundary around the insulating material. The solidus temperature for stainless steel is ~1399 °C (2550 °F); therefore, there is a significant thermal margin of safety in the stainless steel. All top plugs were intact following HAC thermal testing.

4. As documented in Appendix 2.10.3, the recommended use limit temperature for Kaolite 1600 is 871 °C (1600 °F) and the melting point is 1260 °C (2300 °F). This use limit temperature is also the established limit for material in immediate contact with the Kaolite 1600 material and is based on continuous service at this temperature. As previously stated, the external temperature does intermittently exceed the continuous service limit of the Kaolite 1600 material during the thermal test, but it remains well below its melting point. The safety function of the Kaolite 1600 material is to keep the containment vessel as cool as possible and to meet the leaktight criteria established in ANSI N14.5-1997. Based on temperature and pressure calculations, the containment vessel maintains containment during and after thermal testing to the above criteria. Therefore, short-term temperature excursions above 871 °C do not diminish the ability of the Kaolite 1600 material to perform its safety function.

Table 3.16. Summary of results of evaluation for the ES-3100 under NCT

Conditions	Calculated results	Allowable limit	SARP reference
Minimum package temperature, °C (°F)	−40 (−40)	−40 (−40)	Sect. 3.4.1
Maximum drum assembly stress due to cold conditions per 10 CFR 71.71(c)(2), kPa (psia)	61,150 (8,869)	132,379 (19,200)	Appendix 3.6.3
Minimum containment vessel pressure, kPa (psia)	76.74 (11.13)	0.0 (0.0)	Sect. 3.4.1
Maximum drum temperature with insolation, °C (°F)	117.72 (243.89) [a]	N/A	Appendix 3.6.2 Sect. 3.4.1
Maximum drum assembly stress due to hot conditions per 10 CFR 71.71(c)(1), kPa (psia)	66,934 (9,708)	132,379 (19,200)	Appendix 3.6.3
Containment vessel temperature with insolation, °C (°F)	87.81 (190.06) [a]	427 (800) [b]	Appendix 3.6.2 Sect. 3.4.1
Maximum ethylene propylene O-ring temperature, °C (°F)	87.81 (190.06)	150 (302) [c]	Appendix 3.6.2 Sect. 3.4.1
Maximum containment vessel pressure, kPa (psia)	198.98 (28.859) [d]	801.2 (116.2) [e]	Appendix 3.6.4 Sect. 3.4.2
Maximum silicone bronze nut temperature with insolation, °C (°F) [Node 536]	~108.05 (226.49)	871 (1600) [f]	Sect. 3.1.3.1 Table 3.6
Maximum stainless-steel washer temperature with insolation, °C (°F) [Node 536]	~108.05 (226.49)	871 (1600) [f]	Sect. 3.1.3.1 Table 3.6
Maximum stainless-steel mid liner temperature with insolation, °C (°F) [Node 474]	92.89 (199.20)	871 (1600) [f]	Sect. 3.1.3.1 Table 3.6
Maximum stainless-steel inner liner temperature with insolation, °C (°F) [Node 4721]	87.72 (189.90)	871 (1600) [f]	Sect. 3.1.3.1 Table 3.6
Maximum top plug temperature with insolation, °C (°F) [Node 6339]	112.26 (234.06)	871 (1600) [f]	Sect. 3.1.3.1 Table 3.6
Maximum Kaolite 1600 temperature with insolation, °C (°F) [Node 6339]	112.26 (234.06)	871 (1600) [f]	Sect. 3.1.3.1 Table 3.6
Maximum Cat 277-4 temperature with insolation, °C (°F) [Node 4740]	88.32 (190.98)	150 (302) [f]	Sect. 3.1.3.1 Table 3.6
Maximum silicone rubber pad temperature with insolation, °C (°F) [Node 494]	97.53 (207.56)	232 (450) [f]	Sect. 3.1.3.1 Table 3.6
Maximum Viton O-ring temperature with insolation, °C (°F) [Node 6715]	~87.81 (190.06)	204 (400) [f]	Sect. 3.1.3.1 Table 3.6
Maximum brass VCO fitting temperature with insolation, °C (°F) [Node 6715]	~87.81 (190.06)	204 (400) [f]	Sect. 3.1.3.1 Table 3.6

[a] Appendix 3.6.2.
[b] *ASME Boiler and Pressure Code*, Sect. II, Part D, maximum allowable temperature for Sect. III, Div. 1, Subsection NB vessel.
[c] Maximum O-ring seal life up to 150°C (302°F) for continuous service (*Parker O-ring Handbook,* Fig. 2-24).
[d] Appendix 3.6.4.
[e] Appendix 2.10.1 allowable limit.
[f] See Table 3.15.

Table 3.17. Summary of results of evaluation under HAC for the ES-3100 shipping arrangement using bounding case parameters

Condition with HAC temperature adjustments	Calculated results	Allowable limit	SARP references
Maximum adjusted containment vessel temperature during testing, °C (°F)	152.22 (306.00)	426.67 (800)[a]	Sect. 3.5.3
Maximum containment vessel pressure during testing, kPa (psia)	595.99 (86.441)[b]	801.2 (116.2)[c]	Appendix 3.6.5 Sect. 3.5.3
Maximum adjusted ethylene propylene O-ring temperature, °C (°F)	141.22 (286.20)	150 (302)[d]	Sect. 3.5.3
Maximum silicone bronze nut temperature, °C (°F) [Node 536]	<871 (<1600)	871 (1600)[e]	Sect. 3.1.3.2 Figures 4.40, 4.42, 4.44, 4.46, and 4.48 of ORNL/NTRC-013/V1
Maximum stainless-steel drum washer temperature, °C (°F) [Node 536]	<871 (<1600)	871 (1600)[e]	Sect. 3.1.3.2 Figures 4.40, 4.42, 4.44, 4.46, and 4.48 of ORNL/NTRC-013/V1
Maximum stainless-steel mid liner temperature, °C (°F) [Node 474]	~204 (400)[f]	871 (1600)[e]	Sect. 3.1.3.2 Tables 3.6, 3.7, 3.8, and 3.9
Maximum stainless-steel inner liner temperature, °C (°F) [Node 4721]	~203 (397)[g]	871 (1600)[e]	Sect. 3.1.3.2 Tables 3.6, 3.7, 3.8, and 3.9
Maximum top plug temperature, °C (°F) [Node 6339]	<871 (<1600)	871 (1600)[e]	Sect. 3.1.3.2 Figures 4.40, 4.42, 4.44, 4.46, and 4.48 of ORNL/NTRC-013/V1
Maximum Kaolite 1600 temperature, °C (°F)	>871 (>1600)	871 (1600)[e]	Sect. 3.1.3.2 Figures 4.40, 4.42, 4.44, 4.46, and 4.48 of ORNL/NTRC-013/V1
Maximum Cat 277-4 temperature, °C (°F) [Node 4721]	~161 (320)[g]	161 (320)[e]	Sect. 3.1.3.2 Table 3.6, 3.7, 3.8, and 3.9
Maximum silicone rubber pad temperature, °C (°F) [Node 494]	>232 (450)	NSS[h]	Sect. 3.1.3.2 Figure 5.4 of ORNL/NTRC-013/V1
Maximum Viton O-ring temperature, °C (°F) [Node 6715]	~152 (306)	204 (400)[e]	Sect. 3.1.3.2 Tables 3.20 and 3.21
Maximum brass VCO fitting temperature, °C (°F) [Node 6715]	~152 (306)	204 (400)[e]	Sect. 3.1.3.2 Tables 3.20 and 3.21

[a] *ASME Boiler and Pressure Code*, Sect. II, Part D, max allowable temperature for Sect. III, Div. 1, Subsection NB vessel.

[b] Appendix 3.6.5.

[c] Appendix 2.10.1 at 148.89°C (300°F).

[d] Maximum O-ring seal life up to 150°C (302°F) for continuous service (*Parker O-ring Handbook,* Fig. 2-24).

[e] See Table 3.15.

[f] Maximum HAC temperature adjustments for this location are 6.1°C for blackout readings, 6.1°C for crush plate location differences, 1.4°C for decay heat and insolation after thermal test, and 27.8°C for variation in Kaolite 1600 and Cat. 277-4 densities.

[g] Maximum HAC temperature adjustments for this location are 6.1°C for blackout readings, 6.1°C for crush plate location differences, 4.2°C for decay heat and insolation after thermal test, and 9.8°C for variation in Kaolite 1600 and Cat. 277-4 densities.

[h] Considered a non-safety significant (NSS) component. Therefore, maximum allowable temperature limit during HAC is unknown.

5. By using the appropriate temperature adjustments shown in Table 3.20, the maximum recorded HAC temperature shown in Table 3.9, and the data for Node 4740 in Fig. 21 of Appendix 3.6.2, the 277-4 material reaches its peak temperature (~320°F) ~2 h following the thermal test. Figure 21 in Appendix 3.6.2 also shows that this peak temperature drops ~15°F ~4 h after furnace removal and continuously drops thereafter. The maximum temperature in the 277-4 material occurs at the top of neutron absorber cavity (Node 4740 in the analytical models). As shown in Tables 3.7 and 3.8, the temperature in other regions of the 277-4 (e.g., Nodes 351 and 3888) is well below this maximum temperature for the entire length of time associated with the thermal test and cool-down period. For HAC criticality safety analysis, the entire mass of the 277-4 material is conservatively assumed to have the properties resulting from exposure to 320°F for 4 h.

Based on these results, the ES-3100 components will perform their safety functions during both NCT and HAC.

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3.4 THERMAL EVALUATION UNDER NORMAL CONDITIONS OF TRANSPORT

3.4.1 Heat and Cold

The ambient temperature requirement for NCT is 38°C (100°F). The 35.2 kg of HEU shipped in the ES-3100 package generates a maximum bounding heat load of 0.4 W. The insolation heat flux stipulated in 10 CFR 71.71(c)(1) was used in the calculations. If the package is exposed to solar radiation at 38°C (100°F) in still air, the conservatively calculated temperatures at the top of the drum, on the top surface of the containment vessel, and on the containment vessel near the O-ring sealing surfaces, are 117.72, 87.81, and 87.72°C (243.89, 190.06, 189.90°F), respectively, for the ES-3100. Nevertheless, these temperatures are within the service limits of all packaging components, including the O-rings. The normal service temperature range of the O-rings used in the containment boundary is -40 to 150°C (-40 to 302°F), in accordance with B&PVC, Sect. III; thus, the seal will not be affected by this maximum normal operating temperature.

Using the temperatures calculated for the conditions of 10 CFR 71.71(c)(1), Appendix 3.6.4 predicts that the maximum normal operating pressure inside the containment vessel will be 198.98 kPa (28.859 psia). The design absolute pressure of the containment vessel is 801.17 kPa (116.2 psia), and the hydrostatic test pressure is 1135.57 kPa (164.7 psia). Thus, increasing the internal pressure of the containment vessel to a maximum of 198.98 kPa (28.859 psia) during NCT would have no detrimental effect. Stresses generated in the containment vessel at this pressure are insignificant compared to the materials of construction allowable stress. Table 2.20 provides a summary of the pressure and temperature for the various shipping configurations. As discussed in Sect. 2.6.1.4, the containment vessel and vessel closure nut stresses for these pressure conditions are below the allowable stress values.

Summarizing 10 CFR 71.43(f), the tests and conditions of NCT shall not substantially reduce the effectiveness of the packaging to withstand HAC sequential testing. The effectiveness of the ES-3100 to withstand HAC sequential testing is not diminished through application of the tests and conditions stipulated in 10 CFR 71.71. The justification for this statement is provided by physical testing of both the ES-2M and ES-3100 test packages. Due to the similarities in design, fabrication, and material used in construction of both the ES-2M and the ES-3100 package, the Kaolite 1600 physical characteristics will hold true for both designs. The integrity of the Kaolite 1600 is not significantly affected by the NCT vibration and 1.2-m (4-ft) drop tests.

Prior to testing the ES-2M design (a similarly constructed shipping package), each test unit was radiographed to determine the integrity of the Kaolite 1600 impact and insulation material. Following casting of the material inside the drum, some three-dimensional curving cracks were seen in some packages near the top thinner sections from the bottom of the liner to the bottom drum edge. After vibration testing, radiography of the ES-2M Test Unit-4 showed that the lower half of the impact limiter was broken into small pieces (Byington 1997). To evaluate these findings, Test Unit-4 was reassembled and subjected to HAC sequential testing (Byington 1997). After vibration and impact testing, many three-dimensional curving cracks were seen around the impact areas, and the inner liner was also visibly deformed. Nevertheless, temperatures at the containment boundary were also similar to other packages not subjected to vibration testing prior to HAC testing. No inleakage of water was recorded following immersion. Also, Test Unit-4 of the ES-3100 shipping package was subjected to the full NCT test battery including vibration.

Following these tests, the containment vessel of the ES-2M Test Unit-4 was removed, and a full body helium leak check was performed. The test unit passed the leak-tight criteria in accordance with ANSI N14.5-1997. The containment vessel was then reassembled into the previously tested drum assembly and subjected to the complete HAC testing. Based on the success of this unit and the similar design of the ES-2M, it can be concluded that vibration normally incident to transport does not reduce the effectiveness of the ES-3100 packaging during HAC testing. The ES-3100 has been tested to determine the effectiveness of the package following a sequential NCT 1.2-m (4-ft) drop test and HAC test battery. Throughout all of the vibration and structural testing, the effectiveness of the Kaolite 1600 material as an impact limiter and thermal insulation was not substantially reduced.

Since the components to be shipped have an assumed decay heat load of 0.4 W, a thermal analysis was conducted for the ES-3100 package with and without full solar insolation. The package was analyzed using the ABAQUS/Standard computer code, and the finite element geometry was constructed for each model using MSC.Patran 2004. The predicted temperature, while stored at 38°C (100°F) in the shade, for the drum lid center and the containment vessel flange near the inner O-ring, is 37.89°C (100.20°F) and 38.22°C (100.80°F), respectively. The analysis shows that no accessible surface of the package would have a temperature exceeding 50°C (122°F). Therefore, the requirement of 10 CFR 71.43(g) would be satisfied for either transportation mode (exclusive use or nonexclusive use).

Also, in accordance with 10 CFR 71.71(c)(2), the containment vessel pressure must be calculated at −40°C (−40°F). Given the initial conditions of temperature, relative humidity, no silicone rubber or polyethylene bag offgassing, the pressure is calculated as follows:

$$P_1 \text{ @ } 25°C = P_a + P_v + P_{fo},$$

where,

P_a	=	98.15 kPa (14.236 psia)	(Appendix 3.6.4)
P_v	=	3.20 kPa (0.464 psia)	(Appendix 3.6.4)
P_{fo}	=	0	(no offgassing, Appendix 3.6.4)

At −40°C (−40°F), the partial pressure of the water vapor is conservatively assumed to be zero. Therefore, the final pressure of the mixture at −40°C (−40°F) is calculated according to the ideal gas law based solely on the partial pressure of the air.

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

where,

P_1 = 98.15 kPa (14.236 psia)
T_1 = 25°C (298.15 K)
T_2 = -40°C (233.15 K)
V_1 = V_2

rearranging and solving for P_2,

$$\begin{aligned} P_2 &= P_1 (T_2/T_1) \\ &= (98.15)(233.15/298.15) \\ P_2 &= 76.76 \text{ kPa } (11.13 \text{ psia}). \end{aligned}$$

The cold condition for NCT specified in 10 CFR 71.71 is an ambient temperature in still air and shade of −40°C (−40°F). The 35.2 kg (77.60 lb) of HEU contents in the ES-3100 package generates a maximum bounding decay heat load of 0.4 W. However, in accordance with Regulatory Guide 7.8, the thermal effects of this internal heat source are neglected during evaluation of the package performance at −40°C (−40°F). When exposed to this condition, the package component temperatures will stabilize over time at a temperature approaching −40°C (−40°F). The package has been examined for use at −40°C (−40°F) (Sect. 2.6.2). No detrimental effects on the package structure or sealing capability result from this minimum temperature requirement. The normal service temperature range of the O-rings used in the containment boundary is −40 to 150°C (−40 to 302°F), in accordance with the *Parker O-ring Handbook*; thus, the seal will not be affected by this minimum package temperature in accordance with 10 CFR 71.71(c)(2). Leak testing conducted on Test Unit-2 to the leak tight criteria stipulated by ANSI N14.5-1997 following compliance testing provides justification of the above statements.

3.4.2 Maximum Normal Operating Pressure

The stainless-steel drum and cast refractory system will not pressurize as a result of temperature increases because of four ventilation holes (0.795 cm [0.313 in.] in diameter) drilled in the drum side wall 3.81 cm (1.5 in.) from the flanged top and equally spaced around the drum. The holes are filled with nylon plugs, but they are not hermetically sealed. The inner liner encapsulating the noncombustible neutron poison (Cat 277-4) will not pressurize as a result of temperature increases because of three ventilation holes (0.635 cm [0.25 in.] in diameter) and a slot (1.63 cm [0.64 in.] in width and 4.17 cm [1.64 in.] in length) drilled into this inner liner. These features are covered during transport with aluminum tape to prevent contamination of the neutron poison. This tape does not represent a hermetic seal.

The maximum normal operating pressure is defined in 10 CFR 71.4 as the maximum gauge pressure that would develop in the containment system in a period of one year under the heat conditions specified in 10 CFR 71.71(c)(1). The internal pressure developed under these conditions in the ES-3100 containment vessel is calculated in Appendix 3.6.4 for the most restrictive containment vessel configurations. For conservatism, the decay heat of 0.4 W was used for the maximum internal heat load in evaluating the package for NCT. The maximum calculated internal absolute pressure in the containment vessel with solar insolation and the bounding case parameters is 198.98 kPa (28.859 psia). This pressure incorporates offgassing of the silicone rubber pads, polyethylene bottles, Teflon bottles, and polyethylene bagging and hydrogen gas generation from the radiolysis of water and/or other packing materials. The initial environment inside the containment vessel when assembled is at ambient temperature and pressure with 100% relative humidity. The heat-transfer capability of the packaging is not degraded due to gap creation caused by differences in the fabrication material's coefficient of thermal expansion. Modeling assumed nominal gaps and position based on the engineering drawings of Appendix 1.4.8.

3.4.3 Maximum Thermal Stresses

The temperature of the package under NCT will vary from a low of −40°C (−40°F) throughout the package to a maximum of 117.72 and 87.81°C (243.89 and 190.06°F) (Appendix 3.6.2) on the surface of the drum and the containment vessel, respectively (Sect. 3.4.1). The slow temperature increase or decrease experienced in normal conditions between these limits will result in an essentially uniform temperature change throughout the package. All materials of construction are within this operating temperature range (Table 3.15). Thermal stresses due to differences in thermal expansion are insignificant, as discussed in Sects. 2.6.1.2 and 2.6.2.

To determine the maximum pressure inside the containment vessel as a result of thermal testing, the average adjusted gas temperature must be calculated based on the above results. The approach used is to divide the containment vessel volume into three distinct equal regions and then average the three together. The first volume is represented by the gas adjacent to the containment vessel lid and flange region and the top convenience can. Based on the temperature recorded near the O-rings [116.11°C (241°F)] and the temperature recorded on the external surface of the convenience can [98.89°C (210°F)], the average temperature of the gas in this region is 107.50°C (225.50°F). Using the temperature adjustment of 25.11°C (45.20°F) for this region, the adjusted average temperature in the first region is 132.61°C (270.70°F). The second volume is represented by the gas adjacent to the second convenience can from the top. Based on the temperature recorded on the containment vessel wall and convenience can [92.78°C (199°F)], the average temperature of gas in this region is 92.78°C (199°F). Using the temperature adjustment of 27.89°C (50.20°F) for this region, the adjusted average temperature in the second region is 120.67°C (249.20°F). The third and final volume is represented by the gas adjacent to the bottom convenience can. Again based on the convenience can temperature [87.78°C (190°F)] and the containment vessel end cap temperature [98.89°C (210°F)], the average temperature of gas in this region is 93.33°C (200°F). Using the temperature adjustment of 24.94°C (44.90°F) for this region, the adjusted average temperature in the third region is 118.28°C (244.90°F). Averaging these three temperatures, an average adjusted gas temperature of 123.85°C (254.93°F) is determined for the containment vessel.

As shown in Appendix 3.6.5, the maximum adjusted average gas temperature and pressure in the containment vessel during accident conditions was calculated to be 123.85°C (254.93°F) and 595.99 kPa (86.441 psia), respectively.

The maximum adjusted temperature on the surface of the containment vessel, adjacent to the O-rings, was 141.22°C (286.20°F). This is well within the design range for the packaging. The full body helium leak test on all test units following thermal testing meets the "leaktight" criteria in accordance with ANSI N14.5-1997. Visual inspection following testing and unloading indicated that no distortion or damage occurred in the containment vessel wall, sealing lid, closure nut, O-rings, or sealing surfaces. No water was visible inside the containment vessel following the 0.9-m (3-ft) water immersion test or the 15-m (50-ft) water immersion test on Test Unit-6.

The ES-3100 package satisfies the requirements of 10 CFR 71.73 for transport of the 35.2-kg (77.60-lb) arrangements shown in Table 2.8. Section 2.7 has additional details to support this conclusion.

3.5.4 Accident Conditions for Fissile Material Packages for Air Transport

The expanded fire test conditions specified in 10 CFR 71.55(f)(1)(iv) for fissile material package designs for air transportation was not conducted. The issue of subcriticality is addressed in Section 6 with content mass limits as addressed in Section 1 for air transport.

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Appendix 3.6.4

CONTAINMENT VESSEL PRESSURE DUE TO NORMAL CONDITIONS OF TRANSPORT FOR THE PROPOSED CONTENTS

Prepared by:	M. L. Goins B&W Y-12 December 2007
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II. Molar quantity determination due to offgassing for each containment vessel arrangement

The maximum temperature calculated for the containment vessel is 87.81°C (190.06°F). This temperature is assumed to be constant throughout the containment vessel and contents. Therefore, the polyethylene bags, polyethylene bottles, Teflon FEP bottles, and silicone rubber can pads are assumed to be at this temperature.

Using the above calculated results and the specific gas generation of polyethylene bags and silicone rubber pad measurements at temperatures up to 170°C (338°F) conducted by the Y-12 Development Division, the amount of gas (V_{bo} and V_{po}) generated due to offgassing of the polyethylene bags and bottles, and silicone rubber can pads at any temperature is estimated by first determining the offgassing volume per unit mass at temperature and multiplying that by the total mass of the bags and can supports inside the containment vessel. Based on testing at a temperature of 93.33°C (200°F), no recordable offgassing occurred in the polyethylene bags and bottles, or silicone rubber pad material as documented in Y/DZ-2585, Rev. 2 (Appendix 2.10.4). The value for Teflon FEP material offgassing volume per unit mass (V_{tf}) was obtained from Fig. 10 in Appendix 2.10.9. A value of ~0.12 to 0.13 cm^3/g@STP was recorded over a temperature range of 200 to 400°F. This value was conservatively doubled to 0.25 cm^3/g@STP. These values are used to determine the offgassing volumes as shown below:

V_{po} = $W_p \times 0.0 / 16.387$ (in.^{3}) (offgassing volume of silicone rubber pads)

V_{bo} = $W_b \times 0.0 / 16.387$ (in.^{3}) (offgassing volume of polyethylene bags and bottles or lifting sling)

V_{tf} = $W_{tf} \times 0.25 / 16.387$ (in.^{3}) (offgassing volume of Teflon bottles)

From the ideal gas law, the number of gas moles in the volume at standard temperature and pressure is as follows:

$$n_{io} = \frac{P_V \cdot V_i}{R_u \cdot T_{amb} \cdot 12}$$

A summary of the results obtained using the above equations for the bounding containment vessel arrangement is presented in Tables 3, 4, and 5.

Table 3. Molar quantity of gas generated due to the silicone rubber pad offgassing

CVA	W_p (g)	V_{po} (in.^{3})	P_V (psia)	R_u (ft-lb/lb-mole·R)	T_{amb} (R)	n_{po} (lb-mole)
2	240.09	0.00	14.7	1545.32	537	0.0000E+00
7	0.00	0.00	14.7	1545.32	537	0.0000E+00

Table 4. Molar quantity of gas generated due to the polyethylene bag, sling and bottle offgassing

CVA	W_b (g)	V_{bo} (in.^{3})	P_V (psia)	R_u (ft-lb/lb-mole·R)	T_{amb} (R)	n_{bo} (lb-mole)
2	500.00	0.00	14.7	1545.32	537	0.0000E+00
7	500.00	0.00	14.7	1545.32	537	0.0000E+00

Table 5. Molar quantity of gas generated due to the Teflon bottle offgassing

CVA	W_{tf} (g)	V_{tf} (in.^{3})	P_V (psia)	R_u (ft-lb/lb-mole·R)	T_{amb} (R)	n_{tf} (lb-mole)
7	990.00	15.10	14.7	1545.32	537	2.2296E-05

III. Gas generation due to radiolysis of water

Buildup of hydrogen gas (H_2) and oxygen gas (O_2) in the ES-3100 containment vessel due to radiolysis is incorporated into the pressure calculation by assuming that 5 mol % of the free volume is H_2. Since each mole of H_2 generated is accompanied by 0.5 mole of O_2, the concentration of H_2 will reach 5 mol % when volume of H_2 is 0.05405 times the initial void volume (see Sect. 3.6.7.8 of Appendix 3.6.7). Therefore, the volume of H_2 and O_2 in the void volume (V_v) is determined by the following expressions:

$$V_h = 0.05405 \times V_v \quad \text{and} \quad V_o = 0.5 \times V_h\,.$$

Using the ideal gas law, the number of gas moles of H_2 and O_2 in the volume at standard temperature and pressure is:

$$n_{r\text{-}H2} = \frac{P_v \cdot V_h}{R_u \cdot T_{amb} \cdot 12} \qquad n_{r\text{-}O2} = \frac{P_v \cdot V_o}{R_u \cdot T_{amb} \cdot 12}$$

where

$n_{r\text{-}H2}$ = individual molar quantity for H_2,
$n_{r\text{-}O2}$ = individual molar quantity for O_2,
V_h = volume of H_2 assumed generated by radiolysis,
V_o = volume of O_2 assumed generated by radiolysis.

A summary of the results for H_2 and O_2 generation due to radiolysis using the above equation is presented in Table 6.

Table 6. Molar quantity of oxygen and hydrogen gas generation due to radiolysis

CVA	V_v (in.^{3})	V_h (in.^{3})	V_o (in.^{3})	P_v (psia)	R_u (ft-lb/lb-mole · R)	T_{amb} (R)	n_{r-H2} (lb-mole)	n_{r-O2} (lb-mole)
1	399.75	21.61	10.80	14.7	1545.32	537.0	3.1895E-05	1.5948E-05
7	320.32	17.31	8.66	14.7	1545.32	537.0	2.5558E-05	1.2779E-05

IV. Molar quantity of gas generated due to the efflorescence of the uranyl nitrate crystals (UNX)

The uranyl nitrate crystals (UNX) in any hydrated state will decompose and lose water molecules at the temperature shown in Table 3.16 [87.81°C (190.06°F)]. The partial pressure of water vapor in this mixture is conservatively estimated to be the saturated vapor pressure (P_{sv}) of water at 87.81°C (190.06°F) or 9.344 psia. Using the ideal gas law, the molar quantity of water vapor (n_{wv}) in this volume at the maximum containment vessel temperature and the saturated vapor pressure is:

$$n_{wv} = \frac{P_{sv} \cdot V_v}{R_u \cdot T_{cv} \cdot 12}$$

$$n_{wv} = (9.344)\,(320.32)\,/\,(1545.32 \times 12 \times 650.06)$$
$$n_{wv} = 2.4829 \times 10^{-4} \text{ lb-moles}$$

where

n_{wv} = molar quantity for water vapor;
V_v = void volume of containment vessel;
T_{cv} = maximum temperature of containment vessel; and
P_{sv} = interpolated saturated vapor pressure of water at temperature from *Fundamentals of Classical Thermodynamics*, 2d ed, Table A.1.1, p. 650. (Van Wylen 1973)

V. Total pressure due to offgassing and NCT temperatures inside the containment vessel

The total pressure of the mixture at 87.81°C (190.06°F), P_T, for the bounding containment vessel arrangement is the pressure calculated using the sum of the previously calculated molar quantities of the gases in the containment vessel. Table 7 summarizes the molar constituents and total pressure of each bounding containment vessel arrangement. The following equation is used to calculate the final containment vessel pressure:

$$P_{87.81^\circ C} = \left(\sum n_i \cdot R \cdot T \cdot 12\right) / V_{GMV},$$

where

n_i = individual molar quantity for each gas,
T = average gas temperature = 87.81°C (190.06°F),
V_{GMV} = V_v = gas mixture volume.

At −40°C (−40°F), the partial pressure of the water vapor is conservatively assumed to be zero. Therefore, the final pressure of the mixture at −40°C (−40°F) is calculated according to the ideal gas law based solely on the partial pressure of the air.

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2},$$

where

P_1 = 14.236 psi,
T_1 = 77°F = 536.67 R,
T_2 = −40°F = 419.67 R,
V_1 = V_2.

Rearranging and solving for P_2,

P_2 = $P_1 (T_2/T_1)$,
P_2 = (14.236)(419.67/536.67) = 11.13 psia.

Table 7. Total pressure inside the containment vessel at 87.81°C (190.06°F) [a]

CVA	n_a [b] (lb-mole)	n_v [b] (lb-mole)	n_{po} [b] (lb-mole)	n_{bo} [b] (lb-mole)	n_{tf} [b] (lb-mole)	n_{H2} [b] (lb-mole)	n_{O2} [b] (lb-mole)	n_T [b] (lb-mole)	P_T (psia)
2	5.7148E-04	1.8626E-05	0.0000E+00	0.0000E+00	0.0000E+00	3.1895E-05	1.5948E-05	6.3795E-04	19.238
7	4.5793E-04	2.4829E-04	0.0000E+00	0.0000E+00	2.2296E-05	2.5558E-05	1.2779E-05	7.6685E-04	28.859

[a] This assumes that the internal convenience cans, polyethylene or Teflon FEP bottles, and Cat 277-4 spacer cans are not sealed.

[b] n_a –molar quantity of dry air in the gas mixture;
n_v –molar quantity of water vapor in the gas mixture due primarily to efflorescence;
n_{po} –molar quantity of gas due to offgassing of the silicone rubber pads;
n_{bo} –molar quantity of gas due to offgassing of the polyethylene bags, bottles, and lifting sling;
n_{tf} –molar quantity of gas due to offgassing of the Teflon bottles;
n_{H2} –molar quantity of hydrogen gas due to radiolysis of water;
n_{O2} –molar quantity of oxygen gas due to radiolysis of water; and
n_T –total molar quantity in the gas mixture.

Appendix 3.6.5

CONTAINMENT VESSEL PRESSURE DUE TO HYPOTHETICAL ACCIDENT CONDITIONS FOR THE PROPOSED CONTENTS

Prepared by:	M. L. Goins B&W Y-12 December 2007
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Appendix 3.6.5

CONTAINMENT VESSEL PRESSURE DUE TO HYPOTHETICAL ACCIDENT CONDITIONS FOR THE PROPOSED CONTENTS

The following calculations determine the pressure of the containment vessel when subjected to the tests and conditions of Hypothetical Accident Conditions per 10 CFR 71.73 for the most restrictive convenience can arrangements shipped in the ES-3100 package. The following packaging arrangements are evaluated for shipment:

1. one shipment will contain six cans with external dimensions of 4.25-in. diam by 4.875-in. high;
2. one shipment will contain five cans with external dimensions of 4.25-in. diam by 4.875-in. high and three can spacers, the top can is empty;
3. one shipment will contain three cans with external dimensions of 4.25-in. diam by 8.75-in. high and 2 can spacers;
4. one shipment will contain three cans with external dimensions of 4.25-in. diam by 10-in. high;
5. one shipment will contain six nickel cans with external dimensions of 3.00-in. diam by 4.75-in. high;
6. one shipment will contain three polyethylene bottles with external dimensions of 4.94-in. diam by 8.7-in. high; and
7 one shipment will contain three Teflon FEP bottles with external dimensions of 4.69-in. diam by 9.4-in. high.

To determine this pressure, the following assumptions have been made:

1. The highly enriched uranium (HEU) contents are loaded into convenience cans and placed inside the ES-3100 containment vessel at standard temperature [25°C (77°F)] and at the maximum normal operating pressure (see Table 5 of Appendix 3.6.4) with air at a maximum relative humidity of 100%.
2. The convenience cans are assumed to not be sealed.
3. Polyethylene bagging of contents and/or convenience containers is limited to 500 g per containment vessel shipping arrangement.
4. If metal convenience cans are used, the total amount of polyethylene bagging and lifting slings is limited to 500 g per containment vessel shipping arrangement.
5. The mass of offgassing material (polyethylene bagging or bottles, Teflon bottles, silicone pads, lifting slings) is assumed to be 1490 g for the offgassing evaluation of containment vessel arrangement #7 and 500 g for containment vessel arrangement #6.

The offgassing material limits identified in assumptions 4 and 5 have been established based on the needs of shippers. All configurations are limited to 500 g of polyethylene in the form of bags, slings, and/or bottles. When the requirements to ship material in Teflon bottles arose, the upper limit of 1490 g of offgassing material was established. This limit is a combination of three Teflon bottles (990 g) and the original 500 g allowance for polyethylene material. These offgassing material limits have been used in calculations pertaining to containment vessel pressure, radioactive material leakage criteria, and criticality control. Therefore, portion of the safety basis of this shipping package has been based on these material limits.

Applying Dalton's law concerning a mixture of gases, the properties of each component are considered as though each component exists separately at the volume and temperature of the mixture. Therefore, the molar quantities of each constituent inside the containment vessel (i.e., dry air, water vapor, polyethylene bagging and bottles, silicone rubber pads, and teflon bottles) must be calculated individually.

To calculate these molar properties, the void volume of the containment vessel must be determined. The volume inside an empty ES-3100 containment vessel was determined from Algor finite element software to be 637.18 in.^{3} (10,441.51 cm^3).

I. Molar quantity determination based on MNOP

Table 1. Total pressure inside the containment vessel at 87.81 °C (190.06 °F) [a]

CVA	n_a [b] (lb-mole)	n_v [b] (lb-mole)	n_{po} [b] (lb-mole)	n_{bo} [b] (lb-mole)	n_{tf} [b] (lb-mole)	n_{H2} [b] (lb-mole)	n_{O2} [b] (lb-mole)	n_T [b] (lb-mole)	P_T (psia)
2	5.7148E-04	1.8626E-05	0.0000E+00	0.0000E+00	0.0000E+00	3.1895E-05	1.5948E-05	6.3795E-04	19.238
7	4.5793E-04	2.4829E-04	0.0000E+00	0.0000E+00	2.2296E-05	2.5558E-05	1.2779E-05	7.6685E-04	28.859

[a] This assumes that the internal convenience cans, polyethylene or Teflon FEP bottles, and Cat 277-4 spacer cans are not sealed.

[b] n_a –molar quantity of dry air in the gas mixture;
n_v –molar quantity of water vapor in the gas mixture due primarily to efflorescence;
n_{po} –molar quantity of gas due to offgassing of the silicone rubber pads;
n_{bo} –molar quantity of gas due to offgassing of the polyethylene bags, bottles, and lifting sling;
n_{tf} –molar quantity of gas due to offgassing of the Teflon bottles;
n_{H2} –molar quantity of hydrogen gas due to radiolysis of water;
n_{O2} –molar quantity of oxygen gas due to radiolysis of water; and
n_T –total molar quantity in the gas mixture.

To use the maximum normal operating pressure at standard temperature, the number of lb-mole of gas needs to be increased using the following equation:

$$n_{MNOP} = \frac{P_T \cdot V_v}{R_u \cdot T_{amb} \cdot 12}$$

Using the above molar equations, the total number of moles is summarized in Table 2.

Table 2. Molar summary at MNOP and 25°C (77°F)

CVA	P_T (psia)	V_V (in.^{3})	R_u (ft-lb/lb-mole·R)	T_{amb} (R)	n_{MNOP} (lb-mole)
2	19.238	399.75	1545.32	537	7.7228E-04
7	28.859	320.32	1545.32	537	9.2831E-04

II. Molar quantity determination due to offgassing for each containment vessel arrangement

To determine the maximum pressure inside the containment vessel as a result of thermal testing, the average adjusted gas temperature must be calculated based on the results shown in Sect. 3.5.3. The approach used is to divide the containment vessel volume into three distinct equal regions and then average the three together. The first volume is represented by the gas adjacent to the containment vessel lid and flange region and the top most convenience can. Based on the temperature recorded near the O-rings [116.11°C (241°F)] and the temperature recorded on the external surface of the convenience can [98.89°C (210°F)], the average temperature of the gas in this region is 107.50°C (225.50°F). Using the temperature adjustment of 25.11°C (45.20°F) for this region, the adjusted average temperature in the first region is 132.61°C (270.70°F). The second volume is represented by the gas adjacent to the second convenience can from the top. Based on the temperature recorded on the containment vessel wall and convenience can [92.78°C (199°F)], the average temperature of gas in this region is 92.78°C (199°F). Using the temperature adjustment of 27.89°C (50.20°F) for this region, the adjusted average temperature in the second region is 120.67°C (249.20°F). The third and final volume is represented by the gas adjacent to the bottom convenience can. Again, based on the convenience can temperature [87.78°C (190°F)] and the containment vessel end cap temperature [98.89°C (210°F), the average temperature of gas in this region is 93.33°C (200°F). Using the temperature adjustment of 24.94°C (44.90°F) for this region, the adjusted average temperature in the third region is 118.28°C (244.90°F). Averaging these three temperatures, an average adjusted gas temperature of 123.85°C (254.93°F) is determined for the containment vessel.

Using the above calculated results and the specific gas generation of polyethylene bags and silicone rubber pads measurements at temperatures up to 170°C (338°F) conducted by the Y-12 Development Division (Appendix 2.10.4), the amount of gas generated due to offgassing of the silicone rubber can pads, the polyethylene bags and bottles, and the Teflon FEP bottles at 123.85°C (254.93°F), (V_{po}, V_{bo}, and V_{tf}) is estimated by first determining the offgassing volume per unit mass at temperature and multiplying that by the total mass of the bags, bottles, slings, and silicone rubber can supports inside the containment vessel. Based on testing at an approximate temperature of 141.11°C (286.00°F), values of ~7.0 and ~0.8 cm3/g @STP for the polyethylene bagging and bottles, and silicone rubber pads, respectively, were taken from the curves for the offgassing volume per unit mass as documented in Y/DZ-2585, Rev. 2 (Appendix 2.10.4). The value for Teflon FEP material offgassing volume per unit mass (V_{tf}) was obtained from Fig. 10 in Appendix 2.10.9. A value of ~0.12 to 0.13 cm^3/g@STP was recorded over a temperature range of 200 to 400°F. This value was conservatively doubled to 0.25 cm^3/g@STP. These values are used to determine the offgassing volume as shown below:

V_{po} = $W_p \times 0.8 / 16.387$ (in.^{3}) (offgassing volume of silicone rubber pads)

V_{bo} = $W_b \times 7.0 / 16.387$ (in.^{3}) (offgassing volume of polyethylene bags, bottles, and lifting sling)

V_{tf} = $W_{tf} \times 0.25 / 16.387$ (in.^{3}) (offgassing bottles of Teflon FEP bottles)

From the ideal gas law, the number of gas moles in the volume is as follows:

$$n_i = \frac{P_v \cdot V_i}{R_u \cdot T_{amb} \cdot 12}$$

A summary of the results obtained using the above equations for each containment vessel arrangement is presented in Tables 3, 4, and 5.

Table 3. Molar quantity of gas generated due to the silicone rubber pad offgassing

CVA	W_p (g)	V_{po} (in.^{3})	P_V (psia)	R_u (ft-lb/lb-mole·R)	T_{amb} (R)	n_{po} (lb-mole)
2	240.09	11.72	14.7	1545.32	537	1.7302E-05
7	0.00	0.00	14.7	1545.32	537	0.0000E+00

Table 4. Molar quantity of gas generated due to polyethylene bag, sling, and bottle offgassing

CVA	W_b (g)	V_{bo} (in.^{3})	P_V (psia)	R_u (ft-lb/lb-mole·R)	T_{amb} (R)	n_{bo} (lb-mole)
2	500.00	213.58	14.7	1545.32	537	3.1529E-04
7	500.00	213.58	14.7	1545.32	537	3.1529E-04

Table 5. Molar quantity of gas generated due to the Teflon FEP bottle offgassing

CVA	W_{tf} (g)	V_{tf} (in.^{3})	P_V (psia)	R_u (ft-lb/lb-mole·R)	T_{amb} (R)	n_{tf} (lb-mole)
7	990.00	15.10	14.7	1545.32	537	2.2296E-05

III. Gas generation due to radiolysis of water

Buildup of hydrogen gas (H_2) and oxygen gas (O_2) in the ES-3100 containment vessel due to radiolysis is incorporated into the pressure calculation by assuming that 5 mol % of the free volume is H_2. Since each mole of H_2 generated is accompanied by 0.5 mole of O_2, the concentration of H_2 will reach 5 mol % when volume of H_2 is 0.05405 times the initial void volume (see Sect. 3.6.7.8 of Appendix 3.6.7). Therefore, the volume of H_2 and O_2 in the void volume (V_v) is determined by the following expressions:

$$V_h = 0.05405 \times V_v \quad \text{and} \quad V_o = 0.5 \times V_h .$$

Using the ideal gas law, the number of gas moles of H_2 and O_2 in the volume at standard temperature and pressure is:

$$n_{r\text{-}H2} = \frac{P_v \cdot V_h}{R_u \cdot T_{amb} \cdot 12} \qquad n_{r\text{-}O2} = \frac{P_v \cdot V_o}{R_u \cdot T_{amb} \cdot 12}$$

where

$n_{r\text{-}H2}$ = individual molar quantity for H_2;
$n_{r\text{-}O2}$ = individual molar quantity for O_2;
V_h = volume of H_2 assumed generated by radiolysis;
V_o = volume of O_2 assumed generated by radiolysis.

A summary of the results for H_2 and O_2 generation due to radiolysis using the above equation is presented in Table 6.

Table 6. Molar quantity of oxygen and hydrogen gas generation due to radiolysis

CVA	V_v (in.^{3})	V_h (in.^{3})	V_o (in.^{3})	P_v (psia)	R_u (ft-lb/lb-mole · R)	T_{amb} (R)	n_{r-H2} (lb-mole)	n_{r-O2} (lb-mole)
1	399.75	21.61	10.80	14.7	1545.32	537.0	3.1895E-05	1.5948E-05
7	320.32	17.31	8.66	14.7	1545.32	537.0	2.5558E-05	1.2779E-05

IV. Molar quantity of gas generated due to the efflorescence nature of the uranyl nitrate crystals (UNX)

The uranyl nitrate crystals (UNX) in any hydrated state will decompose and lose water molecules at the average gas temperature shown in Sect. 3.4.3 [123.85°C (254.93°F)]. The partial pressure of water vapor in this mixture is conservatively estimated to be the saturated vapor pressure (P_{sv}) of water at 254.93°F or 32.460 psia. Using the ideal gas law, the molar quantity of water vapor (n_{wv}) in this volume at the maximum containment vessel temperature and the saturated vapor pressure is:

$$\begin{aligned} n_{wv} &= (P_{sv} \cdot V_v) / (R_u \cdot T_{cv} \cdot 12) \\ &= (32.460)\,(320.32) / (1545.32 \times 12 \times 714.93) \\ &= 7.8428 \times 10^{-4} \text{ lb-moles} \end{aligned}$$

where

n_v = individual molar quantity for water vapor;
V_v = void volume of containment vessel;
T_{cv} = average gas temperature inside the containment vessel; and
P_{sv} = interpolated saturated vapor pressure of water at temperature from *Fundamentals of Classical Thermodynamics*, 2d ed, Table A.1.1, p. 650. (Van Wylen 1973)

V. Total pressure due to offgassing and HAC temperatures inside the containment vessel

The total pressure of the mixture at 123.85°C (254.93°F), P_T, for each containment vessel arrangement is the pressure calculated using the sum of the previously calculated molar quantities of the gases in the containment vessel. Table 7 summarizes the molar constituents and total pressure of each containment vessel arrangement. The following equation is used to calculate the final containment vessel pressure:

$$P_{123.85°C} = (\sum n_i \cdot R \cdot T \cdot 12) / V_{GMV} ,$$

where

n_i = individual molar quantity for each gas,
T = average gas temperature = 123.85°C (254.93°F),
V_{GMV} = V_v = gas mixture volume.

Table 7. Total pressure inside the containment vessel at 123.85°C (254.93°F) [a]

CVA	n_{MNOP} [b] (lb-mole)	n_{po} [b] (lb-mole)	n_{bo} [b] (lb-mole)	n_{tf} [b] (lb-mole)	n_{r-H2} [b] (lb-mole)	n_{r-O2} [b] (lb-mole)	n_{wv} [b] (lb-mole)	n_T [b] (lb-mole)	P_T (psia)
2	7.7228E-04	1.7302E-05	3.1529E-04	0.0000E+00	3.1895E-05	1.5948E-05	0.0000E+00	1.1527E-03	38.236
7	9.2831E-04	0.0000E+00	3.1529E-04	2.2296E-05	2.5558E-05	1.2779E-05	7.8428E-04	2.0885E-03	86.441

[a] This assumes that the internal convenience cans, polyethylene or Teflon FEP bottles, and Cat 277-4 spacer cans are not sealed.

[b] n_{MNOP} –molar quantity of the gas mixture at maximum normal operating pressure at standard temperature [25°C (77°F)];
n_{po} –molar quantity of gas due to offgassing of the silicone rubber pads;
n_{bo} –molar quantity of gas due to offgassing of the polyethylene bags, bottles, and lifting sling;
n_{tf} –molar quantity of gas due to offgassing of the Teflon bottles;
n_{r-H2} –molar quantity of hydrogen gas due to radiolysis of water;
n_{r-O2} –molar quantity of oxygen gas due to radiolysis of water;
n_{WV} –molar quantity of water vapor due to efflorescence of UNX crystals; and
n_T –total molar quantity in the gas mixture.

Table 4.5. Regulatory leakage criteria for NCT [a]

Verification activity	Fast absorption		Medium absorption		Slow absorption	
	L_{RN-air} (ref-cm^3/s)	L_{RN-He} (cm^3/s)	L_{RN-air} (ref-cm^3/s)	L_{RN-He} (cm^3/s)	L_{RN-air} (ref-cm^3/s)	L_{RN-He} (cm^3/s)
Design	2.6892E-03	2.9222E-03	2.5775E-03	2.8048E-03	2.2976E-03	2.5098E-03

[a] The procedure used to calculate the above criteria is shown in Appendix 4.6.2. This data has been extracted from Table 1 in Appendix 4.6.2.

Table 4.6. Containment vessel verification tests criteria for NCT

Test Type	Test Values	Leakage test procedure
	Design and compliance leakage testing	
Design verification of O-ring seal (air)	$L_T \leq 1.0 \times 10^{-4}$ ref-cm^3/s	See Appendix 2.10.7
Design verification of containment vessel boundary (helium)	$L_T \leq 2.0 \times 10^{-7}$ cm^3/s	See Appendix 2.10.7
	Verification leakage testing	
Fabrication, periodic, and maintenance (helium)	$L_T \leq 2.0 \times 10^{-7}$ cm^3/s	Y51-01-B2-R-140, Rev. A.1 (Appendix 8.3.1)
	$L_T \leq 1.0 \times 10^{-4}$ ref-cm^3/s	Y51-01-B2-R-074, Rev. A.1 (Appendix 7.5.1)

The complete design verification testing of the ES-3100 package for NCT was conducted on test unit TU-4. Since the containment vessel was assembled at ambient conditions, the pressure was nominally 101.35 kPa (14.70 psia) at 25°C (77°F). In accordance with 10 CFR 71.71(b), the initial pressure inside each containment vessel should be the maximum normal operating pressure (MNOP). As calculated in Appendix 3.6.4, the bounding case MNOP is 198.98 kPa (28.859 psia). The stresses at the maximum normal operating pressure [97.62 kPa (14.159 psig)] are insignificant compared to the allowable stresses (Table 2.21). O-ring grooves are designed and fabricated in accordance with guidance from the *Parker O-ring Handbook*. In accordance with Fig. 3-2 of the *Parker O-ring Handbook*, the durometer of the O-ring, and the tolerance gap from the production drawings, the O-ring should be able to withstand ~800 psig before anti-extrusion devices are required. Therefore, conducting a compliance test with the MNOP in the containment vessel will have little, if any, effect on the results.

Following the design verification testing of paragraphs 10 CFR 71.71(c)(5) through 71.71(c)(10) excluding 71.71(c)(8), Test Unit-4 was subjected to the sequential testing of paragraphs 10 CFR 71.73(c)(1) through (c)(4). Upon removal of the containment vessel from the drum assembly, the cavity between the O-rings was leak checked. This unit recorded a leak rate between the O-rings of 2.4773×10^{-5} ref-cm^3/s.

Following the O-ring leak test, the entire containment boundary of TU-4 was helium leak tested to a value $\leq 2 \times 10^{-7}$ cm^3/s, thereby verifying a leak-tight boundary. The leak-test procedure followed to verify this criteria is documented in the ES-3100 test plan (Appendix 2.10.7). The maximum recorded helium leakage rate for this containment vessel was 2.0×10^{-7} cm^3/s after 20 min of testing. Visual inspection following the testing indicated that neither the vessel body, the O-rings, the seal areas, nor the vessel lid assembly were damaged during the tests. Pictures taken of the containment vessel top following testing showed that the closure nut had rotated a maximum of 0.15 cm (0.060 in.) from its original radial position obtained during assembly. Based on the pitch of the closure nut, this rotation translates into only 0.0013 cm (0.0005 in.) decompression of the O-rings. This compares to the original nominal compression of 0.064 cm (0.025 in.). Therefore, O-ring compression was maintained during compliance testing. Based on these results, the ES-3100 package meets and exceeds the containment criteria specified in 10 CFR 71.51 for NCT when used to ship the contents described in the introductory section of this chapter.

Following fabrication, the containment vessel undergoes hydrostatic pressure testing to 1034 kPa (150 psi) gauge. The hydrostatic test is conducted before the final leakage test. Following the hydrostatic pressure test, and prior to conducting the leakage test, the containment vessel and O-ring cavity must be thoroughly dried. Each vessel is then leak tested with either air or helium to $\leq 1 \times 10^{-7}$ ref-cm^3/s or 2×10^{-7} cm^3/s, respectively. This test ensures the containment vessel's integrity (walls, welds, inner O-ring seal) as delivered for use in accordance with paragraph 6.3.2 of ANSI N14.5-1997.

Following placement of the HEU content inside the containment vessel and joining the body and lid assembly, the volume between the containment vessel's O-ring seals is evacuated and checked to leak $\leq 1 \times 10^{-4}$ ref-cm^3/s. This leak-test procedure is a pressure rise air leak test prescribed in Section 7.1.2. This ensures that each containment vessel has been properly assembled in accordance with paragraph 7.6.4 of ANSI N14.5-1997.

The design verification tests were conducted following compliance tests in accordance with 10 CFR 71.71 and 71.73. The effectiveness of this closure system has been demonstrated by the NCT and HAC tests, which show that the complete containment system, including welds and O-ring seals, meet the leaktight criterion as defined in ANSI N14.5-1997 after the conclusion of the test series documented in *Test Report of the ES-3100 Package* (Appendix 2.10.7).

4.4 CONTAINMENT UNDER HYPOTHETICAL ACCIDENT CONDITIONS (TYPE B PACKAGES)

Requirements. A Type B package, in addition to satisfying the requirements of paragraphs 10 CFR 71.41 through 71.47, must be designed, constructed, and prepared for shipment so that under the tests specified in Sect. 71.73 ("Hypothetical Accident Conditions"), there would be no escape of ^{85}Kr exceeding 10 A_2 in one week, no escape of other radioactive material exceeding a total amount A_2 in one week, and no external radiation dose rate exceeding 10 mSv/h (1 rem/h) at 1 m (40 in.) from the external surface of the package.

Analysis. Calculations have been conducted in Appendix 4.6.2 to determine the regulatory leakage criteria to satisfy the above requirements. The results are shown in Table 4.7. These analyses assume that the total mass of uranium for each component is available for release as an aerosol (worst case). From experimental tests, the maximum aerosol density containing uranium particulate was reported by Curren and Bond to be 9.0×10^{-6} g/cm^3. This aerosol density is used to calculate the total activity concentration in ANSI N14.5-1997, Section B.15 examples 13, 27, and 29. Design leakage rate verification testing of the containment boundary (Table 4.8) was conducted on Test Units-1 through -6 and documented in test report (Appendix 2.10.7). Since each containment vessel was assembled at ambient conditions, the pressure was nominally 101.35 kPa (14.70 psi) at 25 °C (77 °F). In accordance with 10 CFR 71.73(b), for these tests, the initial pressure inside each containment vessel should be the maximum normal operating pressure. As shown in Table 2.21, the stresses at the maximum normal operating pressure are insignificant compared to the allowable stresses. Therefore, conducting compliance testing with nominal pressure in the containment vessel would have little, if any, effect on the results. During the structural and thermal tests conducted on the ES-3100 for HAC, the drum experienced plastic deformation, and the insulation and impact limiter material experienced some deterioration, as anticipated (Sect. 2.7). The containment vessels did not exhibit any signs of damage and passed post-test leak tests and the subsequent 10 CFR 71.73(c)(5)–specified 0.9-m (3-ft) water immersion tests except for Test Unit-6. Test Unit-6 was subjected to the test specified by paragraph 10 CFR 71.73(c)(6). After completion of this test, the containment vessel was removed and the lid was drilled and tapped for a helium leak-check port. The entire containment boundary was then helium leak checked and passed the leaktight criteria. Also, no visible water was seen inside the inner O-ring groove of Test Unit-6 and no water was observed inside any of the other test units.

Table 4.7. Regulatory leakage criteria for HAC [a]

Verification activity	Fast absorption		Medium absorption		Slow absorption	
	L_{RA-air} (ref-cm^3/s)	L_{RA-He} (cm^3/s)	L_{RA-air} (ref-cm^3/s)	L_{RA-He} (cm^3/s)	L_{RA-air} (ref-cm^3/s)	L_{RA-He} (cm^3/s)
Design	5.6523	5.4158	5.4161	5.1909	4.8245	4.6273

[a] The procedure used to calculate the above criteria is shown in Appendix 4.6.2.

Table 4.8. Containment vessel design verification tests for HAC

Test Type	Test Values	Leakage test procedure
	Design and compliance leakage testing	
Design verification of O-ring seal (air)	$L_T \leq 1.0 \times 10^{-4}$ ref-cm^3/s	See Appendix 2.10.7
Design verification of containment vessel boundary (helium)	$L_T \leq 2.0 \times 10^{-7}$ cm^3/s	See Appendix 2.10.7

To verify the entire containment boundary to the leaktight criteria, the containment vessels of Test Units-1 through -5 were helium leak tested using the procedure shown in the test report (Appendix 2.10.7). These test units had previously been subjected to the drop test stipulated in 10 CFR 71.71 (c)(6) and the sequential tests stipulated in 10 CFR 71.73 except for Test Unit-4, which had been first subjected to the testing in accordance with 10 CFR 71.71. The maximum recorded helium leak rate for any of these containment vessels was 2.0×10^{-7} cm^3/s after 20 min of testing on Test Unit-4 as documented in Section 5.2 of the test report (Appendix 2.10.7). Test Units-2 and -5 displayed some unusual pulsing action during leak testing. The peak amplitude changed after adding helium in a manner expected for diffusion through the O-rings rather than a rise immediately following the addition of helium that would indicate a leak to the outside of the containment vessel. This is further discussed and graphically presented in Sect. 5.2.2 of the ES-3100 test report (Appendix 2.10.7). These measured leakage rates verify that the containment vessels are leaktight in accordance with ANSI N14.5-1997. Therefore, the containment boundary of the ES-3100 package was maintained during the HAC testing.

The 35.2 kg of HEU content is unirradiated; therefore, only very small quantities of fission gas products will be produced from spontaneous fission and subcritical neutron induced fission. Fission gas products are produced in such small quantities that they have no measurable effect on the releasable content source term or containment vessel pressurization. Fission gas products will not be considered further in this SAR.

4.5 LEAKAGE RATE TESTS FOR TYPE B PACKAGES

The maximum allowable release of radioactive material allowed by 10 CFR 71.51(a)(2) under HAC is A_2 in one week. Title 10 CFR 71.51(a)(2) also specifies that there be no escape of ^{85}Kr exceeding 10 A_2 in one week. ANSI N14.5-1997 specifies the leakage test methods and leakage rates that are accepted in Nuclear Regulatory Commission (NRC) Regulatory Guide 7.4 as demonstrating that a package meets the 10 CFR 71.51(a)(2) requirements for containment. The containment criteria for the ES-3100 package will be leaktight, defined in ANSI N14.5 paragraph 2.1 as having a leakage rate $\leq 1 \times 10^{-7}$ ref-cm^3/s, during the prototype tests. This leaktight criterion satisfies the design verification requirement stipulated in paragraph 7.2.4 of ANSI N14.5-1997. The requirements of ANSI N14.5-1997 are used for all stages of containment verification for the ES-3100 (i.e., design, fabrication, maintenance, periodic and preshipment). The design, fabrication, maintenance and periodic leakage rate limit is 1×10^{-7} ref-cm^3/s air (or 2.0×10^{-7} cm^3/s helium). The pass criterion for the preshipment leakage rate test, which demonstrates correct assembly of the containment vessels, is 1×10^{-4} ref-cm^3/s, which exceeds the requirements given in ANSI N14.5-1997, paragraph 7.6.4. In accordance with the definition of sensitivity of a leakage test procedure provided in Sections 2 and 7.6.4 of ANSI N14.5-1997, the minimum acceptable leakage rate that the procedure needs to be capable of detecting is 1×10^{-3} ref-cm^3/s. The requirements for the ES-3100 exceed the regulatory criterion by specifying a leakage rate of $\leq 1 \times 10^{-4}$ ref-cm^3/s, and equipment used in accordance with Section 7.6.4 of ANSI N14.5-1997 would not detect this leakage. The preshipment, fabrication, maintenance, and periodic leakage rate tests are required to be conducted on each containment vessel in accordance with ANSI N14.5-1997 and are specified in Chapters 7 and 8. These leakage rates are not dependent on filters or mechanical cooling.

The requirements of ANSI N14.5-1997 are used for all stages of containment verification for the ES-3100; the design (HAC test) leakage rate limit is 1×10^{-7} ref-cm^3/s (which is defined as leaktight in ANSI N14.5-1997). The packaging has been shown to maintain containment before and after prototype testing by leakage tests performed for containment verification to the requirements of ANSI N14.5-1997. Test Unit-4's containment vessel was subjected to both the NCT and HAC tests. Test Units-1 through -5 were subjected to the free drop stipulated in 10 CFR 71.71(c)(7) and to the sequential HAC test stipulated in 10 CFR 71.73. Following these tests, each containment vessel was helium leak tested in accordance with the test plan. Again, the test results verified that the containment vessels were leaktight. Thus, there could be no release of radioactive materials from the containment vessels. These leakage rates are not dependent on filters or mechanical cooling. These measured leakage rates verify that the containment vessels are leaktight in accordance with ANSI N14.5-1997.

Therefore, the ES-3100 package meets the containment criteria as specified in 10 CFR 71.73 for HAC when shipping the proposed 35.2 kg of HEU in the containment vessel.

Appendix 4.6.2

CALCULATION OF THE ES-3100 CONTAINMENT VESSEL'S REGULATORY REFERENCE AIR LEAKAGE RATES

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Appendix 4.6.2

CALCULATION OF THE ES-3100 CONTAINMENT VESSEL'S REGULATORY REFERENCE AIR LEAKAGE RATES

Introduction

The ES-3100 leak-testing requirements of the containment boundary are based on the smallest maximum allowable leakage rate generated from the maximum uranium content defined in Table 4.3. Section 5 of ANSI N14.5-1997 defines the maximum allowable leakage rate based on the maximum allowable release rate. These leakage rates, L_N and L_A, are the maximum allowable O-ring seal leakage rates for Normal Conditions of Transport (NCT) and Hypothetical Accident Conditions (HAC). The worst-case maximum allowable leakage rates are used to calculate an equivalent leakage hole diameter following ANSI N14.5-1997, Appendix B, for each condition of transport. This leakage hole diameter is used to calculate a reference air and a helium leakage rate for leak testing. A bounding mass for the highly enriched uranium (HEU) content of 35.2 kg is used in this calculation to certify the ES-3100 package for shipment. The maximum allowable leakage rates are calculated using this maximum content mass in a much more dispersive form (oxide powder) at the highest calculated pressures and temperatures. This appendix shows the procedure used to calculate the leak criteria for the uranium constituents in the "slow lung absorption" group. Table 1 shows the results of using this procedure for fast, medium, and slow absorption uranium constituents as a function of decay time.

HEU Content

Calculate R_N and R_A: Table 4.1

The maximum allowable release rate is based on using A_2.

$A_2 = 1.0997 \times 10^{-3}$ TBq, (2.9720×10^{-2} Ci). Table 6 (Appendix 4.6.1)

The containment requirements for NCT and HAC are:

$$\begin{aligned} R_N &= A_2 \times 10^{-6}\ \text{TBq/h} = A_2 \times 2.78 \times 10^{-10}\ \text{TBq/s}, \\ &= 1.0997 \times 10^{-3} \times 2.78 \times 10^{-10}\ \text{TBq/s}, \\ &= 3.0570 \times 10^{-13}\ \text{TBq/s}, (8.2623 \times 10^{-12}\ \text{Ci/s}). \end{aligned}$$
ANSI N14.5-1997 (Eq. 1)

$$\begin{aligned} R_A &= A_2\ (\text{TBq/week}), \\ &= A_2 \times 1.65 \times 10^{-6}\ (\text{TBq/s}), \\ &= 1.0997 \times 10^{-3} \times 1.65 \times 10^{-6}\ \text{TBq/s}, \\ &= 1.8144 \times 10^{-9}\ \text{TBq/s}, (4.9038 \times 10^{-8}\ \text{Ci/s}). \end{aligned}$$
ANSI N14.5-1997 (Eq. 2)
or limited to 10 A_2/week of ^{85}Kr

Following ANSI N14.5-1997, the medium aerosol activity must be calculated to determine the leakage rates.

m = total nuclide mass in the package available for release (g),
TotA = total activity in the package available for release (TBq),
TSA = total specific activity in the package available for release (TBq/g).

For HEU content:

$$\begin{aligned} TSA &= TotA / m, \\ &= 3.2328 \times 10^{-1}\ (TBq) / 35{,}200\ (g), && \text{Table 6 (Appendix 4.6.1)} \\ &= 9.1842 \times 10^{-6}\ TBq/g. \end{aligned}$$

$$\rho_P = 9 \times 10^{-6}\ g/cm^3. \qquad \text{The maximum density of powder aerosols in the fill gas}$$

For any packaging arrangement:

$$\begin{aligned} C_N &= \text{activity per unit volume of medium that could escape from the containment system } (TBq/cm^3). \\ &= TSA \times \rho_P, \\ &= 9.1842 \times 10^{-6}\ (TBq/g) \times 9 \times 10^{-6}\ (g/cm^3), \\ &= 8.2658 \times 10^{-11}\ TBq/cm^3. \end{aligned}$$

Using Curren's maximum aerosol density, $C_A = C_N$:

$$\begin{aligned} C_A &= \text{activity per unit volume of exiting gas } (TBq/cm^3), && \text{HAC} \\ &= 8.2658 \times 10^{-11}\ TBq/cm^3. \end{aligned}$$

Section 6.1 of ANSI N14.5-1997 calculates L_N with (Eq. 3) and L_A with (Eq. 4). L_N and L_A are the maximum allowable leakage rates for the containment vessel fill gas aerosol during NCT and HAC, respectively.

$$\begin{aligned} L_N &= \text{maximum allowable leakage rate for the medium for NCT } (TBq/cm^3), \\ &= R_N / C_N, && \text{ANSI N14.5-1997 (Eq. 3)} \\ &= 3.0570 \times 10^{-13}\ (TBq/s) / 8.2658 \times 10^{-11}\ (TBq/cm^3), \\ &= 3.6984 \times 10^{-3}\ cm^3/s. \end{aligned}$$

$$\begin{aligned} L_A &= \text{maximum allowable leakage rate for the medium for HAC } (TBq/cm^3), \\ &= R_A / C_A, \\ &= 1.8144 \times 10^{-9}\ (TBq/s) / 8.2658 \times 10^{-11}\ (TBq/cm^3), \\ &= 2.1951 \times 10^{1}\ cm^3/s. \end{aligned}$$

L_N and L_A correspond to the upstream volumetric leakage rate (L_u) at the upstream pressure (P_u) in the ANSI N14.5-1997 formulas for use later in this appendix. The reference air leakage rates $L_{R,N}$ and $L_{R,A}$ for NCT and HAC, based on the L_N and L_A, are then calculated using maximum temperatures and pressure combinations from Table 3.16 and Table 5 in Appendix 3.6.5.

Determination of the Leakage Test Procedure Requirements for the HEU Content

This calculation will examine the most conservative effects of a fully loaded containment vessel with an HEU mass of 35.2 kg. The smallest allowable leakage values are shown in Tables 4.5 and 4.7. The A_2 value and the maximum content activity-to-A_2 value ratio for this mixture were calculated for several different decay times (Table 6, Appendix 4.6.1). As calculated in Appendix 4.6.1, the A_2 value and the maximum content activity-to-A_2 ratio used to qualify this package occur at about 70 years of decay and are 1.0997×10^{-3} TBq (2.9720×10^{-2} Ci) and 293.99, respectively. These values are used to determine the leakage test procedural requirements when packaging any convenience cans/contents arrangements in the ES-3100 package. The convenience cans are sealed inside the containment vessel in an environmentally controlled area. The ES-3100 package has been analyzed thermally in Sect. 3; it was evaluated at a maximum NCT gas temperature of 87.81°C (190.06°F) [100°F with solar insolation] and a maximum adjusted HAC gas temperature of 123.85°C (254.93°F).

The following analysis determines the maximum allowable O-ring seal air reference leakage rate for both NCT and HAC. The ANSI N14.5-1997 recommended method using a straight circular tube to model the leakage path is applied. Using this "standard" leakage hole model permits the calculation of equivalent reference leakage rates from which leak-test requirements can be established. Viscosity data for air and helium used in the following analyses were obtained from curve fitting routines at specific temperatures based on viscosity data for air (Handbook of Chemistry and Physics, 55th ed.) and helium (NBS Technical Note 631).

L_N and L_A correspond to the upstream volumetric leakage rate (L_u) at the upstream pressure (P_u).

$$L_N = 3.6984 \times 10^{-3}\ cm^3/s,$$
$$L_A = 2.1951 \times 10^{1}\ cm^3/s.$$

Find the maximum pressure and temperature in the containment vessel:

Converting the temperature to degrees Kelvin:

$$T = 273.15 + T(°C),$$
$$= 273.15 + 5/9\,(°F - 32)\ (K).$$

$$T_N = 273.15 + 5/9\,(190.06°F - 32)\ (K), \qquad \text{(Sect. 3.4.1, for T = 190.06°F)}$$
$$= 360.961\ K. \qquad \text{NCT}$$

$$T_A = 273.15 + 5/9\,(254.93°F - 32)\ (K), \qquad \text{(Sect. 3.5.3, for T = 254.93°F)}$$
$$= 397.000\ K. \qquad \text{HAC}$$

Converting the pressures from psia to atmospheres:

$$P_N = P\ (psia) / 14.696\ (psia/atm), \qquad \text{where P is the pressure in Sect. 3.4.2}$$
$$= 28.859\ (psia) / 14.696\ (psia/atm), \qquad \text{NCT}$$
$$= 1.9637\ atm.$$

$$P_A = P\ (psia) / 14.696\ (psia/atm), \qquad \text{where P is the pressure in Sect. 3.5.3}$$
$$= 86.441\ (psia) / 14.696\ (psia/atm), \qquad \text{HAC}$$
$$= 5.8819\ atm.$$

NCT Leakage Hole Diameter for the HEU Content

The following calculations determine the leakage hole diameter that generates the maximum allowable leakage rate during NCT. To keep these calculations conservative, the maximum values for temperature and pressure were used as steady-state conditions for NCT.

Input data for NCT with air fill gas:

L_N	=	3.6984×10^{-3} cm^3/s,	Maximum upstream leakage
P_u	=	1.9637 atm,	Upstream pressure = 28.859 psia
P_d	=	0.2382 atm,	Downstream pressure = 3.5 psia, per 10 CFR 71.71(3)
a	=	0.3531 cm,	Leak path length, 0.139-in. O-ring section diameter
T	=	360.96 K,	Fill gas temperature = 190.06°F
μ	=	0.02141 cP,	Viscosity at temperature
M	=	29 g/g-mole.	Molecular weight of fill gas

The average pressure is:

$$P_a = (P_u + P_d) / 2,$$
$$= (1.9637 + 0.2382) / 2,$$
$$= 1.1009 \text{ atm.}$$
Average pressure during NCT

According to ANSI N14.5-1997, the flow leakage hole diameter is unknown. Therefore, the mass-like leakage flow rate must be calculated to calculate the average leakage flow rate.

Q is the mass-like leakage for flow using the upstream leakage, L_u, and pressure, P_u:

$$Q = P_u L_u, \qquad \text{(Eq. B1)}$$
$$L_u = L_N. \qquad \text{NCT leakage}$$

$$Q = (1.9637)(\text{atm})\ (3.6984 \times 10^{-3})(\text{cm}^3/\text{s}),$$
$$= 7.2628 \times 10^{-3} \text{ atm-cm}^3/\text{s}.$$
NCT mass-like leakage rate

$$Q = P_a L_a, \qquad \text{(Eq. B1)}$$

$$L_a = Q / P_a = 7.2628 \times 10^{-3} (\text{atm-cm}^3/\text{s}) / (1.1009)(\text{atm}),$$
$$= 6.5968 \times 10^{-3} \text{ cm}^3/\text{s}.$$
NCT average leakage rate

Solve equations B2–B4 from ANSI N14.5-1997:

$$L_a = (F_c + F_m)(P_u - P_d) \text{ cm}^3/\text{s}, \qquad \text{(Eq. B2)}$$
$$= (F_c + F_m)(1.9637 - 0.2382),$$
$$= (1.7256)(F_c + F_m) \text{ cm}^3/\text{s}.$$

$$F_c = (2.49 \times 10^6)\, D^4 / (a\, \mu)\ (\text{cm}^3/\text{atm-s}), \qquad \text{(Eq. B3)}$$
$$= (2.49 \times 10^6)\, D^4 / [(0.3531)(0.02141)],$$
$$= (3.2943 \times 10^8)\, D^4 \text{ cm}^3/\text{atm-s}.$$

$$F_m = (3.81 \times 10^3)\, D^3 (T / M)^{.5} / (a\, P_a)\ (\text{cm}^3/\text{atm-s}), \qquad \text{(Eq. B4)}$$
$$= (3.81 \times 10^3)\, D^3 (360.96 / 29)^{.5} / [(0.3531)(1.1009)],$$
$$= (3.4581 \times 10^4)\, D^3 \text{ cm}^3/\text{atm-s}.$$

From the mass-like leakage calculation:

$$L_a = 6.5968 \times 10^{-3} \text{ cm}^3/\text{s}.$$
NCT average leakage rate

Find the leakage hole diameter that sets:

$$L_2 = L_a.$$

Using the equations:

$$L_2 = (1.7256)(F_c + F_m) \text{ cm}^3/\text{s},$$
$$F_c = (3.2943 \times 10^8)\, D^4 \text{ cm}^3/\text{atm-s},$$
$$F_m = (3.4581 \times 10^4)\, D^3 \text{ cm}^3/\text{atm-s}.$$

To get a better guess on a new D use:

$$D = D_2 (L_a / L_2)^{0.252}.$$

Now a guess must be made for D_2 to solve Eq. B2 for NCT:

D_2 = 0.001 cm, and solve for $L_a = 6.5968 \times 10^{-3}$ cm^3/s. NCT average leakage rate

Diameter	F_c	F_m	L_2	L_a / L_2
1.0000E-03	3.2943E-04	3.4581E-05	6.2815E-04	1.0502E+01
1.9725E-03	4.9870E-03	2.6539E-04	9.0635E-03	7.2784E-01
1.8208E-03	3.6205E-03	2.0873E-04	6.6078E-03	9.9834E-01
1.8200E-03	3.6145E-03	2.0847E-04	6.5969E-03	9.9999E-01
1.8200E-03	3.6144E-03	2.0847E-04	6.5968E-03	1.0000E+00

The NCT leakage hole diameter for the HEU oxide content:

$D = 1.8200 \times 10^{-3}$ cm. NCT diameter

NCT Reference Air Leakage Rate for HEU Content

The leakage hole diameter found for the maximum allowable leakage rate for NCT will be used to determine the reference air leakage rate. O-ring seal leakage testing must ensure that no leakage is greater than the leakage generated by the hole diameter $D = 1.8200 \times 10^{-3}$ cm. Therefore, the NCT reference leakage flow rate ($L_{R,N}$) must be calculated to determine the allowable test leakage rate.

Input data for NCT reference air leakage rate:

D	=	1.8200×10^{-3} cm,	From NCT
a	=	0.3531 cm,	Leak path length, 0.139-in. O-ring section diameter
P_u	=	1.0 atm,	Upstream pressure
P_d	=	0.01 atm,	Downstream pressure
T	=	298 K,	Fill gas temperature, 77°F
M	=	29 g/g-mole,	Molecular weight of air
μ	=	0.0185 cP,	Viscosity of air at reference temperature

Calculate P_a:

$$
\begin{aligned}
P_a &= (P_u + P_d) / 2, \\
&= (1.0 + 0.01) /2, \\
&= 0.505 \text{ atm.} && \text{NCT average pressure}
\end{aligned}
$$

$$
\begin{aligned}
F_c &= (2.49 \times 10^6)\, D^4 / (a\ \mu)\ (\text{cm}^3/\text{atm-s}), && \text{(Eq. B3)} \\
&= (2.49 \times 10^6)\, (1.8200 \times 10^{-3})^4 / [(0.3531)\,(0.0185)], \\
&= (3.8122 \times 10^8)\, (1.8200 \times 10^{-3})^4, \\
&= 4.1827 \times 10^{-3} \text{ cm}^3/\text{atm-s}.
\end{aligned}
$$

$$
\begin{aligned}
F_m &= (3.81 \times 10^3)\, D^3\, (\,T / M\,)^{.5} / (\,a\ P_a\,)\ (\text{cm}^3/\text{atm-s}), && \text{(Eq. B4)} \\
&= (3.81 \times 10^3)\, (1.8200 \times 10^{-3})^3\, (298 / 29)^{.5} / [(0.3531)\,(0.505)], \\
&= (6.8501 \times 10^4)\, (1.8200 \times 10^{-3})^3, \\
&= 4.1296 \times 10^{-4} \text{ cm}^3/\text{atm-s}.
\end{aligned}
$$

$$
\begin{aligned}
L_u &= (F_c + F_m)\, (P_u - P_d)\, (P_a / P_u)\ (\text{cm}^3/\text{s}), && \text{(Eq. B5)} \\
&= (4.1827 \times 10^{-3} + 4.1296 \times 10^{-4})(\text{cm}^3/\text{atm-s})\ (1.0 - 0.01)(\text{atm})\ (0.505 / 1.0), \\
&= (4.5957 \times 10^{-3})(\text{cm}^3/\text{atm-s})\ (0.49995)(\text{atm}), \\
&= 2.2976 \times 10^{-3} \text{ cm}^3/\text{s}.
\end{aligned}
$$

The reference air leakage rate as defined in ANSI N14.5-1997, Sect. B.3, is the upstream leakage in air.

$$
L_{RN,Air} = 2.2976 \times 10^{-3} \text{ ref-cm}^3/\text{s}. \qquad \text{For HEU oxide content}
$$

The same equations can be used to calculate an allowable leakage rate using helium for leak testing.

$$
\begin{aligned}
M &= 4 \text{ g/g-mole}, && \text{Molecular weight of helium} \\
\mu &= 0.0198 \text{ cP}. && \text{Viscosity of helium at temperature}
\end{aligned}
$$

$$
\begin{aligned}
F_c &= (2.49 \times 10^6)\, D^4 / (a\ \mu\,)\ (\text{cm}^3/\text{atm-s}), && \text{(Eq. B3)} \\
&= (2.49 \times 10^6)\, (1.8200 \times 10^{-3})^4 / [(0.3531)\,(0.0198)], \\
&= (3.5619 \times 10^8)\, (1.8200 \times 10^{-3})^4, \\
&= 3.9081 \times 10^{-3} \text{ cm}^3/\text{atm-s}.
\end{aligned}
$$

$$
\begin{aligned}
F_m &= (3.81 \times 10^3)\, D^3\, (T / M)^{.5} / (a\ P_a)\ (\text{cm}^3/\text{atm-s}), && \text{(Eq. B4)} \\
&= (3.81 \times 10^3)\, (1.8200 \times 10^{-3})^3\, (\,298 / 4\,)^{.5} / [(0.3531)\,(0.505)], \\
&= (1.8444 \times 10^5)\, (1.8200 \times 10^{-3})^3, \\
&= 1.1119 \times 10^{-3} \text{ cm}^3/\text{atm-s}.
\end{aligned}
$$

$$
\begin{aligned}
L_u &= (F_c + F_m)\, (P_u - P_d)\, (P_a / P_u)\ (\text{cm}^3/\text{s}), && \text{(Eq. B5)} \\
&= (3.9081 \times 10^{-3} + 1.1119 \times 10^{-3})(\text{cm}^3/\text{atm-s})\ (1.0 - 0.01)(\text{atm})\ (0.505 / 1.0), \\
&= (5.0200 \times 10^{-3})(\text{cm}^3/\text{atm-s})\ (0.49995)(\text{atm}), \\
&= 2.5098 \times 10^{-3} \text{ cm}^3/\text{s}.
\end{aligned}
$$

The allowable leakage rate using helium for leak testing is:

$$
L_{RN,\,He} = 2.5098 \times 10^{-3} \text{ cm}^3/\text{s}. \qquad \text{NCT helium test value}
$$

HAC Leakage Hole Diameter for HEU Content

The calculation of a maximum allowable leakage rate hole diameter is based on the temperature and pressure of the fill gas aerosol for HAC, assuming the content is in an oxide powder form. Keeping this calculation conservative, the maximum values for temperature and pressure were used as steady-state conditions for a week. The maximum values were generated during the 30-min burn test for HAC.

Input data for HAC:

L_A	=	21.951 cm^3/s,	Maximum exit leakage
P_u	=	5.8819 atm,	Upstream pressure = 86.441 psia
P_d	=	1.0 atm,	Downstream pressure
T	=	397.000 K,	Fill gas temperature = 254.93°F
μ	=	0.02297 cP,	Viscosity of air at temperature
M	=	29 g/g-mole,	Molecular weight of air
a	=	0.3531 cm.	Leak path length, 0.139-in. O-ring section diameter

$$P_a = (P_u + P_d) / 2$$
$$= (5.8819 + 1.0) / 2, \qquad \text{HAC average pressure}$$
$$= 3.4410 \text{ atm.}$$

Q is the mass-like leakage for flow using the upstream leakage, L_u, and pressure, P_u:

$$Q = P_u L_u, \qquad \text{(Eq. B1)}$$
$$L_u = L_A. \qquad \text{HAC leakage}$$

$$Q = (5.8819)(\text{atm}) (21.951)(\text{cm}^3/\text{s}),$$
$$= 129.116 \text{ atm-cm}^3/\text{s}. \qquad \text{HAC mass-like leakage rate}$$

$$Q = P_a L_a, \qquad \text{(Eq. B1)}$$

$$L_a = Q / P_a$$
$$= 129.116 (\text{atm-cm}^3/\text{s}) / (3.4410)(\text{atm}),$$
$$= 37.523 \text{ cm}^3/\text{s}. \qquad \text{HAC average leakage rate}$$

Solve equations B2–B4 from ANSI N14.5-1997:

$$L_a = (F_c + F_m)(P_u - P_d)(\text{cm}^3/\text{s}), \qquad \text{(Eq. B2)}$$
$$= (F_c + F_m)(5.8819 - 1.0),$$
$$= 4.8819 (F_c + F_m) \text{ cm}^3/\text{s}.$$

$$F_c = (2.49 \times 10^6) D^4 / (a\,\mu)(\text{cm}^3/\text{atm-s}), \qquad \text{(Eq. B3)}$$
$$= (2.49 \times 10^6) D^4 / [(0.3531)(0.02297)],$$
$$= (3.0706 \times 10^8) D^4 \text{ cm}^3/\text{atm-s}.$$

$$F_m = (3.81 \times 10^3) D^3 (T / M)^{.5} / (a\,P_a)(\text{cm}^3/\text{atm-s}), \qquad \text{(Eq. B4)}$$
$$= (3.81 \times 10^3) D^3 (397.00 / 29)^{.5} / [(0.3531)(3.4410)],$$
$$= (1.1604 \times 10^4) D^3 \text{ cm}^3/\text{atm-s}.$$

From the mass-like leakage calculation:

L_a = 37.523 cm^3/s. HAC average leakage rate

Find the leakage hole diameter that sets:

$L_2 = L_a$.

Using the equations:

$$L_2 = 4.8819\,(F_c + F_m)\ cm^3/s,$$
$$F_c = (3.0706 \times 10^8)\ D^4\ cm^3/atm\text{-}s,$$
$$F_m = (1.1604 \times 10^4)\ D^3\ cm^3/atm\text{-}s.$$

To get a better guess on a new D use:

$$D = D_2\,(L_a / L_2)^{0.252}.$$

Now a guess must be made for D_2 to solve Eq. B2 for HAC:

D_2 = 0.01 (cm), and solve for L_a = 37.523 (cm^3/s). HAC average leakage rate

Diameter	F_c	F_m	L_2	L_a / L_2
1.0000E-02	3.0706E+00	1.1604E-02	1.5047E+01	2.4937E+00
1.2589E-02	7.7134E+00	2.3154E-02	3.7769E+01	9.9349E-01
1.2569E-02	7.6627E+00	2.3040E-02	3.7521E+01	1.0000E+00
1.2569E-02	7.6631E+00	2.3041E-02	3.7523E+01	1.0000E+00

The HAC leakage hole diameter for the HEU oxide content is:

$D = 1.2569 \times 10^{-2}$ cm. HAC diameter

HAC Reference Air Leakage Rate for HEU Content

The leakage hole diameter found for the maximum allowable leakage rate for HAC will be used to determine the reference air leakage rate. O-ring seal leakage testing must assure that no leakage is greater than the leakage generated by the hole diameter $D = 1.2569 \times 10^{-2}$ cm. Therefore, the HAC reference air leakage rate ($L_{R,\,A}$) must be calculated to determine the acceptable test leakage rate for post-HAC leakage testing.

Input data for HAC reference air leakage rate:

$D = 1.2569 \times 10^{-2}$ cm, From the HAC of transport
a = 0.3531 cm, Leak path length, 0.139-in. O-ring section diameter
P_u = 1.0 atm, Upstream pressure
P_d = 0.01 atm, Downstream pressure

$$T = 298\text{ K}, \qquad \text{Fill gas temperature, } 77°\text{F}$$
$$M = 29\text{ g/g-mole}, \qquad \text{Molecular weight of air}$$
$$\mu = 0.0185\text{ cP}. \qquad \text{Viscosity at temperature}$$

Calculate P_a:

$$\begin{aligned} P_a &= (P_u + P_d) / 2 \\ &= 0.505\text{ atm.} \end{aligned} \qquad \text{HAC average pressure}$$

$$\begin{aligned} F_c &= (2.49 \times 10^6)\, D^4 / (\, a\, \mu\,)\ (\text{cm}^3/\text{atm-s}), \qquad \text{(Eq. B3)} \\ &= (2.49 \times 10^6)\, (1.2569 \times 10^{-2})^4 / [(0.3531)\,(0.0185)], \\ &= (3.8122 \times 10^8)\, (1.2569 \times 10^{-2})^4, \\ &= 9.5139\ \text{cm}^3/\text{atm-s}. \end{aligned}$$

$$\begin{aligned} F_m &= (3.81 \times 10^3)\, D^3\, (T / M)^{.5} / (a\, P_a)\ (\text{cm}^3/\text{atm-s}), \qquad \text{(Eq. B4)} \\ &= (3.81 \times 10^3)\, (1.2569 \times 10^{-2})^3\, (298 / 29)^{.5} / [(0.3531)\,(0.505)], \\ &= (6.8501 \times 10^4)\, (1.2569 \times 10^{-2})^3, \\ &= 1.3601 \times 10^{-1}\ \text{cm}^3/\text{atm-s}. \end{aligned}$$

$$\begin{aligned} L_u &= (F_c + F_m)\, (P_u - P_d)\, (P_a / P_u)\ (\text{cm}^3/\text{s}), \qquad \text{(Eq. B5)} \\ &= (9.5139 + 1.3601 \times 10^{-1})(\text{cm}^3/\text{atm-s})\, (1.0 - 0.01)(\text{atm})\, (0.505 / 1.0), \\ &= (9.6499)(\text{cm}^3/\text{atm-s})\, (0.49995)(\text{atm}), \\ &= 4.8245\ \text{cm}^3/\text{s}. \end{aligned}$$

The HAC reference air leakage rate as defined in ANSI N14.5-1997, Sect. B.3, is the upstream leakage in air.

$$L_{RA,Air} = 4.8245\ \text{ref-cm}^3/\text{s}. \qquad \text{for HEU oxide content}$$

The same equations can be used to calculate an allowable leakage rate using helium for leak testing.

$$M = 4\text{ g/g-mole}, \qquad \text{Molecular weight of helium}$$
$$\mu = 0.0198\text{ cP}. \qquad \text{Viscosity of helium at temperature}$$

$$\begin{aligned} F_c &= (2.49 \times 10^6)\, D^4 / (a\, \mu)\ (\text{cm}^3/\text{atm-s}), \qquad \text{(Eq. B3)} \\ &= (2.49 \times 10^6)\, (1.2569 \times 10^{-2})^4 / [(0.3531)\,(0.0198)], \\ &= (3.5619 \times 10^8)\, (1.2569 \times 10^{-2})^4, \\ &= 8.8892\ \text{cm}^3/\text{atm-s}. \end{aligned}$$

$$\begin{aligned} F_m &= (3.81 \times 10^3)\, D^3\, (T / M)^{0.5} / (a\, P_a)\ (\text{cm}^3/\text{atm-s}), \qquad \text{(Eq. B4)} \\ &= (3.81 \times 10^3)\, (1.2569 \times 10^{-2})^3\, (298 / 4)^{.5} / [(0.3531)\,(0.505)], \\ &= (1.8444 \times 10^5)\, (1.2569 \times 10^{-2})^3, \\ &= 3.6622 \times 10^{-1}\ \text{cm}^3/\text{atm-s}. \end{aligned}$$

$$\begin{aligned} L_u &= (F_c + F_m)\, (P_u - P_d)\, (P_a / P_u)\ (\text{cm}^3/\text{s}), \qquad \text{(Eq. B5)} \\ &= (8.8892 + 3.6622 \times 10^{-1})(\text{cm}^3/\text{atm-s})\, (1.0 - 0.01)(\text{atm})\, (0.505 / 1.0), \\ &= (9.2554)(\text{cm}^3/\text{atm-s})\, (0.49995)(\text{atm}), \\ &= 4.6273\ \text{cm}^3/\text{s}. \end{aligned}$$

The allowable leakage rate using helium for leak testing for HAC is:

$$L_{RA,\,He} = 4.6273\ \text{cm}^3/\text{s}. \qquad \text{HAC helium test value}$$

Table 1. Regulatory leakage criteria for 35.2 kg of HEU

	Years from fabrication	NCT		HAC	
		$L_{RN\text{-}air}$ (ref-cm^3/s)	$L_{RN\text{-}He}$ (cm^3/s)	$L_{RA\text{-}air}$ (ref-cm^3/s)	$L_{RA\text{-}He}$ (cm^3/s)
Fast absorption	0	2.7102E-03	2.9443E-03	5.6965E+00	5.4580E+00
	5	2.6976E-03	2.9311E-03	5.6700E+00	5.4327E+00
	10	2.6958E-03	2.9291E-03	5.6661E+00	5.4290E+00
	20	2.6947E-03	2.9279E-03	5.6637E+00	5.4268E+00
	30	2.6938E-03	2.9270E-03	5.6618E+00	5.4249E+00
	40	2.6928E-03	2.9260E-03	5.6597E+00	5.4230E+00
	50	2.6917E-03	2.9248E-03	5.6574E+00	5.4207E+00
	60	2.6905E-03	2.9236E-03	5.6549E+00	5.4184E+00
	70	2.6892E-03	2.9222E-03	5.6523E+00	5.4158E+00
Medium absorption	0	2.5965E-03	2.8247E-03	5.4562E+00	5.2291E+00
	5	2.5850E-03	2.8126E-03	5.4319E+00	5.2060E+00
	10	2.5833E-03	2.8109E-03	5.4284E+00	5.2026E+00
	20	2.5824E-03	2.8098E-03	5.4263E+00	5.2006E+00
	30	2.5816E-03	2.8090E-03	5.4246E+00	5.1990E+00
	40	2.5807E-03	2.8081E-03	5.4228E+00	5.1973E+00
	50	2.5797E-03	2.8071E-03	5.4207E+00	5.1953E+00
	60	2.5787E-03	2.8060E-03	5.4185E+00	5.1932E+00
	70	2.5775E-03	2.8048E-03	5.4161E+00	5.1909E+00
Slow absorption	0	2.3087E-03	2.5214E-03	4.8478E+00	4.6495E+00
	5	2.3000E-03	2.5123E-03	4.8295E+00	4.6320E+00
	10	2.2990E-03	2.5112E-03	4.8274E+00	4.6301E+00
	20	2.2989E-03	2.5111E-03	4.8272E+00	4.6299E+00
	30	2.2989E-03	2.5111E-03	4.8272E+00	4.6298E+00
	40	2.2988E-03	2.5110E-03	4.8269E+00	4.6296E+00
	50	2.2985E-03	2.5107E-03	4.8263E+00	4.6290E+00
	60	2.2981E-03	2.5103E-03	4.8255E+00	4.6282E+00
	70	2.2976E-03	2.5098E-03	4.8245E+00	4.6273E+00

7. PACKAGE OPERATIONS

The ES-3100 shipping package shall be operated in accordance with applicable Nuclear Regulatory Commission (NRC), U.S. Department of Transportation (DOT), and other federal, state, and local regulations to protect the health and safety of the public, workers, and the environment. Furthermore, the ES-3100 shall be operated according to a site-approved quality assurance plan.

Specific criteria for operating the ES-3100 package with highly enriched uranium (HEU) contents are presented in this section. The packaging user shall develop detailed site-specific operating procedures based on these criteria and on the NRC-issued Certificate of Compliance (CoC). These procedures shall be in accordance with 10 CFR 71, Subparts A, G, and H. The package operations should be consistent with maintaining occupational radiation exposures as low as reasonably achievable (ALARA) as required by 10 CFR 20.1101.

7.1 PACKAGE LOADING

The user of the packaging shall:

1. have authorization to acquire, package, transport, or transfer radioactive, fissile, or special nuclear material;
2. have the latest NRC CoC and referenced SAR sections for the ES-3100 package with HEU contents;
3. comply with all actions and restrictions specified in the CoC;
4. be registered as a user of the packaging with the NRC; and
5. have a site-approved quality assurance program that meets the requirements of 10 CFR 71, Subpart H.

7.1.1 Preparation for Loading

The ES-3100 Containment Vessel (CV) may be loaded while inside or outside the drum. This decision is site dependent. Detailed, written operating procedures shall include, at a minimum, the process steps listed below before the contents are placed in the ES-3100 package. These steps, initiated by the operating personnel and their supervisor, ensure that:

1. All appropriate documents have been reviewed by operating personnel and are available for further review, if necessary.
2. The radioactive material contents are authorized by the CoC, and the use of the package complies with all conditions in the CoC.
3. The packaging has been properly maintained and is in unimpaired condition. (All required refurbishment and periodic maintenance shall have been performed and documented within the scheduled requirements of the CoC, the SAR, and the maintenance program.)

4. A valid leak-test sticker must be present on the containment vessel to ensure that the required acceptance leak test or the annual leak test has been performed.

5. Packaging interior, nonfixed surface contamination levels are not high enough to significantly contaminate the contents. Nonfixed surface contamination limit requirements are given in 10 CFR 20.1906, 10 CFR 71.87(i), and 49 CFR 173.443 for alpha, beta, and gamma-emitting radionuclides.

6. All closure fasteners are those furnished with the packaging or are certified replacements and are acceptable for use.

7. All required parts of the packaging and all necessary equipment are available and ready for use.

8. The silicone rubber pads, if required, have been inspected prior to use.

The user may replace certain parts during loading. Parts that may be replaced by the user are identified in Table 7.1. The certification of all replacement parts must be traceable. The user must document the replacement.

Table 7.1. Replacement parts for the ES-3100 packaging

Part	Description	Material	Specification/ Drawing[a]
Containment vessel inner O-ring	5.359-in. inner diam (ID) by 0.139-in. diam stock	Ethylene propylene	ASTM D-2000 M2E801580A013
Containment vessel outer O-ring	5.859-in. ID by 0.139-in. diam stock	Ethylene propylene	ASTM D-2000 M2E801580A013
Drum lid washer	0.844-in. ID by 1.375-in. outer diam (OD) × 0.25-in.-thick	Stainless steel	ASTM A240 or ASTM A276 M2E801580A005
Drum lid hex nut	⅝-in.-11 unified coarse thread (UNC)	Silicon bronze	ASTM F467 per ANSI B18.2.2 M2E801580A005
Plug	(Plastic plug around circumference of drum assembly and top of top plug)	Nylon 6/6	62MP0312 Micro Plastic, Inc. M2E801580A002 M2E801580A008
Modified VCO Threaded Plug	Leak-test port plug	Brass	P/N 04-2126 M2E801580A011
Silicone rubber pads		Silicone rubber 22 ± 5 Shore A	M2E801580-A009-1 M2E801580-A009-2 M2E801580-A009-3
Aluminum tape	Duct tape, low temperature (−40 to +250°F), 2-in. wide, McMaster Carr Part No. 7616A21 or equivalent	Aluminum foil	M2E801580A002

[a] Drawings are available in Appendix 1.4.8.

6. The annulus between the O-rings shall be leak tested after the CV is loaded in accordance with ANSI N14.5-1997, Sect. 7.6. The user will perform the following steps:

   - ensure that equipment used to perform leak tests has been properly calibrated to ensure the accuracy of test measurements
   - ensure that all leak testing is performed in accordance with a quality assurance program, procedures, and documents the results
   - ensure that the test method used has a sensitivity of at least 1 x 10^{-4} ref-cm^3/s air
   - use either the gas-pressure drop (ANSI N14.5-1997, Section A.5.1) or the gas-pressure rise (ANSI N14.5-1997, Section A.5.1) tests
   - remove the modified VCO threaded brass plug from the leak-test port opening
   - hook-up the leak test equipment into the leak-test port opening using an appropriate fitting
   - either pressurize or evacuate the annulus between the O-rings to a suitable pressure and measure the change in pressure and temperature within the test volume during a specified time period
   - pressure measurements must be accurate within 1% or less and tests should be carried out in isothermal conditions
   - calculate the total leakage rate, using the known test volume and test results and ensure that the measured leak rate is less than 1 x 10^{-4} ref-cm^3/s air.

7. The vacuum coupling is removed.

8. The modified VCO threaded brass plug is tightened into the leak-test port opening.

The user must ensure that their procedure meets the requirements of ANSI N14.5-1997.

If the inner O-ring requires replacement, the containment vessel must be retested per Sect. 8.2.2 prior to use. This requirement does not apply to the outer O-ring, as it is not part of the containment boundary.

Following a successful leak test, the containment vessel with its content is ready to be loaded into the drum assembly.

7.1.2.2 Drum Closing

A radiation check of the contents may be conducted prior to loading to measure the content dose rate. The measured dose rate should be compared with known values for such a test. After loading is complete, radiation measurements shall be taken to determine the package dose rate, which establishes the transport index (TI).

The detailed operating procedures shall include, at a minimum, the process steps listed below when preparing the drum assembly for closing and sealing. The operating personnel and their supervisor shall ensure that:

1. The CV assembly with content is ready for loading into the drum assembly or lowering into the drum assembly, depending on whether it was loaded outside the drum or inside the drum.

2. The drum assembly (with top plug removed) is ready to receive the containment vessel assembly and that the containment vessel assembly, silicone rubber pads, drum lid, drum-lid nuts and washers, and tamper-indicating devices (TIDs) are available.

3. The aluminum foil tape applied over the neutron-absorbing material cavity fill and vent holes (four places) located on the drum liner lower shelf (Drawing M2E801580A002, Appendix 1.4.8) is visually inspected for damage such as tears, holes, or loose edges.

4. The loaded CV is lifted using the swivel hoist ring and site-approved lifting equipment.

5. The CV is positioned in the drum (Drawing M2E801580A001, Appendix 1.4.8), and the swivel hoist ring is removed.

6. The CV flange pad is placed on top of the containment vessel, and the plug pad is placed on the inner liner shelf.

7. The nylon plug is installed in the top plug vent hole, and site-approved lifting hardware is attached to the top plug threaded lifting holes.

8. The top plug is installed in the drum (Drawing M2E801580A001, Appendix 1.4.8), and the lifting hardware is removed.

9. The drum lid, the drum washers, and bronze drum nuts are installed.

10. The nuts are tightened to 40.67 ± 6.78 N·m (30 ± 5 ft-lb) of torque with no sequence specified. No impact wrench shall be used.

11. A nylon plug is installed in each of the four drum vent holes.

12. The TIDs are attached through both TID lugs.

13. The gross package weight does not exceed 190.5 kg (420 lb).

14. Surveys for nonfixed surface contamination and radiation dose rate measurements are conducted. The nonfixed surface contamination survey shall be conducted in accordance with the user's facility procedures. The survey shall use criteria that are derived from the surface radioactivity guidance of 10 CFR 20.1906, 10 CFR 71.87(i), or the user's site-specific criteria, whichever is the most stringent.

15. Nonfixed surface contamination is removed as applicable.

16. All "empty" or inappropriate labels or tags are removed from the exterior surface of the package.

17. The package is labeled with the appropriate material description, nuclides, activity/mass, and TI in accordance with 49 CFR 172.403.

18. The package is marked with the minimum marking "Radioactive Material, Type B(U) Package, Fissile, UN3328" in accordance with 49 CFR 172.301 and 172.310.

19. The package radiation dose rate at the surface is measured. The package radiation dose rate at 1 m from the surface shall be measured to establish the TI for the package and to ensure that the content does not exceed the expected or allowable dose rates (see Sect. 5). The analysis presented in the containment evaluation (Sect. 4) has determined that this is a Type B, fissile material package.

7.1.3 Preparation for Transport

7.1.3.1 Package Handling

Criticality Safety Index (CSI) values for the ES-3100 package with various payloads can be found in Table 1.3.

The ES-3100 is handled using industry-standard drum-handling equipment. Operating procedures shall include requirements to limit clamping pressures on forklift drum-handling equipment to prevent damage to the ES-3100 drum body (see Sect. 1.2.1.1 for limits on forklift gripping forces).

7.1.3.2 Decontamination

The package may be placed onto areas that are covered by disposable covering, such as plastic or paper, to reduce the nonfixed surface contamination of physical structures.

The package must be shipped in an enclosed conveyance. Generally, the exterior surfaces of the package will remain relatively clean. However, each user shall prepare procedures to clean dirty packages. These procedures shall, at a minimum, consider the following:

1. The drum is austenitic stainless steel.
2. The drum nut is silicon bronze.
3. The drum vent holes are covered with nylon plugs (Drawing M2E801580A002, Appendix 1.4.8).
4. The labels and markings on the drum must remain legible.

7.1.3.3 Requirements Prior to Shipment

The shipper shall ensure that the quality control requirements of 49 CFR 173.475 and the routine determination requirements of 10 CFR 71.87 have been satisfied prior to each shipment. Detailed operating procedures [10 CFR 71.87(f)], shall provide evidence that these requirements are met and ensure that:

1. the package is proper for the content shipped and verified with the appropriate records by the user prior to content loading [10 CFR 71.87(a)];
2. when shipping uranium oxides or UNX crystals, the shipper shall provide the receiver with the date and time the containment vessel was sealed. The shipper must verify that the shipment can be completed within the time period allotted for the type of shipment (5 months or 1 year for UNX crystals as noted in Table 1.3a or 1 year for uranium oxides);
3. the package is in unimpaired physical condition [10 CFR 71.87(b)];
4. the closure devices of the package are properly installed, secured, and free of defects [10 CFR 71.87(c)];

5. the containment vessel has been loaded properly and preparation for shipment has been followed, witnessed, and checked;

6. the internal pressure of the containment system does not exceed the design pressure during transportation [10 CFR 71.85(b)] as demonstrated by analysis (Appendix 2.10.1) and that there are no pressure-relief devices [10 CFR 71.87(e)] in the package;

7. the external radiation levels for all transport conditions are within the allowable limits as measured for Normal Conditions of Transport (NCT) [10 CFR 71.87(j)];

8. the nonfixed external contamination levels are within the allowable limits as demonstrated by surface wipes prior to content insertion, containment vessel loading, and package closure [10 CFR 71.87(I)];

9. the contents are adequately sealed and have adequate space for expansion [10 CFR 71.87(d)];

10. all records for shipment are prepared and maintained; and

11. all lifting attachment features are either inoperative during transport [10 CFR 71.87(h)] or meet the requirements of 10 CFR 71.45(a).

7.1.3.4 Leak Testing

Leak tests shall be conducted following the content loading and the containment vessel closure. The annulus between the O-rings shall be leak tested to an acceptable leak rate of 1×10^{-4} ref-cm^3/s air (or equivalent) or lower in accordance with ANSI N14.5-1997, Subclause 7.6.

7.1.3.5 Surveying

The radiation (gamma, neutron) emanating from the contents of the package shall be measured before the package is released for transport [10 CFR 71.47 and 71.87(j)]. The package radiation dose rate at the surface is measured to ensure that the content does not exceed the expected or allowable dose rates. The package radiation dose rate at 1 m from the surface is measured to establish the TI for the package. The package exterior surface contamination level limits are found in 10 CFR 71.87(i) and 49 CFR 173.443. The regulations present both fixed and nonfixed surface contamination level limits for the various radionuclides. In addition to these limits, the user may have more stringent surface contamination levels that shall also be followed.

A final visual survey of the package and loading paperwork shall be conducted to ensure that the package was assembled correctly and that it is ready for final shipment preparation. This survey may include a thorough review of the loading checklists by someone other than those who filled out the list to verify the loading operations. The area immediately surrounding the assembly operations should be surveyed, and all spare or extra parts should be identified. A final package survey may include weighing the package, hand-testing the closure nuts on the drum lid, and flexing the TIDs. The loading checklist should include a place for this final quality check to be properly recorded—including a signature and date—as being successfully completed.

3. all lifting and handling equipment is certified for use,

4. all transfer equipment is certified for use,

5. the package is visually examined to ascertain surface damage that may have occurred during shipping or handling, and

6. the TIDs are examined to ensure that the package has not been tampered with during shipment.

If the package surface was damaged during handling or shipping, a nonconformance tag shall be completed and attached to the package for subsequent refurbishment (10 CFR 71.131). If the TIDs are found to be compromised, the receiver shall investigate and notify the NRC as required.

7.2.2 Removal of Contents

Detailed operating procedures shall describe activities required for content removal and shall identify any safety and health measures required to protect workers and the environment. The procedures shall include, at a minimum, the process steps listed below:

1. All appropriate labels for the material shipped are affixed to the exterior surface of the drum body.

2. Surveys for nonfixed surface contamination and radiation dose rate measurements are conducted.

3. As applicable, nonfixed surface contamination in excess of limits is addressed as required.

4. The TIDs remain intact until removal.

5. The weld stud nuts and washers are removed and controlled.

6. The drum lid is removed.

7. Visible portions of the interior of the drum body and top plug are still in good condition—no visible signs of damage, water damage, or tears.

8. Site-approved lifting hardware is attached to the top plug threaded lifting holes, and the top plug is removed.

9. The silicone rubber CV flange pad is removed from above the containment vessel.

10. The containment vessel top is in good condition—no visible signs of damage or loose closure nut.

11. A surface contamination check is conducted to discover any leak of radioactive material.

12. The containment vessel is removed from the drum assembly. The containment vessel is placed onto the work area. (This step may not be required if CV is unloaded while in the drum.)

13. The external retaining ring, containment vessel closure nut, and containment vessel sealing lid are removed and controlled. (No pressure buildup is expected under NCT.)

14. The O-rings and the O-ring grooves on the containment vessel flange are protected from damage during unloading.

15. The HEU content (convenience cans or bottles) and associated packing materials (can spacers, stainless-steel scrubbers, silicone can pads, etc.) are removed from the containment vessel in accordance with site-specific material-handling procedures.

16. The items removed and the inside of the containment vessel are checked for nonfixed surface contamination.

7.3 PREPARATION OF EMPTY PACKAGE FOR TRANSPORT

The user shall develop detailed procedures to prepare an empty package for storage or transport. These procedures shall, at a minimum, ensure that:

1. The package has been emptied of all radioactive contents.

2. The radiation level at any point on the external surface of the package does not exceed 0.5 mrem/h.

3. The nonfixed radioactive surface contamination on the external surface of the packaging does not exceed the limits specified in 49 CFR 173.443(a), and the internal contamination level does not exceed 100 times the limits in 49 CFR 173.443(a).

4. The package is not damaged, and there is no visible internal or external surface moisture or corrosion.

5. The package is closed.

6. Any labels previously affixed in accordance with Subpart E of 49 CFR 172 are removed, obliterated, or covered. Leak-test labels should not be removed from the drum body.

7. The "EMPTY" label prescribed in 49 CFR 172.450 is affixed to the drum.

8. An appropriate notice is provided giving the name of the consignor or consignee. An example notice is, "This package conforms to the conditions and limitations specified in 49 CFR 173.428 for radioactive material, excepted package—empty packaging, UN2908."

7.4 OTHER OPERATIONS

None.