2. STRUCTURAL EVALUATION

The ES-3100 package is used to ship bulk highly enriched uranium (HEU). Content will be packed in various size convenience cans made of stainless or tin-plated carbon steel. The cans shall have a diameter of ≤ 12.7 cm (5 in.) and heights of ≤ 25.4 cm (10 in.). Any combination of these cans shall be allowed in a single package, as long as the total length of the can stack (with spacers when required) does not exceed the inside working height of the containment vessel. Any closure on the convenience can is allowed. Polyethylene bags may be used inside or outside any convenience can as long as the loading restrictions in Sect. 1.2.3.8 are met. The amount of polyethylene bagging used inside the ES-3100 containment vessel is limited to 500 g. In addition, polyethylene bags or other packing materials that offgas at temperatures above ambient may not be used inside the containment vessel if convenience cans with diameters exceeding 4.25 in. are used. The maximum payload inside the containment vessel will be as follows and as shown in Table 2.1: (1) 24 kg oxide or compounds (up to 100% enrichment in ²³⁵U); (2) HEU oxide shall be in the form of UO₂, UO₃, or U₃O₈; (3) 24 kg of uranyl nitrate crystals; (4) 36 kg of uranium metal and alloy (up to 100% enrichment in ²³⁵U); (5) HEU metal and alloy may be in the form of broken pieces, ingots, buttons, small castings or fuel; and (6) the maximum weight of all contents, including nuclear material, convenience cans, polyethylene bags, spacers, etc., shall not exceed 40.82 kg (90 lb). Uranium and transuranic isotopic allowances are defined in Sect. 4. Mass limits and total weights for each shipping arrangement are defined and described in Sect. 2.1.3. The 40.82-kg (90-lb) maximum containment vessel content weight and 36-kg (79.37-lb) HEU content weight limits have been established as a bounding case for the maximum structural, thermal, and containment limit for the shipping package. The lowest possible mass of 2.77 kg (6.11 lb) HEU has been established as the lower bounding case for structural, thermal, and containment limits for the shipping package. The above content masses and forms used for the proposed content do not take into consideration limits based on shielding and subcriticality.

As described in the following sections, design analysis, similarity, drop simulations, and the fullscale testing documented herein demonstrates that the ES-3100 package is in compliance with the requirements of Title 10 Code of Federal Regulations (CFR) 71 and Title 49 CFR 100–178 when it is used to ship contents described above. The maximum bounding activity of the contents (36 kg of HEU) is 3.1039×10^{-1} TBq (8.39 Ci) when the maximum activity-to-A₂ value is reached at ~50 years from material fabrication. The corresponding maximum number of A₂s carried is 290.26. This information is further discussed in Sect. 4.

	Form	· ·	Chemical or physical description	То	tal weight of HEU contents kg (lb)
HEU oxide			UO ₂ , UO ₃ , U ₃ O ₈		24 (52.91)
Uranyl nitrate	e crystals		UO ₂ (ÑO ₃) ₂ + 6H ₂ O		24 (52.91)
HEU metal a	nd alloy		Specific geometric shapes (spheres, cylinders, square bars or slugs) or broken metal pieces		36 (79.37)
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 Table 2.1. Proposed HEU contents for shipment in the ES-3100

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2.1 DESCRIPTION OF STRUCTURAL DESIGN

2.1.1 Discussion

The principal structural members of the shipping package consist of the following: the drum assembly, the containment boundary, packaging material, and the contents. Each of these will be described and discussed in the following sections.

2.1.1.1 Drum assembly

The drum assembly of the shipping package is defined as the structure that maintains the position of and provides protection to the impact and thermal barrier surrounding the containment boundary. Preserving the location of the containment boundary within the packaging prevents reduction of the shielding and subcriticality effectiveness. The drum assembly for the ES-3100 consists of an internally flanged Type 304L stainless-steel 30-gal modified drum with two type 304L stainless-steel inner liners, one filled with noncombustible cast refractory insulation and impact limiter (Kaolite) and one filled with noncombustible cast neutron absorber (Cat 277-4), a stainless-steel top plug with cast refractory insulation, silicone rubber pads, silicon bronze hex-head nuts, and a stainless-steel lid and bottom (Drawing M2E801580A031, Appendix 1.4.1). The nominal weight of these components is 131.89 kg (290.76 lb).

The drum's diameters (inner diameter of 18.25 in.) and corrugations meet the requirements of Military Standard MS27683-7. All other dimensions are controlled by Drawing M2E801580A004 (Appendix 1.4.1). Modifications to the drum from MS27683-7 include the following: (1) the overall height was increased; (2) the drum was fabricated with two false wire open ends; and (3) a 0.27-cm (12-gauge, 0.1046-in.)-thick concave cover was welded to the bottom false wire opening (Drawing M2E801580A005, Appendix 1.4.1). Four 0.795-cm (0.313-in.)-diameter equally spaced holes are drilled in the top external sidewall to prevent a pressure buildup between the drum and inner liner. The holes are sealed with a plastic plug to provide a moisture barrier for the cast refractory insulation during Normal Conditions of Transport (NCT). The cavity created by the inner liners is a three-tiered volume with a 37.52-cm (14.77-in.) inside diameter 13.26 cm (5.22 in.) deep, a 21.84-cm (8.60-in.) inside diameter 5.59 cm (2.20 in) deep, and an additional 15.85-cm (6.24-in.) inside diameter 78.31-cm (30.83 in.) deep. The volume between the mid liner and the drum and the top plug's internal volume is completely filled with the noncombustible cast refractory insulation called Kaolite 1600 from Thermal Ceramics, Inc. Kaolite properties, such as mechanical, thermal conductivity, and impact, are presented in Appendix 2.10.3. The volume between the most inward liner and the mid liner wall is completely filled with a noncombustible neutron absorber (poison) from Thermo Electronic Corp. called Cat 277-4. Cat 277-4 properties, such as thermophysical, mechanical, and neutron activation, are presented in Appendix 2.10.4. BoroBond4, another noncombustible neutron absorber, was used only in prototype test packages instead of Cat 277-4. The drum body, inner liners, and lid are fabricated from 0.15-cm (16-gauge, 0.0598-in.) thick Type 304/304L stainless-steel sheet. A rolled stainless-steel flange with a $5.08 \times 5.08 \times 0.64$ -cm ($2 \times 2 \times 0.25$ -in.) thick modified stainless-steel structural angle is welded around the top of the mid inner liner. The mid inner liner is then welded to the inside surface of the drum along this flange. Eight %-11-UNC-2A studs welded to the drum and silicon bronze nuts provide the structural attachment for the drum lid, and are torqued to 40.67 ± 6.78 N·m (30 ± 5 ft-lb) at assembly. The drum lid's diameter and shape meet the requirements of Military Standard MS27683-61. All other dimensions are controlled by Drawings M2E801580A006 and A007, Appendix 1.4.1. The welded angle ring (Find Number 3 on Drawing M2E801580A006, Appendix 1.4.1) provides the lid an inner flange. This was incorporated in the ES-3100 package for use during transport to facilitate tie-down as a single unit in the Safe-Secure Trailer/Safeguards Transporter (SST/SGT) in accordance with U.S. Department of Energy (DOE) Order 5610.14. The drum is marked by two stainless-steel data plates. The data plate lettering and

mounting requirements on the drum are shown on Drawings M2E801580A010 and M2E801508A031 (Appendix 1.4.1), respectively. Painting and marking requirements for the drum are shown on Drawing M2E801508A001 (Appendix 1.4.1). Two lugs are welded to the mid inner liner and project through the drum lid at assembly. Each lug has a 0.953-cm (0.38-in.)-diameter hole through which a tamper-indicating device (TID) can be threaded.

The volume between the drum and mid-liner is filled with a lightweight noncombustible cast refractory material called Kaolite 1600. The top plug is also filled with this material and represents the thermal insulation and impact limiting barrier. The material is composed of portland cement, water, and vermiculite and has an average density of 358.8 kg/m³ (22.4 lb/ft³). The procedure for manufacturing and documenting the installation of this material, JS-YMN3-801580-A003 (Appendix 1.4.4), is referenced on Drawings M2E801580A002 and M2E801580A008 (Appendix 1.4.1) for the drum assembly weldment and top plug weldment, respectively. The insulation has a maximum continuous service temperature limit of 871°C (1600°F) due to the presence of the vermiculite and portland cement.

The volume between the most internal liner and the mid-liner is filled with a noncombustible cast neutron absorber (poison) material from Thermo Electronic Corp. called Cat 277-4. The material is a high alumina borated concrete composed of aluminum, magnesium, calcium, boron, carbon, silicon, sulfur, sodium, iron and water. The final mixture has an average density of 1681.9 kg/m³ (105 lb/f³). The procedure for manufacturing and documenting the installation of this material, JS-YMN3-801580-A005 (Appendix 1.4.5), is referenced on Drawing M2E801580A002 (Appendix 1.4.1). This neutron absorber material has a maximum continuous service temperature limit of 150°C (302°F) in order to retain the bound mass of water in the final cured mixture for subcriticality control.

The top plug is fabricated in accordance with Drawing M2E801580A008 with an overall diameter of 36.50 cm (14.37 in.) and a height of 13.41 cm (5.28 in.). The plug's rim, bottom sheet, and top sheet are fabricated from 0.15-cm (16-gauge, 0.0598-in.) thick Type 304/304L stainless-steel sheet per ASME SA240. Four lifting inserts are welded into the top sheet for loading and unloading operations. The internal volume of the top plug is filled with Kaolite 1600 in accordance with JS-YMN3-801580-A003, Appendix 1.4.4.

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Three silicone rubber pads complete the drum assembly. One pad is placed on the bottom of the most internal liner to support the containment vessel during transport. Another pad is placed on the top shelf of the mid-liner to support the top plug during transport. The final plug is placed over the top of the containment vessel during transport. The pads are molded to the shapes as defined on Drawing M2E801580A009 (Appendix 1.4.1). The material is silicone rubber with a Shore A durometer reading of 22 ± 5 .

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2.1.1.2 Containment boundary

The containment vessel's body, lid assembly, and inner O-ring provide the containment boundary (Fig. 1.3). Two methods of fabrication may be used to fabricate the containment vessel body of the ES-3100 package as shown on Drawing M2E801580A012 (Appendix 1.4.1). The first method uses a standard 5-in., schedule 40 stainless-steel pipe per ASME SA-312 Type TP304L, a machined flat-head bottom forging per ASME SA-182 Type F304L, and a machined top flange forging per ASME SA-182 Type F304L. The nominal outside diameter of the 5-in schedule 40 pipe is machined to match the nominal wall thickness of 0.100 in. Each of these pieces is joined with circumferential welds as shown on sheet 2 of Drawing M2E801580A012 (Appendix 1.4.1). The top flange is machined to match the schedule 5-in. pipe, to provide two concentric half-dove tailed O-ring grooves in the flat face, to provide locations for two 18-8 stainless-steel dowel pins, and to provide the threaded portion for closure using the lid assembly. The second method of fabrication uses forging, flow forming, or metal spinning to create the complete body (flat bottom,

cylindrical body, and flange) from a single forged billet or bar with final material properties in accordance with ASME SA-182 Type F304L. The top flange area using this fabrication technique is machined identically to that of the welded forging method. The lid assembly, which completes the containment boundary structure, consists of a sealing lid, closure nut, and external retaining ring (Drawing M2E801580A014, Appendix 1.4.1). The containment vessel sealing lid (Drawing M2E801580A015, Appendix 1.4.1) is machined from Type 304 stainless-steel bar with final material properties in accordance with ASME SA-479. The containment vessel closure nut (Drawing M2E801580A016, Appendix 1.4.1) is machined from a Nitronic 60 stainless-steel bar with material properties in accordance with ASME SA-479. These two components are held together using a WSM-400-S02 external retaining ring made from Type 302 stainless steel. The sealing lid is further machined to accept a 3/8-16 swivel hoist ring bolt to facilitate loading and unloading, to provide a leak-check port between the elastomeric O-rings, and notched along the perimeter to engage two dowel pins. The lid assembly, with the O-rings in place on the body, are joined together by torquing the closure nut and sealing lid assembly to 162.70 ± 6.78 N·m (120 ± 5 ft-lb). The sealing lid portion of the assembly is restrained from rotating during this torquing operation by the two dowel pins installed in the body flange. An evacuation port is located between the O-rings in the containment vessel to facilitate a pressure rise or drop leakage test following assembly or 10 CFR 71 compliance testing. This port is sealed during transport using a modified VCO threaded plug. Only the inner O-ring is considered a part of the containment boundary.

There are no penetrations of, connections to, or fittings for the sealed containment boundary. To meet the requirements for package certification, the containment boundary must remain intact during all conditions of transport. This integrity must be demonstrated by test or other acceptable methodology for NCT and Hypothetical Accident Conditions (HAC) as described in 10 CFR 71.

2.1.1.3 Packaging Materials

Contents will be packed in various size convenience cans made of stainless or tinned carbon steel. The cans shall have a diameter of ≤ 12.7 cm (5 in.) and heights of ≤ 25.4 cm (10 in.). Any combination of these cans shall be allowed in a single package, as long as the total length of the can stack (with spacers and pads as required) does not exceed the inside working height of the containment vessel (31 in.). Any closure on the convenience can is allowed. Polyethylene bags may be used inside or outside any convenience can that has a diameter of ≤ 10.8 cm (4.25 in.). 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 3.12 cm (1.23 in.) in height and weigh ~0.47 kg (1.03 lb). In order to minimize displacement of convenience cans during transport, stainless-steel scrubbers may be added on top of the last can in the containment vessel. If partial loading configurations are employed and empty cans are used, these empty cans will be loaded last and will require a minimum 0.32 cm ($\frac{1}{8}$ 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 71.41(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.).

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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 $\frac{5}{-11}$ -UNC-2B silicon bronze nuts and $\frac{5}{2}$ -in. nominal washers. Two 0.51-cm (0.20-in.)-thick lugs with 0.953-cm (0.38-in.)-diam holes (Drawing M2E801580A005, Appendix 1.4.1) 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 (Appendix 1.4.1) 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 97.63 kPa (14.16 psi) and 206.05 kPa (29.89 psi) attained during NCT (Sect. 3.4.2) 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.

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

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10 CFR 71.43(e)

Requirement: A package value 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 $38^{\circ}C(100^{\circ}F)$ and in the shade, no accessible surface of a package would have a temperature exceeding $50^{\circ}C(122^{\circ}F)$ in a nonexclusive use shipment or $85^{\circ}C(185^{\circ}F)$ 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 $38^{\circ}C$ ($100^{\circ}F$) in the shade, for the drum lid center, and the containment vessel flange, are approximately $38.3^{\circ}C$ ($101^{\circ}F$). The analysis shows that no accessible surface of the package would have a temperature exceeding $50^{\circ}C$ ($122^{\circ}F$). Therefore, the requirement of 10 CFR 71.43(g) would be satisfied for either transportation mode (exclusive or nonexclusive use).

10 CFR 71.43(h)

Requirement. A package must not incorporate a feature intended to allow continuous venting during transport.

Compliance. No penetrations, connections, or fittings into the containment vessel exist that would allow venting during transport. The materials of package construction do not provide any pressure buildup during transportation. Four vent holes through the drum are covered with a plastic plug during NCT. Therefore, the requirements of 10 CFR 71.43(h) are satisfied.

2.1.2.2 Component Design Criteria

The ES-3100 packaging/content combination addressed in this safety analysis report is intended to ship contents with a maximum activity of 3.112×10^{-1} TBq (8.41 Ci) at 10 years from initial fabrication; the maximum number of A₂s carried is 290.26 at 50 years following initial fabrication (Table 4.4). Based on the guidance from Regulatory Guide 7.11, *Fracture Toughness Criteria of Base Material for Ferritic Steel Shipping Cask Containment Vessels with a Maximum Wall Thickness of 4 Inches (0.1 m)*, this package is classified in NUREG-1609 (Table 2.2) as a Category II shipping package. However, since the ES-3100 may be used for future contents that exceed 3000 A₂ (under a different SAR and certificate), this package has been classified as a Category I shipping package. Therefore, the containment vessel is designed (using nominal dimensions for each component), fabricated, and inspected in accordance with the American Society of Mechanical Engineers (ASME) *Boiler and Pressure Vessel Code*, Sect. III, Division I, Subsection NB. The design and subsequent verification comply with the requirements of 10 CFR 71. The structural requirements for the packaging under NCT are addressed in Sect. 2.6. The structural requirements for the packaging under NCT are addressed in Sect. 2.6.

Contents Form/ Category	Category I	Category II	Category III
Special Form	Greater than 3,000 A ₁ or greater than 1.11 PBq (30,000 Ci)	Between 3,000 A ₁ and 30 A ₁ , and not greater than 1.11 PBq (30,000 Ci)	Less than 30 A ₁ and less than 1.11 PBq (30,000 Ci)
Normal Form	Greater than 3,000 A ₂ or greater than 1.11 PBq (30,000 Ci)	Between 3,000 A ₂ and 30 A ₂ , and not greater than 1.11 PBq (30,000 Ci)	Less than 30 A ₂ and less than 1.11 PBq (30,000 Ci)

Table 2.2. Category designations for Type B packages

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The drum assembly of the shipping package is defined as the structure that maintains the position of and provides protection to the impact, thermal barrier, and neutron poison surrounding the containment boundary. Because the location of the containment boundary within the packaging is stable, the shielding and subcriticality effectiveness of the package is not reduced. The drum assembly for the ES-3100 consists of an internally flanged Type 304L stainless-steel 30-gallon modified drum with two Type 304L stainlesssteel inner liners, one filled with noncombustible cast refractory insulation and impact limiter and one filled with noncombustible cast neutron absorber; a stainless-steel top plug with cast refractory insulation, silicone rubber pads, silicon bronze hex-head nuts, and a stainless-steel lid and bottom (Drawing M2E801580A001, Appendix 1.4.1). The drum assembly is maintained when there are no breaches in the drum surface, the lid remains attached, the relative position of the containment boundary is not altered significantly, and no substantial amount of insulation is exposed following testing stipulated in 10 CFR 71.71 and 73. The drum assembly's design requirements for compliance testing are as follows:

1. The drum lid shall remain attached to the drum under all loading conditions.

2. No opening in the drum shall occur large enough to pass a 10-cm cube [10 CFR 71.43(a)].

3. The outer drum's effective diameter shall exceed requirements to maintain subcriticality and shielding effectiveness.

4. The drum assembly shall provide the structural and thermal protection needed to ensure the containment vessel meets the test leakage criteria for both NCT and HAC of $\leq 1.0 \times 10^{-7}$ ref-cm³/s.

5. Neutron poison remains in place and retains the amount of water needed to maintain subcriticality.

In accordance with NUREG/CR-3854, Part 4.3, for a Category I shipping package, an acceptable specification for a drum used in any of the component safety groups is U.S. Department of Transportation (DOT) Specification 17C or better. The drum used in the ES-3100 is fabricated in accordance with the dimensional requirements of MS27683-7 (MIL-D-6054F) and modified as shown on Drawing M2E801508A004 (Appendix 1.4.1). Material, fabrication, and quality control criteria are generally equivalent to those imposed for a DOT Specification 17C drum. The drum weld seam is pressure tested to 68.95 kPa (10 psi) gauge and a rough handling test in accordance with MIL-D-6054F is conducted. As discussed in Sect. 1.2.1.1, the drum used for the ES-3100 is equivalent to or better than that stipulated by NUREG/CR-3854 for a Category I shipping package. In accordance with DOE, a performance-based package is an approved, quality-controlled, hazardous material container that has been tested or analyzed to demonstrate its ability to maintain confinement and/or containment of its contents under both normal use and credible accident conditions as stipulated in 10 CFR 71. The drum assembly and containment boundary have been maintained for the ES-3100 shipping package as demonstrated by test results documented in the test report (ORNL/NTRC-013) and the analytical comparisons discussed in Sects. 2.6 and 2.7.

The codes and standards used for design, analysis, and fabrication of the containment vessel's components are satisfied by complying with the appropriate paragraphs in Sect. III, Div. 1, Subsection NB, and Sect. IX of the *ASME Boiler and Pressure Vessel Code*. Nominal dimensions, not minimum dimensions, were used in the design analysis of the containment vessel components. Though not explicitly expressed, the load combinations and tests stated in Regulatory Guide 7.8, *Load Combinations for the Structural Analysis of Shipping Casks* are used in the structural evaluation of the containment vessel for both NCT and HAC as depicted in Table 2.3. Acceptance criteria for the containment vessel stresses are shown in Table 2.4 and locations are depicted in Fig. 2.1.

The design internal pressure of 699.82 kPa (101.5 psi) gauge for the containment boundary was generated based on its stress capability before the ASME Boiler and Pressure Vessel Code evaluation shown in Appendix 2.10.1 was started. The containment vessel is tested with an internal pressure of 1034.21 kPa (150 psi) gauge or 1.48 times the design pressure, which exceeds the requirement stipulated in Sect. III, Paragraph NB-6221 (a minimum hydrostatic test pressure of 1.25 times the design pressure) and the regulatory requirement of 10 CFR 71.85(b) (1.5 times the 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 122.63 kPa (17.786 psia). The maximum internal gauge pressure calculated for NCT is 97.63 kPa (14.16 psi), which is the maximum normal operating pressure minus the reduced external pressure condition of 10 CFR 71.71(c)(3) [122.63 - 25.00 kPa (17.786 - 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.

		Applicable initial condition								
Normal or Accident Condition	Ambient temperature		Inso	lation	Decay heat		Internal pressure		Fabrication	CAD automas
	38°C	-29°C	Max	0	Max	0	Max	Min	stresses	SAK reference
NORMAL CONDITIONS (analyze separately)						<u></u>	·······			
Hot environment (38°C ambient temperature)			x		x		x		x	Sect. 2.6.1
Cold environment (-40°C ambient temperature)				x		x		x	x	Sect. 2.6.2
Increased external pressure (20 psia)		X		X ,		x		x	x	Sect. 2.6.4
Minimum external pressure (3.5 psia)	x		x		x		x		X .	Sect. 2.6.3
Vibration and shock:	x		x		x		x	·	x	Seet 2651
Normally incident to the mode of transport		x		x		x		x	x	Sect. 2.0.5
Free drop:	x		x		x		· X		x	Sect 2 6 7
1.2-m drop		x		X .	÷.	x		X	x .	Sect. 2.0.7
Compression test	$\mathbf{X} \rightarrow \mathbf{X}$		x	E G P	x	•	x		X	Sect. 2.6.9*
	19 e.	X		\mathbf{x}	•.1	x	1.4	X	X (
Pronotration test	X	Ц.	X		X		x	1	X	Sect. 2.6.10ª
		x		X		X		x	x	
ACCIDENT CONDITIONS (apply sequentially)									· · · · · · · · · · · · · · · · · · ·	
Free days 0 as days	x		X	ſ	x		x		x	Sect. 0.7.15
Pree drop: 9-m drop		x		x		x		x	x	Sect. 2.7.1
Cruchi 0 m dron	x		x		x		x		x	Sect 2 7 25
		х		X ·		x		x	x	Sect. 2.7.2
Buncture: 1-m drop onto bar	x		X		x		x		Х	Sect 2 7 35
		X		x		x		x	x	3001, 2.7.3
Thermal: fire accident	x		x		x		x		x	Sect. 2.7.4

Table 2.3. Summary of load combinations for normal and hypothetical accident conditions of transport

* This condition was conducted at room temperature with atmospheric pressure inside the containment vessel.

^b This condition was conducted at ambient temperature at the time of the test except for Test Unit-2. The containment vessel was at atmospheric pressure except for Test Unit-2. Justification for compliance with the environmental requirements of Reg. Guide 7.8 is provided in Sect. 2.6.

⁶ This condition was conducted at ambient temperature at the time of the test except for Test Unit-2. The containment vessel was at atmospheric pressure except for Test Unit-2. Justification for compliance with the environmental requirements of Reg. Guide 7.8 is provided in Sect. 2.7.

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Stress category	Maximum allowable stress			
	Level A (NCT)	Level D (HAC)		
Primary membrane stress intensity	S _m	Lesser of 2.4 S_m and 0.7 S_u		
Primary membrane + primary bending stress intensity	1.5 S _m	Lesser of 3.6 S_m and S_u		
Range of primary + secondary stress intensity	3.0 S _m	Not applicable		
Fatigue stress range	S ₂ @ 10 ⁶ cycles	2 S, @ 10 ⁶ cycles		
Buckling	No buckling	No buckling		

 Table 2.4. Containment vessel allowable stress

Table 2.5. Allowable stress intensity (S $_{\rm m}$) for the containment boundary construction materials of construction $^{\circ}$

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 × 10⁴ kPa (12,800 psi)⁵
Flange and end cap (Method 1)	ASME SA-182 Forging, F304L stainless steel	8.825 × 104 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)

* 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.

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Fig. 2.1. Containment vessel calculated stress locations.

Stress locations shown in Fig. 2.1	Internal pressur evaluation conta boundary st @ 699.82 k (101.5 psi) g	e design ainment ress Pa auge	External pressu evaluation cont boundary s @ -149.62 (-21.7 psi) g	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)	18.20	1.474×10^{3} (213.8)	88.8	1.727 × 10 ⁵ (19,200) ^b
Closure nut ring (Away from threaded portion)	8.621 × 10⁴ (12,504)	4.30	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 × 10⁴ (4374)	7.78	1.236 × 104 (1793)	20.4	1.324 × 10 ⁵ (38,400) ^c
Cylindrical section (shell to bottom interface)	5.127 × 10⁴ (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 ^r (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)	10.0	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 ^s (19,200) ^b
Closure nut thread load, kg (lb)	2.051 × 10 ³ (4521)	16.29	9.072 × 10 ² ^r (2000)	38.1	3.545 × 10 ⁴ (78154) ^e

Table 2.6. ES-3100 containment boundary design evaluation allowable stress comparisons^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.

Stress interpreted as the sum of P₁ + P_b; allowable stress intensity value is 1.5 × S_m.
Stress interpreted as the sum of P₁ + P_b + Q; allowable stress intensity value is 3.0 × S_m.
Stress interpreted as the primary membrane stress (P_m); allowable stress intensity value is S_m.
Allowable shear capacity is defined as 0.6 × S_m × thread shear area. Thread shear area = 38.026 cm² (5.894 in.²).

¹ Stress and shear load in these areas are dominated by the 162.7 ± 6.8 N·m (120 ± 5 ft-lb) preload.

Component	Specifications
	Drum assembly
Drum washers	1.375 OD \times 0.812 ID \times 0.25 in. thick, 300 Series stainless steel,
Drum threaded weld studs	5/8-11 × 7/8 Lg, ARC FT, type 304/304L stainless-steel studs
Drum hex nuts	%-11 UNC-2B, silicon bronze C65100
Drum lid weldment	Modified 30-gal, 16-gauge (MS27683-61) lid, type 304 or 304L stainless steel; and a 11-gauge thick sheet, type 304 or 304L stainless steel, ASME SA-240
Drum weldment	Modified 30-gal, 16-gauge (MS27683-7), type 304 or 304L stainless steel, ASME SA-240, manufactured per Drawing M2E801580A004 (Appendix 1.4.1)
Drum plugs	Nylon plastic plug, Micro Plastic, Inc.
Impact limiter, i	nsulation enclosure, neutron absorber, and drum packing material
Insulation and impact limiter (not removable)	Lightweight cast refractory insulation, Kaolite 1600, 358.8 kg/m ³ (22.4 lb/ft ³) density, cast in stainless-steel shells in the drum and top plug
Neutron absorber	Cat 277-4, 1681.9 ±80.1kg/m ³ (105 ±5 lb/ft ³) density
Top plug (removable)	Type 304 or 304L stainless steel, ASME SA-240 (body), ASME SA-479 (lifting inserts),
Inner liners	Type 304 or 304L stainless steel, ASME SA-240 (body), ASME SA-479 (modified angle)
Silicone pads	Silicone rubber, 22 ±5 Shore A, color black/gray
Aluminum foil duct tape	McMaster Carr Part # 7616A21, temperature range -40 to 121°C (-40 to 250°F)
	Containment boundary
Containment vessel plug	Part # 04-2126, Modified VCO threaded plug, brass
Containment vessel hoist ring	3052T56, Swivel hoist ring, alloy steel (not used for shipment)
Containment vessel	Method 1: Type TP304L stainless steel ASME SA-312 (welded or seamless pipe body); type F304L, stainless steel, ASME SA-182 (flange, and end cap); type 304, stainless steel, ASME SA-479 (sealing lid), Nitronic 60 SST per ASME SA-479, UNS-S21800 (closure nut)
	Method 2: Type F304L stainless ASME SA-182 (body, flange, and end cap); type 304, stainless steel, ASME SA-479 (sealing lid), Nitronic 60 SST per ASME SA-479, UNS-S21800 (closure nut)
	All components per ASME Boiler and Pressure Vessel Code, Sect. II, Part D, Table 2A
Containment vessel O-rings	Elastomer, ethylene propylene, normal service temperature range of -40 to 150°C, Specification M 3BA712A14B13F17 in ASTM D-2000, per OO-PP-986
Containment vessel lid assembly retaining ring	Part # WSM-400-S02, type 302 stainless steel

Table 2.7. ES-3100 packaging material specifications

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Component	Specifications
Containment vessel O-ring lubricant	Clear dimethyl siloxane polymer
Containment vessel closure nut lubricant	Krytox #240AC
Containment vessel body dowel pins	0.2501/0.2503 OD × 0.50 long, 18-8 stainless steel
	Containment vessel packing material
Convenience cans	Stainless steel or tinned carbon steel with stainless-steel can handles and nylon- coated stainless-steel wire
Silicone rubber pads	Silicone rubber, 22 ±5 Shore A, color black/gray
Can spacers	Stainless-steel can filled with Cat 277-4
Bagging	Polyethylene
Metal scouring scrubbers	Stainless steel, McMaster Carr Part # 7361T13

Table 2.7. ES-3100 packaging material specifications (cont.)

2.1.3 Weights and Centers of Gravity

The weights of the packaging components for the actual proposed contents ready for shipment and the test units are provided in Tables 2.8 and 2.9. The values listed for the test weights are the actual data recorded during compliance testing. The remaining weights listed for the shipping package are calculated weights. Nominal dimensions and densities were used in the calculations. Miscellaneous parts (nuts, and washers) are included.

The range of the centers of gravity for the ES-3100 shipping package with the various HEU arrangements and the test packages is shown in Fig. 2.2. A summary of the calculations are provided in Table 2.10.

2.1.4 Identification of Codes and Standards for Package Design

Based on the discussion in Sect. 2.1.2.2, the shipping package has been designed, analyzed, and will be fabricated, tested and maintained to the requirements of a Category I package. In accordance with the references from NUREG/CR-1815, Table 2.11 describes the appropriate codes and standards that are and will be used to comply with Category I packaging. These requirements have been extracted from NUREG/CR-3854 and NUREG/CR-3019.



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ltem	ES-3100 Three 10" tall can configuration kg (lb)	ES-3100 Six 4.875" tall can configuration kg (lb)	ES-3100 Five 4.875" tall can configuration kg (lb)	ES-3100 Three 8.75" tall can configuration kg (lb)	ES-3100 Empty CV configuration kg (lb)	ES-3100 with maximum weight contents kg (lb)
		Drum asse	mbly			
Drum assembly (drum body, lid, bottom, mid liner, inner liner, cast refractory insulation, cast neutron absorber, nuts, washers, and data plates)	121.96 (268.87)	121.96 (268.87)	121.96 (268.87)	121.96 (268.87)	121.84 (268.61) ^b	121.96 (268.87)
Top plug	8.9 (19.6)	8.9 (19.6)	8.9 (19.6)	8.9 (19.6)	8.9 (19.6)	8.9 (19.6)
Silicone support pads	1.04 (2.29)	1.04 (2.29)	1.04 (2.29)	1.04 (2.29)	1.04 (2.29)	1.04 (2.29)
Total drum assembly weight	131.89 (290.76)	131.89 (290.76)	131.89 (290.76)	131.89 (290.76)	131.78 (290.50)	131.89 (290.76)
		Containment	Vessel			
Containment vessel (flange, dowel pins, cylindrical body, and end cap)	10.18 (22.44)	10.18 (22.44)	10.18 (22.44)	10.18 (22.44)	10.18 (22.44)	10.18 (22.44)
Lid assembly (sealing lid, VCO plug, retaining ring, closure nut and O-rings)	4.92 (10.85)	4.92 (10.85)	4.92 (10.85)	4.92 (10.85)	4.92 (10.85)	4.92 (10.85)
Total containment vessel weight	15.10 (33.29)	15.10 (33.29)	15.10 (33.29)	15.10 (33.29)	15.10 (33.29)	15.10 (33.29)
		Content	's			
Convenience cans with handles	0.72 (1.59)	1.0 (2.22)	0.84 (1.85)	0.67 (1.47)	0.0 (0.00)	
Silicone vibration pads	0.11 (0.23)	0.18 (0.41)	0.16 (0.35)	0.16 (0.35)	0.0 (0.00)	
Spacers with handles	0	0	2.16 (4.76)	1.08 (2.38)	0.0 (0.00)	••
Polyethylene bagging	0.5 (1.10)	0.5 (1.10)	0.5 (1.10)	0.5 (1.10)	0.0 (0.00)	
Metal scouring pads	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.14 (0.30)	0.0 (0.00)	
HEU content	36.0 (79.37)	36.0 (79.37)	36.0 (79.37)	36.0 (79.37)	0.0 (0.00)	
Total proposed content weight	37.32 (82.29)	37.69 (83.10)	39.77 (87.67)	38.35 (84.55)	0	40.82 (90)
Total shipping package weight	184.31 (406.34)	184.68 (407.15)	186.64 (411.48)	185.34 (408.60)	146.88 (323.79)	187.81 (414.05)

Table 2.8. Packaging weights for various ES-3100 shipping package arrangements *

* Calculated weight using Pro/ENGINEER software with nominal dimensions and densities (Pro/ENGINEER Version 20).

Item	Test Unit ,,,, kg (lb)							
· · · · · · · · · · · · · · · · · · ·	1	2	3	4 -	5	6		
Drum body assembly ^b	126.6 (279)	127.9 (282)	127.9 (282)	127.9 (282)	128.8 (284)			
Top plug	9.5 (21)	9.5 (21)	9.53 (21)	8.6 (19)	9.5 (21)			
Drum silicone support pads	0.9 (2)	0.9 (2)	0.9 (2)	0.5 (1)	0.9 (2)			
Containment boundary c	15.4 (34)	15.0 (33)	15.0 (33)	14.5 (32)	15.0 (33)	15.0 (33)		
Mock-up test contents ^d	49.9 (110)	49.9 (110)	50.3 (111)	49.9 (110)	3.6 (8)			
Contents ^e						6.3 (14)		
Total test unit weight	202.3 (446)	202.8 (447)	203.7 (449)	201.8 (445)	157.4 (347)	21.3 (47)		

Table 2.9. Compliance test unit weights*

Total weight may be different from sum of individual component weights due to scale tolerance of ±0.45 kg (1 lb).

^b This weight includes the drum, mid liner, inner liner, cast refractory, cast neutron absorber, bottom, lid, washers and nuts.

* This weight includes containment vessel cylindrical body, end cap, flanged top, and lid assembly.

* This weight was added to reduce buoyancy of containment vessel during 15-m (50 ft) immersion test.

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2.2 MATERIALS

2.2.1 Material Properties and Specifications

The mechanical properties and specifications of the packaging materials are presented in Tables 2.12–2.17. See the drawings in Appendix 1.4.1 for details of all components. Design temperature ranges are listed where they are required to establish the allowable stresses used in the design calculations for the containment boundary (Appendix 2.10.1). Service temperature ranges for the remaining shipping container components were obtained from the references shown in Tables 2.12–2.17.

Appendix 2.10.3 contains the Kaolite 1600 property values presented in Table 2.14, as well as additional Kaolite property and source information. Appendix 2.10.4 contains the Cat 277-4 property and source information. Appendix 2.10.5 contains *Compressive Strength and Coefficient of Thermal Expansion of BoroBond4*. (BoroBond4 was used in the prototype test units, but it is not used in the package to be certified.)

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		1.1.05	nte i
2.2.2	Chemical, Galvanic, or Other Re	eactions	1

Requirement. A package must be 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 a possible reaction resulting from inleakage of water, to the maximum credible extent. Account must be taken for the behavior of materials under irradiation.

^d This weight includes convenience cans, silicone rubber pads, can handles, spacers (if required), and HEU mockup.

Content description	Distance from drum's bottom (in.)
SPHERES - 32,938 g (72.616 lb) max - no can spacers	
3 full 8.75" high cans	22.129
2.5 full 8.75" high cans + 0.5 empty 8.75" high can	21.959
2 full 8.75" high cans + 1 empty 8.75" high can	21.882
1.5 full 8.75" high cans + 1.5 empty 8.75" high cans	21.985
1 full 8.75" high can + 2 empty 8.75" high cans	22.206
3 full 10" high cans	22.366
2.5 full 10" high cans + 0.5 empty 10" high can	22.124
2 full 10" high cans + 1 empty 10" high can	21.972
1.5 full 10" high cans + 1.5 empty 10" high cans	22.036
1 full 10" high cans + 2 empty 10" high cans	22.216
CYLINDERS - 18,000 g (39.683 lb) max - no can spacers	
3 full 4.88" high cans + 1 empty 4.88" high can + 1 empty 10" high can	21.930
2 full 4.88" high cans + 2 empty 4.88" high cans + 1 empty 10" high can	22.147
1 full 4.88" high can + 3 empty 4.88" high cans + 1 empty 10" high can	22.570
3 full 10" high cans	22.497
2 full 10" high cans + 1 empty 10" high can	22.351
1 full 10" high can + 2 empty 10" high cans	22.584
3 full 8.75" high cans	22.353
2 full 8.75" high cans + 1 empty 8.75" high can	22.295
1 full 8.75" high can + 2 empty 8.75" high cans	22.575
CYLINDERS - 36,000 g (79.366 lb) max - with can spacers	
3 full 8.75" high cans + 2 can spacers	22.130
2 full 8.75" high cans + 1 empty 8.75" high can + 2 can spacers	21.736
1 full 8.75" high can + 2 empty 8.75" high cans + 2 can spacers	22.041
3 full 4.88" high cans + 2 empty 4.88" high cans + 4 can spacers	21.367
2 full 4.88" high cans + 3 empty 4.88" high cans + 4 can spacers	21.456
1 full 4.88" high cans + 4 empty 4.88" high cans + 4 can spacers	22.025
3 full 4.88" high cans ± 1 empty 10" high can ± 3 can spacers	21 343
2 full 4.88" high cans + 1 empty 4.88" high can + 1 empty 10" high can + 3 can spacers	21.836
1 full 4.88" high can + 2 empty 4.88" high cans + 1 empty 10" high can + 3 can spacers	22.151

Table 2.10. Calculated center of gravity for the various ES-3100 shipping arrangements

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Content descrip	Distance from drum's bottom (in.)	
BARS - 36,000 g (7	9.366 lb) max - no can spacers	
3 full 8.75" high cans		22.134
2 full 8.75" cans + 1 empty 8.75" high can		21.836
1 full 8.75" high can + 2 empty 8.75" high cans		22.151
3 full 10" high cans		22.386
2 full 10" high cans + 1 empty 10" high can		21.932
1 full 10" high can + 2 empty 10" high cans	677 NA 2025-14	22.160
4 full 4.88" high cans + 1 partially full 10" high can		21.953
4 full 4.88" high cans + 1 empty 10" high can	1	21.808
3 full 4.88" high cans + 1 empty 4.88" high can + 1	21.781	
2 full 4.88" high cans + 2 empty 4.88" high cans +	21.989	
1 full 4.88" high can + 3 empty 4.88" high cans + 1	empty 10" high can	22.457
SLUGS - 31,070 g (68	8.498 lb) max - with can spacers	
3 full 4.88" high cans + 1 empty 10" high can + 3 c	an spacers	21.420
2 full 4.88" high cans + 1 empty 4.88" high can + 1	empty 10" high can + 3 can spacers	21.524
1 full 4.88" high can + 2 empty 4.88" high cans + 1	empty 10" high can + 3 can spacers	22.076
3 full 4.88" high cans + 2 empty 4.88" high cans +	4 can spacers	21.444
2 full 4.88" high cans + 3 empty 4.88" high cans +	21.549	
1 full 4.88" high cans + 4 empty 4.88" high cans + 4	22.100	
3 full 8.75" high cans + 2 can spacers		22.088
2 full 8.75" high cans + 1 empty 8.75" high can + 2	can spacers	21.808
1 full 8.75" high can + 2 empty 8.75" high cans + 2	can spacers	22.117

Table 2.10. Calculated center of gravity for the various ES-3100 shipping arrangements (cont.)

	Containment ASME Boiler and Pressure Vessel Code, Sect. III, Subsection NB	Criticality •
Materials		Cat 277-4ª
Base materials	NB-2000 (except NB-2300) and NB-4100	
Welding materials	NB-2400	
Fabrication		
Forming, fitting, aligning, and joint preparation	NB-4200	
Welding	NB-4400	
Qualification of procedures and personnel	NB-4300	
Examination	NB-5000	Ъ
Acceptance testing	NB-6000	c
Quality assurance	Subpart H in Title 10, CFR, Part 7	1

Table 2.11. Applicable codes and standards for Category I packaging

NUREG/CR-3854 states "The designer may specify a neutron absorber material by a commercial trade name or as a mixture of elements or common compounds. When appropriate, qualification data should be included to demonstrate that the material functions as specified. When special absorber materials are used to control criticality, an acceptance test should be performed for each container to ensure that the absorber material has been properly installed."

^b NUREG/CR-3854 states "Packages designed to transport fissile material which contain neutron absorber material should be tested to demonstrate the presence of the neutron absorber material. The test description should include information similar to that requested for gamma shield testing 3.2.1. Fabrication records of the absorber material and its installation and testing should be maintained."

• NUREG/CR-3854 states "Gamma scanning or probing may be used to demonstrate the soundness of the neutron absorber. Alternatively, ultrasonic testing may be used. Whatever method is used, the following information should be provided in the test procedure:

(1) Description of the measuring technique including the electronics;

(2) The source type and strength used to measure the neutron absorber effectiveness;

(3) The standards and methods use to calibrate the source, sensors, and other pertinent equipment;

(4) The grid pattern used to check the neutron absorber;

- (5) The type of gamma sensor used to measure the neutron absorber effectiveness;
- (6) The specific test requirements and measurements;

(7) The acceptance criteria."

Drum, bottom cover and lid	ASME SA-240 type 304 or 304L, stainless-steel plate		
Inner liners	ASME SA-240 type 304 or 304L, stainless-steel plate		
Top plug weldment	ASME SA-240 type 304 or 3041	., stainless-steel plate	
Materials of construction	ASME SA-240 type 304	ASME SA-240 type 304L	
Design stress intensity, MPa (ksi) at:	· · · · · · · · · · · · · · · · · · ·		
-40°C (-40°F)	137.9 (20)	115.1 (16.7)	
37.78°C (100°F)	137.9 (20)	115.1 (16.7)	
93.33°C (200°F)	137.9 (20)	115.1 (16.7)	
148.89°C (300°F)	137.9 (20)	115.1 (16.7)	
Ultimate strength, MPa (ksi) at:			
-40°C (-40°F)	517 1 (75)	482 6 (70)	
37.78°C (100°F)	517.1 (75)	482.6 (70)	
93.33°C (200°F)	489.5 (71)	455.7 (66.1)	
148.89°C (300°F)	456.4 (66.2)	422.0 (61.2)	
Yield strength, MPa (ksi) at:			
-40°C (-40°F)	206.8 (30)	172.4 (25)	
37.78°C (100°F)	206.8 (30)	172.4 (25)	
93.33°C (200°F)	172.4 (25)	147.5 (21.4)	
148.89°C (300°F)	154.4 (22.4)	. 132.4 (19.2)	
Elongation in 5.08 cm (2 in.) (%)	40 ^b	40 ^b	
Coefficient of thermal expansion, cm/cm/°C (in./in./°F) at:			
-40°C (-40°F)°	0.00001476 (0.0000082) ^c	0.00001476 (0.0000082) ^c	
37.78°C (100°F)	0.00001548 (0.0000086)	0.00001548 (0.0000086)	
93.33°C (200°F)	0.00001602 (0.0000089)	0.00001602 (0.0000089)	
148.89°C (300°F)	0.00001656 (0.0000092)	0.00001656 (0.0000092)	
Modulus of elasticity, GPa (Mpsi) at:			
-40°C (-40°F)	197.2 (28.6)	197.2 (28.6)	
37.78°C (100°F)	194.0 (28.14)	194.0 (28.14)	
93.33°C (200°F)	190.3 (27.6)	190.3 (27.6)	
148.89°C (300°F)	186.2 (27.0)	186.2 (27.0)	

Table 2.12. Mechanical properties of the metallic components of the drum assembly^a

ASME Boiler and Pressure Vessel Code, Sect. II, Part D, Subpart 1, Tables 2A, U, and Y-1; and Subpart 2, Tables TE-1, B column, and TM-1.
ASME Boiler and Pressure Vessel Code, Sect. II, Part A for ASME SA-240 material.

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Drum weld studs	Specification
Material	ASTM A-493 Type 304/304L stainless steel
Fabrication standard	ASTM F593
Service temperature range, °C (°F)	-40 to 816 (-40 to 1500) ^a
Maximum allowable stress, S, MPa (ksi) at temperatures -29°C to 38°C (-20 to 100°F) 93.3°C (200°F) 148.9°C (300°F)	129.6 (18.8) 115.1 (16.7) 103.4 (15.0)
Coefficient of thermal expansion, cm/cm/°C (in./in./°F) * 21.1°C (70°F) 93.3°C (200°F) 148.9°C (300°F)	$1.53 \times 10^{-5} (8.5 \times 10^{-6})$ $1.60 \times 10^{-5} (8.9 \times 10^{-6})$ $1.66 \times 10^{-5} (9.2 \times 10^{-6})$
Drum hex-head nuts	Specification
Material	silicon bronze
Fabrication standard	ASTM F-467
UNS designation	С65100 в
Minimum proof stress, MPa (ksi)	485 (70) ^b
Drum washer	Specification
Drum	1.375 OD × 0.812 ID × 0.25 in. thick, Series 300 stainless steel

Table 2.13. Mechanical properties of the lid fastening components for the drum assembly

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ASME Boiler and Pressure Vessel Code, Sect. II, Part D, Subpart 1, Table 3; and Subpart 2, Table TE-1, group 3, B value.
ASTM F-467M.

Material composition:		Cast Refractory, Kaolite 1600
Flexural tensile strength, kPa (psi) Standard deviation		133 (19.4)* 32 (4.7)
Average coefficient of thermal expansion, cm/cm/°C (in./in./°F)		9.07 × 10 ⁻⁶ (5.04 × 10 ⁻⁶) ^b
Average modulus of rupture per ASTM C133-84	4, kPa (psi)	258.6 (37.5) °
Normal operating temperature, °C (°F)	- 9 - 92 - 29	-40 to 871 (-40 to 1600) ^c
Density after curing, kg/m ³ (lb/ft ³)		358.8 (22.4) °
Force/deflection curves		Smith, Appendix 2.10.3

 Table 2.14. Mechanical properties of the cast refractory insulation

144 - 1865 - 1 19 - 19 - 19 - 19

* Mechanical Properties of a Low-Density Concrete for the New ES-2 Shipping/Storage Container Insulation, Impact Mitigation Media and Neutron Absorber (Appendix 2.10.3).

^b Fax from J. Street, Thermal Ceramics, Inc. (Appendix 2.10.3).

^c Product Information, Refractory Castables and Monolithics (Appendix 2.10.3).

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 Table 2.15. Mechanical properties of containment vessel O-rings

Material composition:	Ethylene propylene, Spe	ecification-M3BA712A14B13F17*b
Normal service temperature range, °C (°F)		-40 to 150 (-40 to 302) °
Permissible exposure time at 150°C (302°F), h		1000 °
Hardness durometer, Shore A	يعد بالاستراك .	70 ± 5 *
Minimum elongation, %		· 100* ·
Fabrication method		Molded *

• ASTM D-2000.

^b Per Specification OO-PP-986.

* Parker O-ring Handbook, Sect. 2.13.2 and Fig. 2-24, p. 2-30.

Containment vessel: body; flange; and seal lid		Specifications		
Material of construction: stainless steel, type 304L		ASME SA-312 (pipe); ASME SA-182 (flange, formed body, or end cap); ASME SA-479 (seal lid		
Design temperature range, °C (°F)		-40 to 176.67 (-40 to 350)		
Minimum ultimate strength, MPa (ksi)		482.6 (70)*		
Yield strength, 0.2% offset, MPa (ksi) at temperatures, 37 14 176.6	.8°C (100°F) 49°C (300°F) 57°C (350°F)	172 (25)* 132 (19.2) ^b 126.52 (18.35) ^b		
Elongation in 5.08 cm (2 in.), %		57°		
Modulus of elasticity, GPa (Mpsi) at temperature ^b -4 37.7 93.3 121.1 148.8 176.6	10°C (-40°F) 78°C (100°F) 33°C (200°F) 11°C (250°F) 39°C (300°F) 57°C (350°F)	197.2 (28.60) 194.0 (28.14) 190.3 (27.60) 188.2 (27.30) 186.2 (27.00) 184.4 (26.75)		
Allowable stresses $(S_m)^d$ at 149°C (300°F)				
Welded pipe, MPa (ksi)				
14 176.6	19°C (300°F) 57°C (350°F)	115.14 (16.7) 112.03 (16.25)		
Forged flanges, lids, end caps, MPa (ksi)	· · ·	()		
at 14 176.6	9°C (300°F) 57°C (350°F)	115.14 (16.7) 112.03 (16.25)		
Coefficient of thermal expansion, cm/cm/°C (in./in./	°F)			
-4 37.7 93.3 121.1 148.8 176.6	0°C (-40°F) 78°C (100°F) 13°C (200°F) 1°C (250°F) 99°C (300°F) 77°C (350°F)	0.00001476 (0.00000820) 0.00001548 (0.00000860) 0.00001602 (0.00000890) 0.00001638 (0.00000910) 0.00001656 (0.00000920) 0.00001674 (0.00000930)		
Containment vessel closure nut		Specification		
Material of construction:		Nitronic 60, UNS-S21800		
Elongation, %		10–12 ^r		
Design temperature range, °C (°F)		-40 to 176.67 (-40 to 350)		
Ultimate strength, MPa (ksi), room temperature		1655–1813 (240–263) ^r		
Yield strength, 0.2% offset, MPa (ksi), room temperature		1344–1496 (195 – 217) ^r		
Coefficient of thermal expansion, cm/cm/°C (in./in./° at temperatures °	°F)			
93.3 204.4	3°C (200°F) 0°C (400°F)	0.0000158 (0.000088) 0.00001660 (0.000092)		

Table 2.16. Mechanical properties of the metallic components of the containment boundary

Listed in the appropriate material specification identified under materials of construction.
ASME Boiler and Pressure Vessel Code, Sect. II, Part D, Tables Y-1 and TM-1.
Value presented in THERM 1.2, thermal properties database by R. A. Bailey.
ASME Boiler and Pressure Vessel Code, Sect. II, Part D, Table 2A.
ASME Boiler and Pressure Vessel Code, Sect. II, Part D, Table 2A.
ASME Boiler and Pressure Vessel Code, Sect. II, Part D, Subpart 2, Table TE-1, Column B, except that -40°C is from MIL-HDBK-5H, Table 2.7.1.0.
Value presented in ADMCO NUTRONIC (0 Statistics Steel Brades Data Data Data Data Steel

^f Value presented in ARMCO NITRONIC 60 Stainless Steel Product Data Bulletin, S-56b.

Material	NA 3121	Cat 277-4
Service temperature range, °C (°F)	 CB112 M G 	-40 to 150 (-40 to 302)
Modulus of elasticity in tension, GPa (Mpsi) at temperatures *	11.11 号: 1997年11.11日 	
	-40°C (-40°F) 21.11°C (70°F) 37.78°C (100°F)	13.72 (1.991) 4.72 (0.684) 2.78 (0.403)
	n an	:
Coefficient of thermal expansion, cm/cm/°C (in./in./°F)	
	-40°C (-40°F) -20°C (-4°F)	12.700 × 10 ⁻⁶ (7.056 × 10 ⁻⁶) 13.000 × 10 ⁻⁶ (7.222 × 10 ⁻⁶)
	0°C (32°F) 40°C (104°F)	13.000 × 10 ⁻⁶ (7.222 × 10 ⁻⁶) 12.600 × 10 ⁻⁶ (7.000 × 10 ⁻⁶)
	60°C (140°F) 80°C (176°F)	$11.599 \times 10^{-6} (6.444 \times 10^{-6})$ $10.400 \times 10^{-6} (5.778 \times 10^{-6})$
•	100°C (212°F) 120°C (248°F)	9.700 × 10* (5.389 × 10*) 9.101 × 10* (5.056 × 10*)
Poisson Ratio		
	-40°C (-40°F) 21.11°C (70°F) 37.78°C (100°F)	0.33ª 0.28 0.25
	Margan and	
Density, g/cm ³ (lb/in. ³)		1.682 (0.0608)

Table 2.17. Mechanical properties of the cast neutron absorber

Mechanical Properties of 277-4 (Appendix 2.10.4).

^b Thermophysical Properties of Heat Resistant Shielding Material (Appendix 2.10.4).

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Analysis. Starting with the outer components, the packaging consists of the drum (austenitic type 304 stainless steel), weld studs (austenitic stainless steel), nuts (silicon bronze), insulation (cast refractory), neutron absorber (Cat 277-4), silicone support pads, containment vessel (austenitic type 304L stainless steel), closure nut (Nitronic 60), silicone support pads, can spacers (stainless steel and Cat 277-4), stainless-steel scrubbers, convenience cans (stainless steel or tinned steel), polyethylene bags, and the HEU contents.

The cast refractory insulation (Kaolite) is contained between the drum and mid liner and within the top plug assembly's stainless-steel sheet metal. Due to the alkaline nature of this material, greater permanence of the surrounding structure is assured. Also, this material has been used successfully for years as an insulation heat treatment liner adjacent to metal surfaces of furnaces.

The cast neutron absorber (Cat 277-4) is contained between the inner liner and mid liner. During the casting process, the chlorine content is limited to 100 parts per million. The small quantity of chlorine will not affect the stainless-steel liners.

The nuts used to attach the drum to the lid are silicon bronze. All other metal components of the packaging are either stainless steel, Nitronic 60, or tinned steel. All stainless-steel components are passivated per ASTM A380, Paragraph 6.4, and Table A2.1, Part II. Prior to assembly, the packaging will be kept inside

a building or transported between buildings in an enclosed truck. The assembled components are protected from the weather and inspected at the time of packaging; therefore, the package will not contain any free water at the time it is loaded for transport. Under NCT, the only moisture present will be the relative humidity or moisture absorbed by the cast refractory or neutron absorber materials. When the package is subjected to a water-spray type environment, some water may leak into the cavity formed by the inner liner and occupied by the containment vessel. To minimize the possibility of any potentially corrosive situation, a visual examination of the interior surface of the inner liner and the exterior surface of the containment vessel shall be conducted prior to packing and following transport of the shipping package (see Sect. 7). Any free water present and any corrosion discovered shall be promptly removed.

During immersion under HAC, water can enter the holes at the top of the drum, be absorbed into the cast refractory material, and fill all void spaces within the drum and inner liner. The insulating value of the insulation material may be decreased, and an overall weight increase would occur. The most important consideration is that the containment boundary remain intact and leaktight. This situation has been evaluated by completely immersing the containment vessel in a tank simulating 0.9-m and 15-m (3- and 50-ft) immersion depths. The containment vessel remained intact and water tight, as demonstrated by the analysis and testing discussed in Sect. 2.7.

All physical contact between the convenience cans and the containment vessel wall, bottom, or top is minimized through the use of the silicone support pads. Additionally, polyethylene bagging may be used around individual convenience cans and the HEU contents as required by packaging personnel. Therefore, galvanic corrosion between the containment vessel and HEU contents is highly unlikely. Since the environment inside the containment vessel is free of electrolytic solutions, there will not be any galvanic reaction occurring inside the containment vessel.

Although the HEU metal contents are not pyrophoric, there is a minimum size restriction. No metal pieces can be of a size or shape with a specific surface area >1.00 cm²/g or weighing <50 g. Foils, turnings, and wires which can easily have much higher specific surface areas are categorically prohibited.

The containment boundary remains intact even when the drum and inner liner are filled with water; therefore, the package is acceptable to the maximum credible extent from the standpoint of chemical, galvanic, or other reactions.

2.2.3 Effects of Radiation on Materials

The HEU material is not irradiated. The neutron and photon dose rates (Sect. 5) are well below those required to damage any of the package materials by radiolytic interactions.

2.3 FABRICATION AND EXAMINATION

2.3.1 Fabrication

2.3.1.1 Drum assembly fabrication

The drum assembly is fabricated in accordance with equipment specifications JS-YMN3-801580-A002 (Appendix 1.4.2), JS-YMN3-801580-A003 (Appendix 1.4.4), and JS-YMN3-801580-A005 (Appendix 1.4.5). The later two specifications control the casting of the Kaolite 1600 and Cat 277-4 materials inside the liners, spacer cans and the top plug as appropriate.

The drum assembly and top plug are fabricated according to the design drawings (Appendix 1.4.1), and the portions of the codes, standards, and regulations to the extent described below:

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1. ASME, Boiler and Pressure Vessel Code, Sect. VIII, Division 1, 2004 edition;

2. ASME, Boiler and Pressure Vessel Code, Sect. II, Parts A and C, 2004 edition;

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3. ASME, Boiler and Pressure Vessel Code, Sect. IX, 2004 edition;

4. Military Standard, MS27683, Drum, Metal-Shipping and Storage 16 to 80 Gallons; and

5. ASTM A 380-99e1, Standard Practice for Cleaning, Descaling, and Passivation of Stainless Steel Parts, Equipment and Systems.

Detailed dimensional requirements, and the materials of construction are called out on the drawings in Appendix 1.4.1. Except for the weld study, documented Certified Material Test Reports (CMTRs) are provided for all materials used in weldments for the fabrication of the drum, including weld filler metal. The CMTRs are traceable to heat numbers and demonstrate compliance with the SA or SFA material specifications called out. For all other materials, documented Certificates of Compliance (CoC) are provided certifying that the materials provided comply with the requirements stated on the drawings and specifications. All welding is done in accordance with welding procedure specifications that are written and performance qualified in accordance with the ASME B&PV Code, Section IX. All welders are performance qualified to weld using these procedures, and their qualifications documented in accordance with the ASME Code, Section IX. The welding fabrication requirements stated in the ASME Code, Section VIII, Division 1, paragraphs UW-26 through UW-48 are met. All butt welds in rolled sheet, pipe and angle joints are full penetration butt welds. With the exception of the seam welds in the drum body, all welds shall be done by the GTAW, GMAW, PAW or a Capacitive Discharge (CD) stud welding process. The weld filler metal used in the fabrication of the drum assembly is procured to comply with the SFA specifications of Section II, Part C of the ASME Code that are stated in the welding procedure specifications. Weld filler metal is procured traceable to heat numbers, and CMTRs are furnished for each heat of weld wire filler. The control of weld filler permits a weld examiner to be able to determine the heat number of the weld filler used in any weld on the drum assembly. Weld symbols are provided on the drawings indicating for each weld the type of weld and dimensions of weld. These weld symbols are interpreted in accordance with the American Welding Society, Section A2.4. 1. 1. <u>1. 1. 1. 1. 1.</u>

2.3.1.2 Containment boundary fabrication

The containment boundary consists of the containment vessel, lid assembly and inner O-ring. The containment vessel is manufactured in accordance with the applicable requirements stated in the ASME Boiler and Pressure Vessel Code, Section III, Division 1, Subsection NB for Class 1 Components as described on the drawings in Appendix 1.4.1 and equipment specification JS-YMN3-801580-A001 (Appendix 1.4.3). The containment vessel is fabricated according to the design drawings and the following codes, standards, and regulations as described in JS-YMN3-801580-A001.

- 1. ASME, Boiler and Pressure Vessel Code, Sect. III, Division 1 Subsections NB and NCA, Class 1 Components, 2004 edition;
- 2. ASME, Boiler and Pressure Vessel Code, Sect. II, Parts A and C, 2004 edition;

3. ASME, Boiler and Pressure Vessel Code, Sect. IX, 2004 edition; and

4. ASTM A 380-99e1, Standard Practice for Cleaning, Descaling, and Passivation of Stainless Steel Parts, Equipment and Systems.

Detailed dimensional requirements, and the materials of construction are called out on the drawings in Appendix 1.4.1. CMTRs are provided for the materials used to fabricate these components in accordance with NCA-3860. The suppliers of these materials will meet the requirements of NCA-3800. Such parts are traceable to each containment vessel by means of a serial number. The fabricator maintains control of materials to ensure this traceability. Other metallic materials, and the O-ring seals are supplied with CoCs in accordance with NCA-3862(g) and (h). The weld filler metal used in the fabrication, and repair welding as permitted, of the containment vessels meets the applicable requirements of NB-2400. It is procured to comply with the SFA specifications of Section II, Part C of the ASME B&PV Code that is stated in the fabricator's welding procedure specifications. Weld metal is procured traceable to heat numbers, and CMTRs are furnished for each heat of weld wire filler used. The results of the delta ferrite determination is included in the CMTR for the weld filler metal (see NB-2433). There are two containment vessel assemblies shown on drawing M2E801580A012 (Appendix 1.4.1), part number M2E801580A012-1, and M2E801580A012-4. Part number M2E801580A012-4 is fabricated by welding a forged bottom and forged top flange to a cylindrical shell machined from seamless pipe as shown on the drawing. All welds on the containment vessels are accomplished by either the GTAW or GMAW process, manual or automatic, at the discretion of the fabricator unless specifically called out on the drawings. Backing rings, even if removed after the weld has been made, are not be used. As previously stated, weld symbols are provided on the drawing indicating the type of weld and dimensions of the weld. These weld symbols are interpreted in accordance with the American Welding Society, section A2.4. The forming, fitting and alignment requirements stated in paragraph NB-4200 are met in the fabrication of the containment vessels unless more stringent requirements are called out on the design drawings.

The preferred fabrication method for the containment vessel body (part number M2E801580A012-1), is from a single forged billet or bar by any process that meets the requirements stated in JS-YMN3-801580-A001 (Appendix 1.4.3), and shown on the design drawings. Such processes may include forging, flow forming, or metal spinning. The formed, heat treated, and finished machined containment vessel body shall meet the applicable requirements of ASME SA 182 for Grade F304L for a forged component. After final forming, parts are solution annealed and quenched per the requirements of ASME SA 182 for Grade F304L. A certified heat treatment report is provided stating the following information for each furnace charge: the serial numbers of the containment vessel bodies heat treated in the furnace charge, the time and date of the heat treating, the person responsible for the heat treating, the time-temperature profile of the furnace and representative parts of the furnace charge, the quench medium, and all other pertinent details of the heat treating. Such a heat treating report is required for all heat treating, both in process annealing and final heat treatment.

2.3.2 Examination

2.3.2.1 Examination of the drum assembly fabrication

The drum and top plug assemblies are examined and tested according to the design drawings, and the portions of the codes, standards, and regulations to the extent described below:

- 1. ASME, Boiler and Pressure Vessel Code, Sect. VIII, Division 1, 2004 edition;
- 2. ASME, Boiler and Pressure Vessel Code, Sect. V, 2004 edition; and

3.

SNT-TC-1A-1992, Recommended Practice for Nondestructive Testing Personnel Qualification and Certification, American Society For Nondestructive Testing, December 1992.

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All welds are visually examined by a qualified weld examiner using a written weld examination procedure. Weld examiners are qualified to perform visual weld inspections in accordance with SNT-TC-1A-1992. The weld examination procedure meets the requirements of the ASME Code, Section V. The weld examination procedures, the weld examiners qualifications, and the weld examination reports are submitted to BWXT Y-12 for records. The acceptance criteria for joint fit-up and alignment, and for visual examination of welds are given in the ASME B&PV Code, Section VIII, Division 1, paragraphs UW-31 through UW-36. In addition, any visible defects such as lack of fusion, lack of penetration, linear or crack-like defects, and visible porosity, are cause for rejection. Straightening, flattening, and forming by mechanical or thermal means of some features and components after welding may be required to ensure proper assembly. The surfaces of areas of the weldment that have been worked are visually examined to ensure that no cracks are present or that the weldment has not been degraded. Adjacent welds to these areas shall are also visually examined. The acceptance criteria is that no cracks are found. The areas worked and the visual inspections are noted on the dimensional inspection report. The external seam weld of the drum assembly is pressure tested by attaching removable lids on both the top and bottom false wire locations and injecting water and air inside the assembly up to the final pressure of 149.61 kPa (21.7 psia). After all testing, inspection and final machining, the drum assembly and top plug are dimensionally inspected. The dimensions, and features such as flatness, run-out, etc, to be inspected are indicated on the design drawings. A written inspection report is prepared, submitted and maintained for each ES-3100 drum assembly.

The above examination criteria address the stainless-steel components. However, the drum assembly also consists of the Kaolite 1600 material and the Cat 277-4 neutron poison. Acceptance criteria for the installation of the Kaolite 1600 material are addressed by specification JS-YMN3-801580-A003 (Appendix 1.4.4). This specification controls and documents the raw materials used for mixing, casting and vibration methodology, and the baking of the material inside the drum assembly. The final acceptance criterion is achieved by producing a cast Kaolite 1600 material density of $358.8 \pm 48 \text{ kg/m}^3$ ($22.4 \pm 3 \text{ lb/ft}^3$). Acceptance criteria for the installation of Cat 277-4 neutron poison are addressed in specification JS-YMN3-801580-A005 (Appendix 1.4.5). This specification also controls and documents the raw materials used for mixing, casting and vibration methodology, and the final density of the casting [$1682 \pm 80 \text{ kg/m}^3$ ($105 \pm 5 \text{ lb/ft}^3$)]. Further examination criteria to verify the concentration and homogeneity of the Cat 277-4 in each drum assembly are also provided in specification JS-YMN3-801580-A005. The various parameters specified in NUREG/CR-3854 and in Table 2.11 for a neutron poison are addressed in detail in this specification.

2.3.2.2 Examination of the containment vessel fabrication

The containment vessel is examined and tested according to the design drawings and the following codes, standards, and regulations as described below:

- 1. ASME, Boiler and Pressure Vessel Code, Sect. III, Division 1 Subsections NB and NCA, Class 1 Components, 2004 edition;
- 2. ANSI N14.5-1997, American National Standard for Radioactive Materials Leakage Tests on Packages for Shipment;
- 3. ASME, Boiler and Pressure Vessel Code, Sect. V, 2001 edition and 2002 and 2003 addenda; and
- 4. SNT-TC-1A-1992, Recommended Practice for Nondestructive Testing Personnel Qualification and Certification, American Society For Nondestructive Testing, December 1992.

Procured materials are examined in accordance with the applicable paragraphs of NB-2500, and meet the stated acceptance criteria. The results of these examinations are be included with the CMTRs provided to BWXT Y-12. Prior written approval is obtained for any weld repair on materials, and the weld repair areas are both surface and volumetrically examined. The repair area is noted in a sketch supplied with the CMTR for the material that was weld repaired and the documented results of the weld examination are provided to BWXT Y-12. The markings on the weldment materials are not removed until after all weld examination is complete. The heat numbers of base metals and weld filler are required on all weld examination reports. Control of weld filler by the fabricator permits a weld examiner to be able to determine the heat number of the weld filler used in any weld on the containment vessel.

As previously stated, the containment vessel body may be fabricated by two different methods shown on drawing M2E801580A012 (Appendix 1.4.1). Part number M2E801580A012-4 is fabricated by welding a forged bottom, and forged top flange to a cylindrical shell machined from seamless pipe as shown on the drawing. Prior to welding these components, all weld preparation areas and the surfaces within one inch of the weld are examined visually and with liquid penetrant. The acceptance criteria for these examination are those stated in NB-5130(a) through NB-5130(d). The applicable requirements in paragraphs NB-5110, NB-5120, NB-5210, NB-5220, NB-5260, and NB-5300 apply to the containment vessels. The plug weld shown on Drawing M2E801580A015 (Appendix 1.4.1) shall be examined visually and with penetrant. The applicable requirements in paragraphs NB-5110, and NB-5350 shall apply to the plug weld. Materials used in the penetrant examination of welds and in the final surface examination of finished components (see Section 3.7) shall be specifically recommended by their suppliers for use with austenitic stainless steels, and copies of the certification of contaminant content of materials used (see ASME, Section V, Article 6, T-641) shall be supplied with the examination reports. Repair welding shall meet the applicable requirements of NB-2500. Certified written weld examination reports together with the corresponding material surface examination reports, and weld map shall be submitted as stated in the procurement specification for the containment vessel. Weld examination reports for all weld and surface examination shall include: the containment vessel serial number, a weld map showing the location of the weld and examination area, the welder's name, the examiner's name, the time and date of the weld examination, the examination procedure(s) number used, the WPS number, the heat numbers of the materials joined, the heat number of the weld filler, and examiner's remarks. The examiner's remarks shall include the results of the examination and acceptance, or rejection of the weld based on the stated criteria. One set of radiographs shall be provided with radiographic examination reports. If the weld or surface is rejected, a description of the defect and sketch showing the location shall be provided.

The nonwelded containment vessel body, part number M2E801580A012-1, shall be formed from a single forged billet or bar by any process that meets the requirements stated in JS-YMN3-801580-A001 (Appendix 1.4.3), and shown on the design drawings (Appendix 1.4.1). Such processes may include forging, flow forming, or metal spinning. The formed, heat treated, and finished machined containment vessel body shall meet the applicable requirements of ASME SA 182 for Grade F304L for a forged component. Mechanical properties are verified by testing of coupons. The test coupons are to be machined from the same heats of materials used to form the containment vessel bodies, and shall have the same or greater amount of cold word (plastic strain) as the containment vessels will have as a result of the forming process. The mechanical tensile testing of coupons shall be done in accordance with ASME SA 370. A minimum of six test coupons shall be tested for each final heat treatment furnace charge. The first set of three test coupons, chosen at random, shall be tested without being heat treated. The second set of three or more test coupons shall be heat treated together with the containment vessel bodies, and then tested. The heating rates and maximum temperatures of the test coupons shall be representative of the entire furnace charge. Test coupons are not required to be heat treated with intermediate processing annealing steps, but are required in the final heat treatment furnace charge. The results of all the testing of the sample coupons shall be documented, certified and reported to BWXT Y-12. The mechanical properties test report shall contain the following

information: a descriptor of the furnace charge in which the test coupons are to represent; the times and dates of the heat treating and the testing; the person responsible for the testing; a statement that these coupons are prior to or after heat treatment; a description of the testing including a sketch of the tensile test specimen; the make, model, serial number, and current calibration data of the testing machine(s) used in the testing; reference to the written testing procedure used; the resulting measure yield strength, ultimate strength, % elongation and % reduction in area; and any pertinent remarks.

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2.4 LIFTING AND TIE-DOWN STANDARDS FOR ALL PACKAGES

This section addresses the requirements of 10 CFR 71.45, "Lifting and Tie-Down Standards for All Packages."

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2.4.1 Lifting Devices

Requirement. Any lifting attachment that is a structural part of a package must be designed with a minimum safety factor of three against yielding when used to lift the package in the intended manner, and it must be designed so that failure of any lifting device under excessive load would not impair the ability of the package to meet other requirements of 10 CFR 71, Subpart E. Any other structural part of the package that could be used to lift the package must be capable of being rendered inoperable for lifting the package during transport, or must be designed with strength equivalent to that required for lifting attachments.

Analysis. The ES-3100 packages, as delivered for transport, have no lifting devices or structural parts that can be used for lifting. Therefore, the lifting devices requirements of 10 CFR 71.45 are not applicable.

2.4.2 Tie-Down Devices

Requirement. If there is a system of tie-down devices that is a structural part of the package, the system must be capable of withstanding, without generating stress in any material of the package in excess of its yield strength, a static force applied to the center of gravity of the package having a vertical component of two times the weight of the package with its contents, a horizontal component along the direction in which the vehicle travels of ten times the weight of the package with its contents, and a horizontal component in the transverse direction of five times the weight of the package must be capable of being rendered inoperable for tying down the package during transport, or must be designed with strength equivalent to that required for tie-down devices. Each tie-down device that is a structural part of a package must be designed so that failure of the device under excessive load would not impair the ability of the package to meet other requirements of this part.

Analysis. The ES-3100 package, as delivered for transport, has no tie-down devices. Therefore, the tie-down requirements of 10 CFR 71.45 are not applicable.

2.5 GENERAL CONSIDERATIONS

Package structural evaluation is performed by the combination of full scale testing, similarity, and analysis as described in the following sections.

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2.5.1 Evaluation by Test

The ES-3100 package was tested in accordance with Test Plan and Procedures for Certification Testing of the ES-3100 Shipping Package: Final Version w/Field Modifications. (ORNL/NTRC-013, Vol. 3) Testing of ES-3100 prototype units was performed at the National Transportation Research Center (NTRC), except as noted below. Five full-scale test units were assembled with content weights ranging from 3.6 kg (8 lb) to 50.3 kg (111 lb). One of these test units (TU-4) was subjected to the tests specified in 10 CFR 71.71(c)(5) through (c)(10) excluding (c)(8) prior to the HAC sequential tests stipulated in 10 CFR 71.73 and shown in Table 2.18. Test Unit 2 was chilled prior to being subjected to any structural testing (i.e., 1.2-m NCT drop, 9-m HAC drop, HAC crush, and HAC puncture tests). This unit was 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 the Oak Ridge National Laboratory (ORNL) with initially setting of the chamber at ~ -57°C (-70°F) for 24 h. After this initial period, the control on the environmental chamber was set to ~ -43 °C (-45 °F) for another 48 h. Prior to the initiation of structural testing of this unit, it was removed from the environmental chamber and placed in an insulated box. Once transported to the NTRC, sequential structural testing, as shown in Table 2.19 was performed as quickly as possible. The other test units were first subjected to the free drop from 1.2 m (4 ft) test prior to the HAC testing of 10 CFR 71.73. These additional tests were conducted to show that the NCT testing would not reduce the effectiveness of the package to withstand HAC testing. Tables 2.18 and 2.19 summarize the testing procedure and the drop orientations for each ES-3100 test unit.

The essentially unyielding surface used for the 1.2-m (4 ft) drop test was the indoor drop test pad at the NTRC. All 9-m (30-ft) drop and crush tests were conducted at the outside drop pad at the NTRC. The indoor pad consists of a 5.08-cm (2-in.)-thick steel plate embedded inside a reinforced concrete pad ~127 cm (50 in.) thick. The outside drop pad consists of a 10.16-cm (4-in.)-thick steel plate embedded inside a reinforced concrete pad ~167.6 cm (66 in.) thick. An article has been prepared by the NTRC staff to describe the integrity of these test pads (Shappert 1991).

Thermal testing of the five test units was conducted at the No. 3 furnace at Timken Steel Company in Latrobe, Pennsylvania. Prior to the testing, the furnace was characterized for temperature and heat recovery times. Oxygen content in stack gases of the furnace was not monitored 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 liners and the top plugs of the packages. However, it should be noted that this furnace employs "pulsed" fire burners. This type of burner is unique in that 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, thereby ensuring a very rich furnace atmosphere capable of supporting any combustion of package materials of construction. The support stand was welded to a large steel plate which had been placed on the floor of the furnace prior to heating. This steel plate acted as the radiating surface at the bottom of the furnace as well as providing the ability to hold the test stand rigidly in place. Before heating the furnace, workers practiced loading and unloading test packages from the cold furnace to assure that the furnace door would not remain open >90 s during each loading. In fact, the maximum time the door was open during any loading was 64 s.

Damage resulting from physical testing is quantitatively described including photographs in Sect. 2.7. The full-scale test units were fabricated in accordance with drawings created for production hardware. During the procurement process for the full-scale test units, several small changes were suggested by the manufacturer to improve the efficiency and to reduce the cost of fabrication. These changes were incorporated and tested. However, following compliance testing the following changes have been made to the proposed production hardware. First, a change in the neutron poison from BoroBond4 to Cat 277-4 has been adopted; second, the mid liner design has been changed to a continuous shell by reducing the diameter

Test	TU-1 (heavy) 12* Slap-down	TU-2 (heavy) Side Drop	TU-3 (heavy) CG over Top Corner	TU-4 (heavy) Top Down	TU-5 (light) 12° Slap-down
Operational Leak Test (CALT5)	1		1	- 1	1
NCT – 10CFR71.71 (c)(5) Vibration		utrana ^{ta} Ku		5	•
NCT – 10CFR71.71 (c)(6) Water Spray		a the f		2	· · ·
NCT – 10CFR71.71 (c)(7) 1.2 m (4 ft) Free Drop	2	· ····································	.2	3.	2.
NCT – 10CFR71.71 (c)(9) Compression		i sufficienti Anna instituti		6	
NCT – 10CFR71.71 (c)(10) Penetration		an tean tra A second second		4	

Table 2.18. Summary of NCT - 10CFR71.71 tests for ES-3100 package*

* The numbers 1 through 6 indicate the sequence of the tests.

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Table 2.19. Summary of HAC - 10CFR71.73 tests for ES-3100 package*

Test	TU-1 (heavy) 12° Slap-down	TU-2 (heavy) Side Drop	TU-3 (heavy) CG over Top Corner	TU-4 (heavy) Top Down	TU-5 (light) 12* Slap-down	TU-6 ^b 15m Immersion
10CFR71.73 (c) (1) Free Drop 9m (30 ft.)	1 -	aliga. Sites	1	1.	1 .	· .:
10CFR71.73 (c) (2) Crush 9m (30 ft.)	2	2 (article)	2	. 2	2	
10CFR71.73 (c) (3) Puncture 1m (40 in.)	3,4,5,6	- i 3 -r.c.	. 3	3	3	· ·
Preheat to above 38 °C (100 °F) before Thermal test	7	in la 4 ages. La coule tar	4	4	4	
10CFR71.73 (c) (4) Thermal 800°C (1475°F)	8	5	5	5	5	
Operational Leak Test of CV (CALT5)	9	6 2 - 1 - 1 - 1 - 1 - 1 - 1 - 1 - 1 - 1 -	6	6	6	1
Full Containment Boundary Leak Test (He Leak Test)	10	1 1 7 (1973) 1993 - 17 (1973)	~ 7	7	7	
10CFR71.73 (c) (5) Immersion Test Fissile materials – 0.9 m (3 ft.)	11	8777	8	· 8	8	
10CFR71.73 (c) (6) Immersion Test –All Packages 15 m (50 ft.)	1 .	9 1.25% P 19 1001 1	X.			2

The numbers 1 through 11 indicate the sequence of the tests.
TU-6 is only a containment vessel with ballast to ensure non-buoyancy.

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of the step in the inner liner for the CV flange from 22.35 cm (8.8 in.) to 21.84 cm (8.6 in.); and third, the silicone rubber pad thickness on the drum assembly bottom liner was increased by ~0.15 cm (0.06 in.). The second change increased the amount of Kaolite 1600 around the CV flange, increased the final volume of the neutron poison, and slightly decreased the volume of the Kaolite 1600 adjacent to the neutron poison. The third change was made to stiffen the rubber pad so it would remain in place during vibration normally incurred during transport. In order to evaluate the impact of these changes, analytical drop simulations were conducted and documented in Appendix 2.10.2. The drop simulations were conducted in the same attitude and temperature regime as those conducted during the compliance testing phase for certification. The results of the structural deformation from compliance testing, drop simulation using BoroBond4 and drop simulations using Cat 277-4 material are presented in Sect. 2.7.8. The analytical structural deformation results shown in Tables 2.52 through 2.61 are nearly identical between the two neutron poisons. The analytical results are also well representative of the results recorded during compliance testing. Analytical strain prediction in the structural components are also compared. Although there are minor differences between simulations, the overall magnitude of the strains are very similar. The thermal aspects of these changes are addressed in Sect. 3. NCT and HAC results predicted for an undamaged package show that the change in neutron poison actually reduces the final temperature of the containment vessel components. Therefore, the substitution of Cat 277-4 material and the minor changes in the inner and mid liners for production hardware should not reduce the effectiveness of the packaging when subjected to the regulatory requirements of 10 CFR 71 and the results of compliance testing would be analogous.

The contents used as surrogate payloads for the test units are shown on drawings M2E801580A029, and M2E801580A027. In the light-weight configuration, the contents consist of three 25.4 cm (10 in.) high convenience cans with handles, and 4 silicone rubber pads. These convenience cans, handles and silicone rubber pads are identical to those proposed for transport. The bottom convenience can was filled with tungsten grit until the convenience can and grit assembly weighed \sim 3 kg (6.6 lb). The actual weight of the tungsten grit was 2.77 kg (6.11 lb). The total content weight for the light- weight content configuration including the convenience cans, silicone rubber pads, can handles, and tungsten grit was \sim 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 \sim 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 (-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).

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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 $\leq 3.8445 \times 10^{-3}$ ref-cm³/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.

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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 $\times 10^{5}$ to 1.696 × 10⁶ 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 122.63 kPa (17.786 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 122.63 kPa (17.786 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 122.63 kPa (17.786 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 (122.63 - 76.74) kPa or 45.89 kPa (6.656 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.

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) °	122.63 (17.786)		

Table 2.20. Summary of temperatures and pressures for NCT

* Analysis conducted with no decay heat load in accordance with 10 CFR 71.71(c)(2).

^b Assembly temperature and pressure.

⁶ 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 $38^{\circ}C$ (100°F) in still air and insolation as stated in 10 CFR 71.71(c)(1).

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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 122.63 kPa (17.786 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 122.63 kPa (17.786 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 $25 \,^{\circ}$ C (77 $^{\circ}$ 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.

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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 1.4.1). Although some contraction of these material 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 are not addressed. No credit is taken for the ability of the convenience can 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 is taken. Based on assembly clearances and insignificant differences in the coefficient of thermal expansion between the stainless-steel or tin-plated carbon steel convenience cans and the stainless-steel containment vessel, no radial or vertical interferences will develop during NCT testing.

2.6.1.3 Stress calculations

During normal conditions, stresses are only imposed by changes in internal pressure of the containment boundary as the temperature varies slowly over the operating range as shown in Table 2.20. Stress levels imposed on the package during NCT are insignificant, as shown in Tables 2.21, and 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 Sect. 2.6.1.4, all stresses in the containment boundary components are well below the *ASME Boiler and Pressure Vessel Code* allowable stress intensity limits.

2.6.1.4 Comparison with allowable stresses

NCT containment vessel stresses are calculated in accordance with the load combinations listed in Table 2.3 and their values are shown in Tables 2.21 and 2.22. The hot environment, cold environment, minimum external pressure, increased external pressure condition, and vibration normally incident to transport are addressed in Sects. 2.6.1, 2.6.2, 2.6.3, 2.6.4, and 2.6.5, respectively. The fatigue or endurance limits for austenitic stainless steel are normally assumed to be about one-half the ultimate tensile strength (*Design Guidelines for Selection of Stainless Steel*, pp. 17–18). For type 304 stainless steel, one-half the ultimate tensile strength is 2.4×10^5 kPa (35,000 psi). Tensile and compressive hoop stresses of the magnitude shown in Tables 2.21 and 2.22 are insignificant compared to the endurance limit of 2.4×10^5 kPa (35,000 psi). As shown in Tables 2.21 and 2.22, the containment vessel stresses during NCT are insignificant. Even at the maximum test temperature and internal pressure (Sect. 3.5.3), the stresses in the containment boundaries were insignificant when compared with the allowable stress intensities shown in Tables 2.4 and 2.5. Corresponding calculated stress regions are shown in Fig. 2.1. Thermal expansion or contraction issues are addressed in Sects. 2.6.1.2 and 2.6.2.

2.6.2 Cold

Requirement. An ambient temperature of -40° C (-40° F) in still air and shade, as required by 10 CFR 71.71(c)(2).

Analysis. The drum is fabricated from type 304 stainless-steel sheet (Table 2.7). As discussed in Sect. 2.6, stainless steel is excellent for low-temperature service, particularly regarding tensile and impact strength. The thermal insulation (Kaolite) is a lightweight noncombustible cast refractory made from portland cement and vermiculite. The only moisture available for freezing at -40°C (-40°F) would be moisture that had not been removed during the curing and cool-down phase of fabrication. Because there will be no free water present for freezing and the insulation is a bonded mass of random fibers and cement, the properties of the insulation will not change appreciably. The matrix may become less flexible when subjected to the cold temperature, but the inner liner will remain in the position in which it was placed at the time of fabrication. The Kaolite 1600 insulation and Cat 277-4 materials are poured and cast in place during the fabrication of the drum weldment (Drawing M2E801508A002, Appendix 1.4.1). Although some contraction of these material may occur during curing, it is assumed for analysis purposes 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 the coefficient of thermal expansion, some radial and axial interference is expected due to contraction of the outer drum and inner liners. These radial and axial interferences and induced stresses are calculated in Appendix 3.6.3. A maximum von Mises stress of 6.115×10^4 kPa (8869 psi) was calculated for the inner liners. This stress value is well below the allowable yield strength of 1.724 × 10⁵ kPa (25000 psi) at -40°C (-40°F). A maximum von Mises stress of 979 kPa (142 psi) and 510 kPa (74 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 Y/DW-1972 (Smith, Appendix 2.10.3) at -40°C (-40°F), these compressive stresses are well below the failure limit of ~ 6.895×10^3 kPa (1000 psi) and 5.308×10^3 kPa (770 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 containment boundary is fabricated from type 304L stainless steel, which is suitable for low-temperature service, particularly regarding impact resistance. This material does not show a transition from ductile to brittle failure at this temperature. The *ASME Boiler and Pressure Vessel Code*, Sect. III, Subsection NB-2311, exempts impact testing of type 304L stainless steels. The Izod impact strength for type 304 stainless steel is 149.14 N·m (110 ft-lb) from 21.11 to -195.5° C (70 to -320° F). The tensile strength increases from -4.826×10^5 to 1.696×10^6 kPa (70,000 to 246,000 psi) between 21.11 and -195.5° C (70 and -320° F), and the yield strength increases about 10% over the same range. NRC Regulatory Guide 7.6, Part B, states, "these designs were made of austenitic stainless steel which is ductile even at low temperatures. Thus, this guide does not consider brittle fracture." The drum, inner liner, top plug, and containment boundary are made from austenitic stainless steel. Similarly, the containment boundary closure nut material is a galling and wear resistant austenitic stainless steel. Therefore, brittle fracture of these structural materials at -40° C (-40° F) is not possible.

The specified O-rings used in the containment boundary have a continuous service temperature range of -40 to 150°C (-40 to 302°F) as shown in Table 2.15. The low temperature extreme has been verified by compliance testing of Test Unit-2 (Sect. 2.7.1.2). 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 NTRC for testing.

As previously noted, the containment vessels will be assembled for shipment in a temperature environment of ~25°C (77°F). If the package should be exposed to -40°C (-40°F) for an extended period, all components will equalize near this low temperature. The absolute internal pressure inside the containment boundary would decrease to a pressure of 76.74 kPa (11.13 psi), assuming no decay heating (Table 2.20). Therefore, the pressure differential across the containment vessel at -40°C (-40°F) is

-24.61 kPa (-3.57 psia) [76.739 - 101.350 kPa] (11.13 - 14.7 psia). Due to similarities of the coefficient of thermal expansion between type 304/304L and the containment vessel closure nut material (Nitronic 60, ASME SA-479), the compression of the O-rings does not change appreciably during the temperature excursion from $25^{\circ}C$ (77°F) to $-40^{\circ}C$ ($-40^{\circ}F$). The calculated stresses shown in Table 2.21 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 pressure to design pressure and adding any contribution from the closure nut preload. This methodology is based on linear elastic material behavior. As shown in Sect. 2.6.1.4, all stresses in the containment boundary components are well below the *ASME Boiler and Pressure Vessel Code* allowable stress intensity limits. As demonstrated by the information presented above, the packaging is acceptable for NCT at $-40^{\circ}C$ ($-40^{\circ}F$).

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 97.63 kPa (14.16 psi) [122.63 - 25 (17.786 - 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).

Stress locations shown in Fig. 2.1	Hot con [10 CFR 71 containment bo @ 21.30 (3.090 ps)	ditions 1.71(c)(1)] oundary stress 0 kPa i) gauge	Cold condi [10 CFR 71 containment bout @ -24.61 (-3.57 psi)	tions (c)(2)] 1dary stress kPa 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)	2.099 × 10 ² (30.44)	630	2.425 × 10 ² (35.17)	545	1.324 × 10 ⁵ (19,200) ^b
Closure nut ring (away from threaded portion)	4.537 ×10⁴ (6580)	1.5 9.1	4.246 × 10 ^{4 f} (6158)	9.8	4.571 × 10 ³ (66,300) ^c
Top flat head (sealing surface region)	1.779 × 10 ⁴ (2580)	13.9	1.665 × 10 ^{4 f} (2415)	14.9	2.648 × 10 ^s (38,400) ^c
Cylindrical section (middle)	6.085 × 10 ² (88.3)	144	7.030×10^2 (102)	124.5	8.825 × 10 ⁴ (12,800) ^d
Cylindrical section (shell to flange interface)	7.920 × 10 ³ (1148.6)	32.4	8.034 × 10 ³ (1165.2)	32.0	2.648 × 10 ⁵ (38,400) ^c
Cylindrical section (shell to bottom interface)	1.561 × 10 ³ (226.4)	168.6	1.803 × 10 ³ (261.5)	145.8	2.648 × 10 ⁵ (38,400)°
Body flange threads load, kg (lb)	9.420 × 10² (2076.8)	20.8	9.072 × 10 ^{2 f} (2000)	21.6	2.053 × 10 ⁴ (45266) ^e
Body flange thread region (under cut region)	2.561 × 10⁴ (3714)	9.3	2.256 × 10 ^{4 f} (3272)	10.0	2.648 × 10 ⁵ (38,400) ^c
Flat bottom head (center)	1.469 × 10 ³ (213.1)	89.1	1.698 × 10 ³ (246.2)	77	1.324 × 10 ⁵ (19,200) ^b
Closure nut thread load, kg (lb)	9.420 × 10² (2076.8)	36.6	9.072 × 10 ^{2 f} (2000)	38.1	3.545 × 10 ⁴ (78154) [¢]

Table 2.21. ES-3100 containment boundary evaluation for both hot and cold conditions*

* 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 $P_1 + P_b$; allowable stress intensity value is $1.5 \times S_m$. ^c Stress interpreted as the sum of $P_1 + P_b + Q$; allowable stress intensity value is $3.0 \times S_m$.

⁴ Stress interpreted as the primary membrane stress (P_m); allowable stress intensity value is S_m.
 ⁵ Allowable shear capacity is defined as 0.6 × S_m × thread shear area. Thread shear area = 38.026 cm² (5.894 in.²).
 ⁶ Stress and shear load in these areas are dominated by the 162.7 ± 6.8 N m (120 ± 5 ft-lb) preload.

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

Stress locations shown in Fig. 2.1	Reduced exter [10 CFR 71 containment bo @ 97.63 kPa (14 kPa (nal pressure .71(c)(3)] undary stress .16 psi) gauge psi)	Increased exte [10 CFR 7 containment bo @ -63.26 kPa (- kPa	rnal pressure 1.71(c)(4)] oundary stress -9.18 psi) gauge (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)	9.619 × 10 ² (139.50)	137	6.236 × 10 ² (90.4)	211.3	1.324 × 10 ⁵ (19,200) ^b
Closure nut ring (away from threaded region)	5.031 × 10 ⁴ (7296.9)	8.1	4.246 × 10 ^{4 f} (6158)	9.8	4.571 × 10 ⁵ (66,300)°
Top flat head (sealing surface region)	1.899 × 10⁴ (2754.4)	12.9	1.665 × 10 ^{4 f} (2415)	14.9	2.648 × 10 ⁵ (38,400)°
Cylindrical section (middle)	2.789 × 10 ³ (404.4)	30.6	1.808 × 10 ³ (262.2)	47.8	8.825 × 10 ⁴ (12,800) ^d
Cylindrical section (shell-to-flange interface)	1.056 × 10 ⁴ (1532.1)	24.1	9.374 × 10 ³ (1359.6)	27.2	2.648 × 10 ⁵ (38,400) ^e
Cylindrical section (shell-to-bottom interface)	7.152 × 10 ³ (1037.4)	36	4.637 × 10 ³ (672.5)	56.1	2.648 × 10 ⁵ (38,400) ^e
Body flange threads load, kg (lb)	1.067 × 10 ³ (2352)	18.2	9.072 × 10 ^{2 f} (2000)	21.6	2.053 × 10 ⁴ (45266)
Body flange thread region (under cut region)	2.954 × 10 ⁴ (4285)	8.0	2.397 × 10 ^{4 f} (3476)	10.0	2.648 × 10 ⁵ (38,400) ^c
Flat bottom head (center)	6.733 × 10 ³ (976.6)	18.7	4.365 × 10 ³ (633)	29.3	1.324 × 10 ⁵ (19,200) ^b
Closure nut thread load, kg (lb)	1.067 × 10 ³ (2352)	32.2	9.072 × 10 ² f (2000)	38.1	3.545 × 104° (78154)

* 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.

Stress values are taken from ratio 2.5.
Stress interpreted as the sum of P₁ + P_b; allowable stress intensity value is 1.5 × S_m.
Stress interpreted as the sum of P₁ + P_b + Q; allowable stress intensity value is 3.0 × S_m.
Stress interpreted as the primary membrane stress (P_m); allowable stress intensity value is S_m.
Allowable shear capacity is defined as 0.6 × S_m × thread shear area. Thread shear area = 38.026 cm² (5.894 in.²).
Stress and shear load in three areas are dominated by the 162.7 + 6.8 N·m (120 + 5 ft.lb) preload.

^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 (ORNL/NTRC-013, Vol. 3) and documented in the test report. (ORNL/NTRC-013) 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 (ORNL/NTRC-013) 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 ($\leq 2 \times 10^{-7}$ cm³/s) in accordance with ANSI N14.5-1997.

Following compliance testing of the ES-3100 shipping package, minor changes were incorporated into the proposed design as described in Sect. 2.5.1. During the vibration test, the shipping package is restrained from movement in the vertical direction with a tie-down arrangement similar to that used on a



Fig. 2.3. ES-3100 vibration testing arrangement. (MD-1 test unit removed during actual testing.)

SST/SGT for a single package. Based on the acceleration spectral density presented in Appendix 2.10.6, the largest contributor to shipping package motion is in the vertical direction. Since the containment vessel and contents are not restrained within the inner liner cavity, the containment vessel is free to bounce up and down. In the vertical direction, the top plug and the bottom of the inner liner restrict the movement of this vessel. Since the inner liner contour has not changed with respect to the containment vessel, and the fact that there are clearances between the containment vessel flange and the inner liner in the vertical direction, the cast neutron poison and inner liner are not directly impacted by the movement of the containment vessel. Therefore, changes in the neutron poison and minor radial dimension changes in the mid liner will not affect the outcome from vibration testing. Based on the success of the previously tested units and the fact that these proposed changes will have little or no effect on testing, 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)

Procedures will be followed to ensure that the packaging is assembled as specified (Sect. 7). The drum, lid, and fasteners are refurbished as required before each use. The 3/8-in.-diam flange nuts on the drum are torqued to 40.67 N·m (30 ft-lb) nominal. The closure nut on the containment boundary is torqued to 162.7 N·m (120 ft-lb) nominal. The package is acceptable for vibration normally incident to transport in an SST/SGT.

2.6.6 Water Spray

Requirement. A water spray that simulates exposure to rainfall of ~5.08 cm (2 in.) per hour for at least 1 h is required by 10 CFR 71.71(c)(6).

Analysis. A water spray of 5.08 cm (2 in.) per hour was directed from above and around the periphery of the ES-3100 Test Unit-4 for a minimum of 1 h as shown in Fig. 2.4. The drum had four plastic plug-sealed ventilation holes near the top which prevents water from entering the insulation cavity. Aluminum duct tape, covering the installation holes in the mid liner, prevents water from entering the neutron poison cavity. There was evidence of water leakage into the volume between the containment boundary and the inner liner at the conclusion of the test. Water entered this cavity through the holes provided in the lid for the TID lugs, but none penetrated the containment boundary. The criticality analysis shown in Sect. 6 was conducted with moderation by water to the most reactive credible extent and close full reflection of the containment system by water on all sides. Because the package remained subcritical under these conditions, the ES-3100 package is acceptable for use under the water spray conditions of NCT.



Fig. 2.4. Water spray test arrangement for Test Unit-4.

2.6.7 Free Drop

Requirement. A free drop of 1 m (4 ft) onto a flat, essentially unyielding, horizontal surface in a position for which maximum damage is expected is required by 10 CFR 71.71(c)(10). This test shall be made between $1\frac{1}{2}$ and $2\frac{1}{2}$ h after the conclusion of the water spray test (Sect. 2.6.6).

Analysis. The ES-3100 test package, Test Unit-4, previously sprayed with water (Sect. 2.6.6) with a measured gross weight of 201.85 kg (445 lb) and containing a content weight of 49.90 kg (110 lb) was tested in accordance with 10 CFR 71.71(c)(7). The temperature and pressure at the time of the drop test was 22.8 °C (73 °F) and ~101.35 kPa (14.70 psi), respectively. As discussed in Sect. 2.6, the response of the test package would not have been significantly different if it had been tested at the extremes of the temperature range dictated by 10 CFR 71.71(b) with the containment vessel at the maximum normal operating pressure.

The essentially unyielding surface used for this test was the indoor drop test pad at the NTRC. All 9-m (30-ft) drop and crush tests were conducted at the outside drop pad at the NTRC. The indoor pad consists of a 5.08-cm (2-in.) thick steel plate embedded inside a reinforced concrete pad \sim 127-cm (50-in.) thick. The outside drop pad consists of a 10.16-cm (4-in.) thick steel plate embedded inside a reinforced concrete pad \sim 167.6-cm (66-in.) thick. An article has been prepared by the NTRC staff to describe the integrity of these test pads (Shappert 1991).

Test Unit-4 was dropped from 1.2 m (4 ft) in a vertical position, with the drum's top initially striking the unyielding surface (Fig. 2.5). This attitude was assumed to be the most vulnerable orientation for producing damage to the sealing surfaces of the containment vessel and for introducing buckling into the cylindrical portion of the containment vessel body. The long axis of the drum was 0° from vertical. The test package made a free fall, with initial contact on the drum's lid. Damage consisted of shortening the drum height from 110.81 cm (435% in.) to 110.49 cm (431/2 in.) There were no breaks in the drum assembly. Additional details and sketches can be obtained from the test report. (ORNL/NTRC-0013, Test Form 1) Based on the HAC analytical structural deformation results shown in Sect. 2.7.8, the drop test damage would be nearly identical had this test been conducted on the proposed configuration using the Cat 277-4 neutron absorber. On this basis, the ES-3100 package meets the requirements of 10 CFR 71.71(c)(7).

In addition to the tests conducted on Test Unit-4, all test units (except Test Unit-6) were initially subjected to a free drop of 1.2-m (4 ft) onto a flat, essentially unyielding horizontal surface. As shown in Table 2.18, the orientations for these drops were two drops bottom to lid slapdown with the long axis of the drum ~ 12° from parallel to the drop pad; one drop with the long axis of the test unit parallel to the drop pad; one drop with the long axis of the test unit parallel to the drop pad; one drop with the center of gravity drop over the drum/lid interface with the long axis of the drop rotated ~24.6° from perpendicular to the drop pad; and one with the long axis of the drum perpendicular to the drop pad. Package description, damage from testing, and drop orientation concerns are discussed in Sect. 2.7.1 for each test unit. Following the 1.2-m (4-ft) drop, each of these test units was subjected to the full HAC sequential test battery. The robustness of the ES-3100 containment vessel was demonstrated through whole boundary helium leak testing to <2.0 × 10⁻⁷ cm³/s (leaktight). This helium leak test eclipses the required criteria for both NCT and HAC based on the bounding case contents. Visual inspection of the containment boundaries showed no distortion or deformation from testing. Therefore, based on the various drop orientations, the severity of the HAC test sequence, and the testing conducted on Test Unit-4, the ES-3100 shipping package has been shown to meet the requirements of 10 CFR 71.43, 71.51(a)(1), and 71.71(c)(7).

2.6.8 Corner Drop

Requirement. 10 CFR 71.71(c)(8) requires a free drop onto each corner of the package in succession, or in the case of a cylindrical package, onto each quarter of each rim, from a height of 0.3 m(1 ft) onto a flat, essentially unyielding, horizontal surface. This test applies only to fiberboard, wood, or fissile



Fig. 2.5. NCT free drop test on Test Unit-4.

material rectangular packages not exceeding 50 kg (110 lb) and fiberboard, wood, or fissile material cylindrical packages not exceeding 100 kg (220 lb).

Analysis. This test is not applicable because the range of package weights for the ES-3100 [146.88 kg (323.79 lb) to 187.81 kg (414.05 lb)] exceed the above-weight restrictions for fissile material cylindrical packages.

2.6.9 Compression

Requirement. Title 10 CFR 71.71(c)(9) requires that packages weighing up to 5000 kg (11,000 lb) must be subjected for a period of 24 h to a compressive load applied uniformly to the top and bottom of the package in the position in which the package would normally be transported. The compressive load must be the greater of the following:

- 1. the equivalent of five times the weight of the package; or,
- 2. the equivalent of 13 kPa (2.0 psi) multiplied by the vertically projected area of the package.

Analysis. The proposed maximum weight of the ES-3100 shipping package is calculated to be 187.81 kg (414.05 lb) [Table 2.8]. As shown on Drawing M2E801580A010 (Appendix 1.4.1), the data plate states that the maximum gross weight of the ES-3100 shipping package is 190.51 kg (420 lb). In accordance with Item 1 above, the minimum compressive load would be 5×190.51 kg or 952.55 kg (2100 lb). The vertically projected area of the package is 1891 cm² (293.16 in.²) or the area of the lid weldment. Based on Item 2 above, the minimum compressive load would be 13 kPa × 1891 cm² or 250.72 kg (552.75 lb). Therefore, the approach stipulated in Item 1 above represents the greatest compressive load for this configuration. A conservative 1043 kg (2300 lb) compressive load was uniformly applied to the top and bottom of Test Unit-4 for at least 24 h (Fig. 2.6). The test package had been sprayed with water as noted in Sect. 2.6.6. No change in height or diameter of the test unit resulted from the test.

Due to the design of the ES-3100 drum lid, the applied compressive load was distributed equally around the lid and supported primarily through the outer drum contour and Kaolite 1600 substrate. Little or no load is transferred to the neutron poison (BoroBond4 in the test units) and internal liners. Therefore, the changes in the design of the liners and neutron poison proposed for this shipping packages should not impact the outcome resulting from compression testing. Based on the results of compliance testing of Test Unit-4 and the insignificant changes in the design, the ES-3100 package meets the requirements of 10 CFR 71.71(c)(9).



Fig. 2.6. Compression test on Test Unit-4.

2.6.10 Penetration

Requirement. Impact of the hemispherical end of a vertical steel cylinder of 3.2 cm (1.25 in.) diameter and 6 kg (13 lb) mass dropped from a height of 1 m (40 in.) onto the exposed package surface that is expected to be most vulnerable to puncture is required by 10 CFR 71.71(c)(10). The long axis of the cylinder must be perpendicular to the package surface.

Analysis. A 6-kg (13-lb) steel cylinder was dropped from 1 m (40 in.) onto the surface of Test Unit-4, which was previously subjected to water spray, free drop, vibration and compression tests. The penetration bar impacted the side of the drum at the welded seam near the package's center of gravity. The bar did not penetrate the drum, but an indentation 0.64-cm (0.25-in.) deep was recorded at the drum seam weld as shown in Fig. 2.7. The magnitude of this indentation is insignificant. Based on the HAC analytical structural deformation results shown in Sect. 2.7.8, the magnitude of indentation would be nearly identical had this test been conducted on the proposed configuration using the Cat 277-4 neutron absorber. On this basis, the ES-3100 package meets the requirements of 10 CFR 71(c)(10).



Fig. 2.7. Penetration test damage on Test Unit-4.

2.7 HYPOTHETICAL ACCIDENT CONDITIONS

This section demonstrates compliance with 10 CFR 71.73, "Hypothetical Accident Conditions." It shows that the package will experience no loss in shielding effectiveness or spacing and no release of radioactive content or leakage of water into the containment boundary during HAC. A summary of the tests and analyses conducted on the ES-3100 configuration is shown in Table 2.23.

Title 10 CFR 71.51 requires that the ES-3100 package satisfy the standards under HAC specified in 10 CFR 71.73. For the tests specified in 10 CFR 71.73, five test packages were subjected to the five sequential tests: free drop, crush, puncture, thermal, and immersion. The configuration for Test Units-1 through -4 used full-scale shipping packages with steel mock-ups similar to the maximum contents to be shipped in the ES-3100 configuration. Test Unit-5, also a full-scale shipping package, was dropped with a mock-up of the lightest component proposed for shipping. All test units were first subjected to the NCT free drop from 1.2 m (4 ft). In addition to the 1.2-m (4-ft) drop, Test Unit-4 was also subjected to the full battery of tests in accordance with applicable paragraphs of 10 CFR 71.71(c)(5) through (c)(10) except (c)(8). These preliminary tests were conducted to provide evidence that the ES-3100 package's ability to satisfy the requirements of HAC is provided in the following sections. A summary of the test results is provided in each area of Sect. 2.7; details are documented in the test report. (ORNL/NTRC-013)

Extensive computer impact simulation and analysis was conducted using LS-Dyna software. (LS-Dyna 2002) The results are documented in Appendix 2.10.2. Early in the design phase, the simulation was used to determine areas of large structural deformation and stress concentrations. Prior to the compliance testing in accordance with 10 CFR 71.71, the simulation was used to determine the drop orientation that would cause the most structural damage to the drum assembly and thereby propose a worstcase scenario for potential breeching of the containment boundary. Prior drop test programs have shown the slapdown orientation to cause the most structural degradation of a drum-style container. Computer software LS-DYNA-3D was used to simulate a 9-m (30-ft) drop orientation at a slapdown angle of 12° with a friction factor of $\mu = 0.0$ as calculated using the computer code Slapdown, Version 05.20.93. Slapdown calculated that no matter what friction factor was assumed, the tail-end velocity peaked at approximately 14° (Handy 1997, Appendix 6.10). The maximum tail-end velocity versus slapdown angle is presented in Fig. 6.10.4 in Handy 1997, and the logic for the development of this figure is explained in Appendix 6.10 in Handy 1997. Due to the mitigating effects of the length to diameter ratios and the relative closeness of the 12° increase in velocity to the maximums (shown in Fig. 6.10.4 in Handy 1997), the 12° slapdown is considered to be representative of the worst-case slapdown. Based on the correlation of data obtained from preliminary drop tests of the similar ES-2M configuration and computer-simulated drops, several orientations were eliminated from the drop test matrix (Table 2.23). Several other impact simulations have been conducted using a wide range of material properties for the impact limiter material (Kaolite 1600) to determine the variance in structural deformation. Results of these simulations are documented in Sect. 5.6 in Handy (1997). Although the analysis shows some variance, the magnitude of difference was not large enough to degrade the performance of the drum assembly and containment boundary. Due to the similarities in design, fabrication, and material used in construction of the shipping packages, these same results would hold true for the ES-3100 package.

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 $38^{\circ}C$ (-20 to $100^{\circ}F$). 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 $38^{\circ}C$ (-20 to $100^{\circ}F$). Buckling failures are not anticipated for this package design. This assumption is based on the fact that no evidence of buckling

	NCT water spray, 1.2-		9-1	n (30 ft) dro	op and crush (lest	1.2-m	Preheat	IIAC	O-ring	Full-body	0.9-m (3-ft)	15-m (50-ft)
Container	compression, penetration, vibration	(4 ft) drop	Top drop	CG over lid corner	Bottom to lid slapdown	Side drop	puncture drop	38°C (100°F)	burn test	cavity leak check (operational)	helium leak test ^b	immer. test	immer. test
Τυ-Ι		I—YES			12° 2—YES		3—YES	4—YES	5—YES	6-YES ≤1.0 × 10 ^{.3} rcf. cm³/s	7—YES 1.6 × 10 ⁻⁷ cm³/s	8—YES	
TU-2		I—YES				2—YES	3—YES	4YES	5—YES	6-YES ≤1.0 × 10 ⁻³ rcf. cm³/s	7—YES Pulsing between 1.0× 10.9 to 1.4 × 10.6 cm ³ /s	8—YES	
TU-3		1—YES		24.6° 2—YES			3—YES	4—YES	5—YES	6−YES ≤1.0 × 10 ⁻³ rcf. cm³/s	7—YES 1.0 × 10 ⁻⁷ cm ³ /s	8—YES	
TU-4	Ycs	I—YES	2—YES	•			3—YES	4—YES	5—YES	6−YES ≤1.0 × 10 ⁻³ rcf. cm³/s	7—YES 2. × 10 ⁻⁷ cm³/s	8—YES	
TU-5		I—YES			12° 2—YES		3—YES	4—YES	5—YES	6-YES ≤1.0 × 10 ⁻³ ref. cm ³ /s	7-YES 3.1 × 10 ⁻⁸ cm ³ /s	8—YES	
TU-6										1-YES ≤1.0 × 10 ⁻³ rcf. cm³/s			2—YES
Impact Analysis		YES	YES	YES	YES	YES							
Thermal Analysis	YES⁴							YES	YES⁴				

Table 2.23. Test and analysis summary for the ES-3100 package *

Numbering refers to sequence of activities.
 Full-body helium leak test conducted following HAC testing. Leakage value recorded after 20 minutes of the test period.

⁵ Test Unit-1 was puncture tested in four different orientations.

⁴ Thermal analysis was conducted to determine time for cooling to -40°C and to evaluate the application of decay heating and insolation during the cool-down phase.

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 122.63 kPa (17.786 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, with details given in the test report. (ORNL/NTRC-013) 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.

2.7.1.1 End Drop

Test Unit-4, weighing 201.8 kg (445 lb), was dropped from 9-m (30 ft) with the long axis of the drum perpendicular to the impact surface within 0.2°. The mock-up components are shown on Drawing M2E801580A027. The concern for this drop orientation was that the containment boundary assembly would crush, buckle or compress the insulation to a thickness that would result in excessive O-ring temperatures during the thermal testing cycle. Following initial impact, the package bounced very little before landing on its side. The damage to the drum consisted of reducing the overall height from 43.5 in. [following the 1.2 m (4 ft) drop] to a minimum 42.63 in. The diameter of the drum was measured at six locations along the long axis of the package and at two radial locations. The measurements and pictorials of the damage are recorded on Test Form 1 of procedure TTG-PRF-08 shown in the test report (ORNL/NTRC-013, Vol. 3) and are summarized in Tables 2.24 and 2.25 and Fig. 2.9.

	0°	90°	180°	270°
Pre-drop height (in.)	43.50	43.50	43.63	43.63
Post 1.2-m drop height (in.)	43.50	43.50	43.50	43.50
Post 9-m drop height (in.)	43.00	43.13	42.88	42.63

Table 2.24. Recorded height damage to Test Unit-4 from 1.2-m and 9-m drop testing

Table 2.25.	Recorded	diametrical	damage to) Test U	nit-4 from	1.2-m and	l 9-m dro	p tests	[Diameter (in.)	l

Axial measurement location		0 to 180°	_	90 to 270°			
	Pre drop test	Post 1.2-m drop test	Post 9-m drop test	Pre drop test	Post 1.2-m drop test	Post 9-m drop test	
Top false wire	19.25	19.25	19.25	19.38	19.38	19.38	
Top rolling hoop	19.25	19.25	19.13	19.25	19.25	19.88	
CG & top rolling hoop	19.25	19.25	19.81	19.25	19.25	19.38	
CG rolling hoop	19.13	19.13	19.13	19.25	19.25	19.25	
Bottom rolling hoop	19.13	19.13	19.25	19.25	19.25	19.25	
Bottom false wire	19.38	19.38	19.25	19.25	19.25	19.25	



Fig. 2.9. 9-m drop test damage on Test Unit-4.

2.7.1.2 Side Drop

Test Unit-2, weighing 202.8 kg (447 lb) was chilled to -40° C (-40° F) prior to conducting the drop tests. This unit was sequentially dropped from 1.2 m (4 ft), 9 m (30 ft), crushed from 9 m (30 ft), and puncture tested with the long axis of the drum parallel to the impact surface. The mock-up component used in Test Unit-2 is shown on Drawing M2E801580A027 and weighed 49.9 kg (110 lb). There were two concerns for this drop orientation. The primary concern was that the containment boundary assembly would crush or compress the insulation to a thickness that would result in excessive O-ring temperatures during the thermal testing cycle. Another concern was that the cold temperatures might cause excessive loads and deformation in the containment vessel body during impact. This, in turn, might cause leaking above the regulatory limit to occur. The test package made a free fall with initial contact occurring between the rolling hoops of the drum and the impact surface with the ambient temperature at 24.2°C (75°F). Since it was important to evaluate the package at the regulatory minimum temperature, individual results of each test were not recorded. Time required to measure the package between drops would have allowed the package to further increase in temperature. Cumulative results of damage to Test Unit-2 from drop testing is shown in Tables 2.26, 2.27, and 2.28 and Fig. 2.10.

Axial measurement location	0 to	0 to 180° 90		
	Pre drop test	Post drop test ^a	Pre drop test	Post drop test*
Top false wire	19.25	17.63	19.25	19.81
Top rolling hoop	19.25	17.38	19.25	19.75
CG & top rolling hoop	19.25	17.00	19.25	20.00
CG rolling hoop	19.25	16.00	19.25	20.25
Bottom rolling hoop	19.25	15.50	19.25	20.13
Bottom false wire	19.25	18.00	19.25	19.38

Table 2.26. Recorded diametrical damage to Test Unit-2 from NCT and HAC drop testing [Diameter (in.)]

* Includes cumulative damage from 1.2-m drop, 9-m drop, and crush test.

Table 2.27. Recorded flat contour damage to Test Unit-2 from NCT and HAC drop testing

Axial measurement location	Flat width @ 0° (in.)	Flat width @ 180° (in.)
Top false wire	8	6.25
Top rolling hoop	9	8.88
CG & top rolling hoop	10.13	9.63
CG rolling hoop	9.88	12.00
Bottom rolling hoop	9.88	14.88
Bottom false wire	9.38	0
Crease (see Fig. 2.10 for location)		15.25

Table 2.28. Recorded height damage to Test Unit-2 from NCT and HAC drop testing

	0°	90°	180°	270°
Pre-drop height (in.)	43.50	43.50	43.50	43.50
Post-drop height (in.) ¹	44.75	43.75	42.75	43.63

* Includes cumulative damage from 1.2-m drop, 9-m drop, and crush test.



Fig. 2.10. Cumulative damage from 9-m drop and crush testing on Test Unit-2.

2.7.1.3 Corner Drop

Test Unit-3, weighing 203.7 kg (449 lb), was dropped from 9 m (30 ft), with the long axis of the drum at an oblique angle of 24.8° (desired angle was 24.6°) from the impact surface. The mock-up component used in Test Unit-3 is shown on Drawing M2E801580A027 and weighed 50.3 kg (111 lb). The primary concern for this drop orientation was that the combination of plastic deformation at impact on the corner of the drum and the crushing or compacting of the adjacent insulation by the containment vessel flange would result in excessive O-ring temperatures during thermal testing. Another concern was that the mock-up contents would be forced against the containment boundary lid at impact. This, in turn, might yield the flange or closure nut, resulting in loss of containment. The test package made a free fall, with initial contact occurring between the top rim of the drum and the impact surface with the ambient temperature at 28°C (82.4°F). A secondary contact occurred between the bottom drum rim and the impact surface. No drum studs, nuts, or washers were lost due to the impact. The lid was still firmly attached to the drum with no visible separation or rips; thus, confinement of the containment vessel and contents was maintained. A general description of damage to Test Unit-3 is summarized in Tables 2.29 and 2.30. Pictorials of damage are shown on Test Form 1 of procedure TTG-PRF-08 shown in the test report (ORNL/NTRC-013, Vol. 3) and Fig. 2.11.

	0°	90°	180°	270°
Pre-drop height (in.)	43.50	43.50	43.50	43.50
Post 1.2-m drop height (in.)	43.00	43.50	43.63	43.50
Post 9-m drop height (in.)	40.63	43.25	43.75	43.38

Table 2.29. Recorded height damage to Test Unit-3 from 1.2-m and 9-m drop testing

Table 2.30. Recorded diametrical damage to Test Unit-3 from 1.2-m and 9-m drop testing [Diameter (in.)]

Axial measurement location		0 to 180°			90 to 270°	
	Pre drop test	Post 1.2-m drop test	Post 9-m drop test	Pre drop test	Post 1.2-m drop test	Post 9-m drop test
Top false wire	19.25	19.25	19.25	19.13	19.38	19.19
Top rolling hoop	19.13	19.13	18.63	19.13	19.25	19.88
CG & top rolling hoop	19.13	19.13	19.13	19.13	19.25	19.38
CG rolling hoop	19.13	19.13	19.13	19.13	19.25	19.38
Bottom rolling hoop	19.13	19.13	19.13	19.13	19.25	19.38
Bottom false wire	19.13	19.13	19.13	19.13	19.25	19.25



Fig. 2.11. Test Unit-3 damage from 1.2 and 9-m drop tests.

2.7.1.4 Oblique Drops

Two oblique (slapdown) drops were conducted in the same attitude with maximum and minimum content weights to determine the structural response on the package in accordance with Regulatory Guide 7.8. Paraphrasing Regulatory Position 1.6, a local structural response might be greater during an impact test if the weight of the contents were less than the maximum. Therefore, Test Units-1 and -5 contained the maximum and minimum weight configurations, respectively.

2.7.1.4.1 Test Unit-1 Slapdown

Test Unit-1, weighing 202.3 kg (446 lb) was dropped from 9-m (30 ft) with the long axis of the unit at an oblique angle of 12.2° (desired angle was 12°) to the essentially unyielding surface. The mock-up component used in Test Unit-1 is shown on Drawing M2E801580A027 and weighed 49.90 kg (110 lb). Based on Sect. 3.1 of Regulatory Guide 7.8, the structural performance of the package must be evaluated for the minimum and maximum weight of the contents. Therefore, this unit was tested above the maximum proposed content weight to see if the containment vessel would react differently from the much lighter mock-up used in Test Unit-5 in a similar drop orientation. The primary concern was that the orientation would cause greater angular acceleration of the contents near the package top. This in turn would cause the containment boundary to crush or compress the insulation to a thickness that would result in excessive O-ring temperatures during the thermal testing cycle. The test package made a free fall with initial contact occurring between the rolling hoops of the drum and the impact surface with the ambient temperature at 28°C (82.4°F). No drum studs, nuts, or washers were lost due to the impact. The lid was still firmly attached to the drum with no visible separation or rips; thus, confinement of the containment vessel and contents was maintained. A general description of damage is provided in Tables 2.31, 2.32, and 2.33 and Fig. 2.12.

	0°	90°	180°	270°
Pre-drop height (in.)	43.50	43.50	43.50	43.50
Post 1.2-m drop height (in.)	43.50	43.50	43.50	43.50
Post 9-m drop height (in.)	42.63	43.38	43.25	43.38
Buckle (in.)	44.50			

Table 2.31. Recorded height damage to Test Unit-1 from 1.2-m and 9-m drop testing

Table 2.32.	Recorded diametrical	damage to	Test Unit-1	from 1.2-m	and 9-m	HAC drop	testing
[Diameter (in.)]			-			-	-

Axial massurement	0 to 180°			90 to 270°		
location	Pre drop test	Post 1.2-m drop test	Post 9-m drop test	Pre drop test	Post 1.2-m drop test	Post 9-m drop test
Top false wire	19.25	19.13	18.50	19.25	19.25	19.38
Top rolling hoop	19.25	19.00	18.50	19.25	19.25	19.38
CG & top rolling hoop	19.25	19.13	18.50	19.25	19.25	19.38
CG rolling hoop	19.25	19.13	18.63	19.25	19.25	19.38
Bottom rolling hoop	19.25	19.00	18.63	19.25	19.25	19.25
Bottom false wire	19.25	19.00	17.81	19.25	19.25	19.38

Axial measurement location	Flats width maximum post 1.2-m drop (in.)	Flats width maximum post 9-m drop (in.)
Top false wire	5.25	8.00
Top rolling hoop	4.38	7.38
CG & top rolling hoop	4.50	7.13
CG rolling hoop	3.00	6.38
Bottom rolling hoop	4.00	6.75
Bottom false wire	4.63	10

Table 2.33.	Recorded flat	contour damage	to Test Unit-I	l from 1.2-m an	d 9-m drop testing
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Fig. 2.12. 1.2 and 9-m drop test damage on Test Unit-1.

2.7.1.4.2 Test Unit-5 Slapdown

Test Unit-5, weighing 157.4 kg (347 lb), was dropped from 9-m (30 ft), with the long axis of the drum at an oblique angle of 12.5° (desired angle was 12°) from the impact surface. The mock-up component (Drawing M2E801580A029), weighing 3.6 kg (8 lb), was the hardware with the majority of the mass located near the bottom of the containment vessel (Sect. 2.5.1). Based on Sect. 3.1 of Regulatory Guide 7.8, the structural performance of the package must be evaluated for the minimum and maximum weight of the contents. Therefore, this unit was tested at the minimum proposed weight to see if the containment vessel would react differently from the much heavier mock-up used in Test Unit-1 in a similar drop orientation. The test package made a free fall with initial contact occurring between the bottom rim of the drum and the impact surface. No drum studs, nuts, or washers were lost during this impact test. The lid was still firmly attached to the drum, with no visible separation or rips; thus, confinement of the containment vessel and contents was maintained. A general description of damage is provided in Tables 2.34, 2.35, and 2.36 and Fig. 2.13.

	0°	90°	180°	270°
Pre-drop height (in.)	43.50	43.50	43.50	43.50
Post 1.2-m drop height (in.)	43.88	43.50	43.50	43.50
Post 9-m drop height (in.)	44.50	43.50	43.38	43.50

Table 2.34. Recorded height damage to Test Unit-5 from 1.2-m and 9-m drop testing

Table 2.35. Recorded diametrical damage to Test Unit-5 from 1.2-m and 9-m HAC drop testing [Diameter (in.)]

	0 to 180°			90 to 270°		
Axial measurement location	Pre drop test	Post 1.2-m drop test	Post 9-m drop test	Pre drop test	Post 1.2-m drop test	Post 9-m drop test
Top false wire	19.25	18.88	18.75	19.38	19.38	19.38
Top rolling hoop	19.25	19.00	18.75	19.25	19.25	19.38
CG & top rolling hoop	19.25	19.13	18.75	19.25	19.25	19.38
CG rolling hoop	19.25	19.13	18.75	19.25	19.25	19.25
Bottom rolling hoop	19.25	19.13	18.75	19.25	19.25	19.25
Bottom false wire	19.25	19.13	18.44	19.25	19.25	19.31

Axial measurement location	Flats width maximum post 1.2-m drop (in.)	Flats width maximum post 9-m drop (in.)
Top false wire	5.38	8.38
Top rolling hoop	4.25	8.38
CG & top rolling hoop	3.88	7.63
CG rolling hoop	2.50	7.50
Bottom rolling hoop	3.25	8.25
Bottom false wire	5.00	9.25

Table 2.36. Recorded flat contour damage to Test Unit-5 from 1.2-m and 9-m drop testing



Fig. 2.13. 1.2 and 9-m drop test damage to Test Unit-5.

2.7.2 Crush

Requirement. Title 10 CFR 71.73(c)(2) requires that the specimen be subjected to a dynamic crush test in which the specimen is placed on a flat, essentially unyielding, horizontal surface so as to suffer maximum damage by the drop of a 500-kg (1100-lb) mass from 9 m (30 ft) onto the specimen. The mass must consist of a solid mild steel plate 1 m (40 in.) by 1 m (40 in.) and must fall in a horizontal attitude. The crush test is required only when the specimen has a mass $\leq 500 \text{ kg} (1100 \text{ lb})$, an overall density $\leq 1000 \text{ kg/m}^3$ (62.4 lb/ft³) based on external dimensions, and radioactive contents $\geq 1000 \text{ A}_2$ not as special form radioactive material. For packages containing fissile material, the radioactive contents greater than 1000 A₂ criterion does not apply.

Analysis. Five test packages were subjected to the dynamic crush test from 9 m (30 ft) in accordance with 10 CFR 71.73(c)(2). The previously drop-tested packages (described in Sect. 2.7.1) were restrained in the orientation used for drop testing. Discussion of the damage to each test package that resulted from the crush test is given in subsequent paragraphs, with details given in the test report. (ORNL/NTRC-013) Rationale for the three drop positions is included in Sect. 2.7.1 for each test unit. The impact of the steel plate only increased the overall concern for each orientation.

Test Unit-1, weighing 202.3 kg (446 lb), was positioned in a horizontal attitude with the damaged portion of the test unit, resulting from prior drop tests, placed on the drop pad (0° mark facing down on test pad). The 500-kg (1100-lb) crush plate was centered over the sealing lid location on the containment vessel and dropped from 9 m (30 ft) and squarely contacted the top false wire of the drum at an ambient temperature of 29°C (84.2°F). Following initial impact, the package bounced very little before landing on its side. No drum studs, nuts, or washers were lost due to the impact. The lid was still firmly attached to the drum, with no visible separation or rips; thus, the position of the thermal barrier and neutron poison was maintained. A summary of the resulting damage is shown in Tables 2.37, 2.38, and 2.39. Since the length of the crush plate did not encompass the entire length of the test package, a crush edge indentation is recorded in Table 2.39. Additional pictorials of damage are recorded on Test Form 3 of procedure TTG-PRF-11 shown in the test report (ORNL/NTRC-013, Vol. 3) and Fig. 2.14.

	0°	90°	180°	270°
Pre-crush height (in.)	44.50	43.38	43.25	43.38
Post 9-m crust test height (in.)	44.88	43.38	44.00	43.63

Table 2.37. Recorded height damage to Test Unit-1 from the 9-m crush test

Table 2.38.	Recorded diametrical	damage to Test	Unit-1 from the 9-m crush test	[Diameter ((in.)]	
				1 (

	0 to	180°	90 to 270°	
Axial measurement location	Pre crush test	Post 9-m crush test	Pre crush test	Post 9-m crush test
Top false wire	18.50	15.63	19.38	20.63
Top rolling hoop	18.50	16.00	19.38	20.43
CG & top rolling hoop	18.50	16.25	19.38	20.25
CG rolling hoop	18.63	16.50	19.38	19.88
Bottom rolling hoop	18.63	18.25	19.25	19.50
Bottom false wire	17.81	17.81	19.38	19.25

Axial measurement location	Flats width maximum @ 0° (in.)	Flats width maximum@ 180° (in.)
Top false wire	9.00	8.50
Top rolling hoop	10.00	10.00
CG & top rolling hoop	10.00	10.13
CG rolling hoop	9.00	10.63
Bottom rolling hoop	8.25	
Bottom false wire	9.75	
Dent where edge of plate struck test unit		9.13

Table 2.39.	Recorded fla	t contour damage to	n Test Unit-1	from the 9-m crush test
THOIC 20071	Itecordea ma	c contour dannage t	o rear onne-r	nom the y-m crush test



Fig. 2.14. Cumulative damage following 9-m crush on Test Unit-1.

Test Unit-2 (chilled package), weighing 202.8 kg (447 lb), was positioned in an horizontal attitude with the long axis of the drum parallel with respect to the drop pad. The damaged portion of the test unit, resulting from prior drop tests, was placed nearest the drop pad (0° mark facing down on pad). The 500-kg (1100-lb) crush plate was centered over the test unit's center of gravity and dropped from 9 m (30 ft) squarely onto the top false wire of the drum at an ambient temperature of 26.8°C (80.4°F). Following initial impact, the package bounced very little before landing on its side. No drum studs, nuts, or washers were lost due to the impact. The lid was still firmly attached to the drum, with no visible separation or rips; thus, the position of the thermal barrier and neutron poison was maintained. A summary of the cumulative damage is shown in Tables 2.26, 2.27, and 2.28 in Sect. 2.7.1.2. Additional pictorials of damage are recorded on Test Form 3 of procedure TTG-PRF-11 shown in the test report (ORNL/NTRC-013, Vol. 3) and Fig. 2.10.

Test Unit-3, weighing 203.7 kg (449 lb), was positioned in the same oblique attitude as previously drop tested from 9 m (30 ft). The long axis of the drum was at an oblique angle of 24.7° (desired angle was 24.6°) from the impact surface with the damaged portion of the lid in contact with the drop pad (0° mark in contact with pad). The 500-kg (1100-lb) crush plate was dropped from 9 m (30 ft) with the center of gravity of both the plate and test unit in line at an ambient temperature of 30.5°C (86.9°F). The initial impact of the plate was with the edge of the drum bottom. A secondary contact occurred between the bottom drum rim and the impact surface. One drum stud was sheared from the test unit; however, the lid was still firmly attached to the drum, with no visible separation or rips. Therefore, the thermal barrier and neutron poison was maintained in position. Tables 2.40, 2.41, and 2.42 describe the measured damage which is recorded on Test Form 3 of procedure TTG-PRF-11 shown in the test report. (ORNL/NTRC-013, Vol. 3) A photograph of the damage to Test Unit-3 is shown in Fig. 2.15.

Table 2.40. Recorded height damage to Test Unit-3 from the 9-m crush test

	0°	90°	180°	270°
Pre-crush height (in.)	40.63	43.25	43.75	43.38
Post 9-m crust test height (in.)	39.38	42.43	39.13	42.50

Axial measurement location	Flats width maximum pre crush (in.)	Flats width maximum post crush (in.)
Top of test unit	14.00	18.38
Bottom of test unit	0.00	17.88

Table 2.41. Recorded flat contour damage to Test Unit-3 from the 9-m crush test

Table 2.42.	Recorded	diametrical	damage to 1	Fest Unit-3 from t	he 9-m crush t	est [Diameter]	(in.)]
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	0 to	180°	90 to 270°	
Axial measurement location	Pre crush test	Post 9-m crush test	Pre crush test	Post 9-m crush test
Top false wire	19.25	19.25	19.19	19.06
Top rolling hoop	18.63	18.75	19.88	20.25
CG & top rolling hoop	19.13	19.25	19.38	19.75
CG rolling hoop	19.13	19.13	19.38	19.25
Bottom rolling hoop	19.13	19.13	19.38	19.75
Bottom false wire	19.13	18.00	19.25	19.38



Fig. 2.15. Cumulative damage following 9-m crush test on Test Unit-3.

Test Unit-4, weighing 201.8 kg (445 lb), was positioned vertically with the previously damaged drum top in contact with the drop pad. The 500-kg (1100-lb) crush plate was dropped from 9 m (30 ft) and squarely contacted the bottom of the test unit. The center of the 500-kg (1100-lb) crush plate was positioned over the radial test unit's center of gravity, in this case over the center of the drum's bottom at an ambient temperature of 29.8°C (85.6°F). Following initial impact, the package bounced very little before landing on its side. No drum studs, nuts, or washers were lost due to the impact. The lid was still firmly attached to the drum, with no visible separation or rips; thus, the position of the thermal barrier and neutron poison was maintained. A summary of the resulting damage is shown in Tables 2.43 and 2.44 and a photograph is shown in Fig. 2.16.

	0°	90°	180°	270°
Pre-crush height (in.)	43.00	43.13	42.88	42.63
Post 9-m crust test height (in.)	39.38	40.38	40.63	39.75

 Table 2.43. Recorded height damage to Test Unit-4 from the 9-m crush test

	0 to	180°	90 to 270°	
Axial measurement location	Pre crush test	Post 9-m crush test	Pre crush test	Post 9-m crush test
Top false wire	19.25	19.25	19.38	19.38
Top rolling hoop	19.13	20.00	19.88	20.13
CG & top rolling hoop	19.81	20.00	19.38	20.06
CG rolling hoop	19.13	19.43	19.25	19.50
Bottom rolling hoop	19.25	19.94	19.25	20.00
Bottom false wire	19.25	19.25	19.25	19.25



Fig. 2.16. Cumulative damage from 9-m drop and crush testing on Test Unit-4.

Test Unit-5, weighing 157.4 kg (347 lb), was positioned in a horizontal attitude with the damaged portion of the test unit, resulting from prior drop tests, placed on the drop pad (0° mark facing down on test pad). The 500-kg (1100-lb) crush plate was centered over the test unit's center of gravity and dropped from 9 m (30 ft) squarely onto the top false wire of the drum at an ambient temperature of 29.6°C (85.3°F). Following initial impact, the package bounced very little before landing on its side. No drum studs, nuts, or washers were lost due to the impact. The lid was still firmly attached to the drum, with no visible separation or rips; thus, the position of the thermal barrier and neutron poison was maintained. A summary of the resulting damage is shown in Tables 2.45, 2.46, and 2.47. Additional pictorials of damage are recorded on Test Form 3 of procedure TTG-PRF-11 shown in the test report (ORNL/NTRC-013, Vol. 3) and Fig. 2.17. Since the length of the crush plate did not encompass the entire length of the test package, additional indentations are recorded on Test Form 3.

Table 2.45.	Recorded height	damage to	Test Unit-5	from the 9	-m crush test

	0°	90°	180°	270°
Pre-crush height (in.)	44.50	43.50	43.38	43.50
Post 9-m crust test height (in.)	45.00	43.50	43.75	43.88

	0 to	180°	90	to 270°
Axial measurement location	Pre crush test	Post 9-m crush test	Pre crush test	Post 9-m crush test
Top false wire	18.75	18.69	19.38	19.38
Top rolling hoop	18.75	17.13	19.38	19.63
CG & top rolling hoop	18.75	17	19.38	20
CG rolling hoop	18.75	16.75	19.25	20
Bottom rolling hoop	18.75	16.50	19.25	19.75
Bottom false wire	18.44	17.00	19.31	19.38

Table 2 16	Depended diametrical	damage to Test I	Init 5 from the O	m anuch tasta (Diama	ton (in)]
1 able 2.40.	Recorded diametrical	damage to lest u	Jnit-5 from the 9-	-m crush tests i Diame	eter (in.)

Table 2.47. Recorded flat contour damage to Test Unit-5 from the 9-m crush test

Axial measurement location	Flats width maximum @ 0° (in.)	Flats width maximum @ 180° (in.)
Top false wire	8.88	0.00
Top rolling hoop	8.50	12.50
CG & top rolling hoop	8.00	12.00
CG rolling hoop	8.75	11.38
Bottom rolling hoop	10.25	11.38
Bottom false wire	11.38	10.50



Fig. 2.17. Cumulative damage from 9-m drop and crush testing on Test Unit-5.

Conclusion. As noted in the discussion above, plastic deformation of the drum occurred in all test packages at the impacted areas. However, the position of the impact limiting material (Kaolite) and neutron poison material (BoroBond in the test packages) was maintained in all test packages. The maximum areal deformation along the side of the test packages was a flat measuring 31.75 cm (12.50 in.) wide at the drum's top rolling hoop and ending with a width of 26.67 cm (10.50 in.) at the drum bottom in Test Unit-5.

2.7.3 Puncture

Requirement. A free drop of 1 m (40 in.) from a position to obtain maximum damage onto the upper end of a solid, vertical, cylindrical, 15-cm (6-in.)-diameter mild steel bar mounted on an unyielding horizontal surface, is required by 10 CFR 71.73(c)(3). The bar must be ≥ 20 cm (8 in.) long with the top end rounded to 6-mm (0.25-in.) maximum radius. The long axis of the bar must be vertical.

Analysis. The five units previously dropped and crushed from 9-m (30 ft) [Sects. 2.7.1 and 2.7.2] were dropped from 1 m (40 in.) in accordance with 10 CFR 71.73(c)(3). The puncture bar was bolted to the steel plate of the inside drop pad surface at NTRC (see Sect. 2.6.7 regarding the indoor drop test pad). A description of the drop orientations and results are shown in Table 2.48. Figures 2.18 through 2.24 show the results of puncture testing.

Test Unit	Test unit's long axis drop orientation	Axial and radial location from drum lid ^a	Recorded damage (indentation depth - in.) ^b	Photograph
1	Horizontal	Test Unit's CG (0° mark)	0.63	Fig. 2.18
1	Horizontal	8 in. down (180° mark)	0.38	Fig. 2.20
1	28° oblique from vertical	Drum lid's edge (90° mark)	three impact locations 1. 0.63 2. 0.38 3. 0.13	Fig. 2.18
1	40° oblique from vertical	In line with test unit's CG (270° mark)	two impact locations 1. 0.75 2. 0.13	Fig. 2.19
2	Horizontal	Test Unit's CG (0° mark)	0.13	Fig. 2.21
3	24.6° oblique from vertical	In line with test unit's CG (270° mark)	two impact locations 1. Additional flattening of lid 2. 0.88	Fig. 2.22
4	Vertical	Center of drum's lid & CG	0.13	Fig. 2.23
5	Horizontal	8 in. down (0° mark)	0.13	Fig. 2.24

Table 2.48. 1-m (40-in.) puncture drop test description and results

* See detailed description of test units in Sect. 5.4.3 of ORNL/NTRC-013.

^b For detailed description of damaged locations, see Test Form 4 for Test Units 1, 3, 4, and 5 and Test Form 3 for Test Unit-2.

Conclusion. Although all test units were deformed by this puncture test, no drum surfaces were breached, thereby maintaining the integrity of the thermal barrier and neutron poison.

2.7.4 Thermal

Requirement. Exposure of the specimen fully engulfed, except for a simple support system, in a hydrocarbon fuel/air fire of sufficient extent and in sufficiently quiescent ambient conditions to provide an average emissivity coefficient of at least 0.9, with an average flame temperature of at least 800°C (1475°F) for a period of 30 min, or any other thermal test that provides the equivalent total heat input to the package and that provides a time-averaged environmental temperature of 800°C (1475°F). The fuel source must extend horizontally at least 1 m (40 in.) but may not extend more than 3 m (10 ft) beyond any external surface of the specimen, and the specimen must be positioned 1 m (40 in.) above the surface of the fuel source. For purposes of calculation, the surface absorptivity must be either that value which the package may be expected to possess if exposed to the fire specified or 0.8, whichever is greater; and the convective coefficient must be that value which may be demonstrated to exist if the package were exposed to the fire specified. Artificial cooling may not be applied after cessation of external heat input, and any combustion of materials of construction must be allowed to proceed until it terminates naturally.

Analysis. The five test units previously subjected to both NCT and HAC drop testing were thermal tested in accordance with 10 CFR 71.73(c)(4). To determine the maximum temperatures reached during thermal testing, temperature indicating patches were placed at various locations throughout the test packages at assembly. The temperature range for each patch used is identified in Table 2.49. When the temperature of an indicator was reached, the color would change to black (i.e., blackout temperature). The range of possible blackout temperatures of the patches was from 51.67 to 260°C (125 to 500°F). For Test Units-1 through -5, Table 2.49 defines the number and location of the temperature indicating patches.



Fig. 2.18. 28° oblique and horizontal puncture tests on Test Unit-1.



Fig. 2.19. 40° oblique puncture test on Test Unit-1.



Fig. 2.20. Horizontal puncture test over Test Unit-1's containment vessel flange.



Fig. 2.21. Horizontal CG puncture test on Test Unit-2.


Fig. 2.22. 24.6° oblique puncture test on Test Unit-3.



Fig. 2.23. Vertical puncture test on Test Unit-4.



Fig. 2.24. Horizontal puncture test over Test Unit-5's containment vessel flange.

Patch Location	Internal surface	External surface	Temperature range °C (°F)	Test report figure (ORNL/NTRC-013)
Inner liner of drum assembly		8 (Full Range) 10 (5B & 5C)	52 to 260 (125 to 500) "B" 77 - 127 (171-261) "C" 132 - 182 (270-360)	5.3
Top plug weldment		4 (Full Range)	52 to 260 (125 to 500)	5.31
Containment vessel body flange	8 (4B & 4C)	8 (4B & 4C)	"B" 77 - 127 (171-261) "C" 132 - 182 (270-360)	5.28
Containment vessel body (end cap and cylinder)		5 (B)	"B" 77 - 127 (171-261)	5.28
Containment vessel sealing lid	4 (B)	4 (B)	"B" 77 - 127 (171-261)	5.29
Test mock-up components		6 (B)	"B" 77 - 127 (171-261)	5.26 & 5.27

Table 2.49. Thermax temperature indicating patches for test units

Prior to the beginning of the thermal test, the No. 3 furnace at Timken Steel Company in Latrobe, Pennsylvania, was characterized for temperature and heat recovery times. Oxygen content in stack gases of the furnace was not monitored 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 liners and the top plugs of the packages. However, it should be noted that this furnace employs "pulsed" fire burners. This type of burner is unique in that 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, thereby ensuring a very rich furnace atmosphere capable of supporting any combustion of package materials of construction. The support stand was welded to a large steel plate which had been placed on the floor of the furnace prior to heating. This steel plate acted as the radiating surface at the bottom of the furnace as well as providing the ability to hold the test stand rigidly in place. Before heating the furnace, workers practiced loading and unloading test packages from the cold furnace to assure that the furnace door would not remain open >90 s during each loading. In fact, the maximum time the door was open during any loading was 64 s.

A total of 18 thermocouples was installed on the furnace surfaces and on the test package support stand. (ORNL/NTRC-013) All units were tested in a horizontal attitude with the end of the package facing the right and left side walls of the furnace. The test units were thermally tested with the 0° mark on the drum facing the floor of the furnace.

Each test unit was preheated to over 37.78° C (100°F) by placing the packages in an environmental chamber. The environmental chamber was heated by a torpedo-type kerosene space heater controlled by a mechanical bulb thermostat with a control range of 100°F to 200°F. The environmental chamber is a welded steel frame with fiberglass insulation panels. It was heated from the bottom with four floor register vents located around the perimeter and an 8 in. manual dampened center venting stove pipe. The setpoint temperature of the environmental chamber was monitored and adjusted for the duration of the preheat cycle. Initially, the thermostat was set to 66°C (150°F) for ~23 h. The thermostat set point was then reduced to $\geq 43^{\circ}$ C (110°F) for the remainder of the preheat cycle. All packages were preheated for at least 47 h.

Six thermocouples were attached to the exterior surface of each test package after preheating. Metal retainer clips were welded to the drum to hold the thermocouples in place. The thermocouple tips were inserted underneath the metal clips and the wire was wrapped around the metal clip. To eliminate any radiant heat exchange between the thermocouples and the furnace walls, the tips and metal clips were covered with a ceramic coating.

No test package was loaded into the furnace until all functioning thermocouples on the furnace walls and support stand had a reading of 800°C (1475°F) or higher. All packages were placed in the preheated furnace on the support stand positioned with the long axis horizontal, the package lid facing toward a furnace side wall and oriented as described above. These packages were exposed to the radiation environment for a minimum of 30 min after all functioning furnace thermocouples, and at least five of the six test package exterior surface thermocouples reached a temperature of 800°C (1475°F). During the testing, the thermocouple temperature data were recorded every 15 s.

A minimum of 24 h prior to the beginning of all testing, the furnace was turned on with a set-point temperature of 871°C (1600°F). After each test, the furnace was allowed to reheat for a minimum of 45 min after obtaining the setpoint temperature before testing the next unit. The furnace control temperature data recorder ran continuously for the duration of the preheat. No test package was loaded into the furnace until all functioning thermocouples on the furnace walls and support stand had a reading of 800°C (1475°F) or higher.

Each test package was removed from the furnace and placed in an area where it was not exposed to artificial cooling. As the furnace door was opened for each test unit, smoking or flaming was visible from the TID lug hole at 0°. Flaming continued on some packages for 22 minutes and smoking continued up to one hour on others. All of the packages were allowed to cool naturally to room temperature. The post-thermal test weights of each unit were recorded on Test Form 1 of the test report. (ORNL/NTRC-013) 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 operation 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 (ORNL/NTRC-013, Vol. 1) 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 $\leq 2.0 \times 10^{-7}$ cm³/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.

-		E	S-3100 Test I	Unit	
Temperature patch location *	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) [⊳]	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)

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

* 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 307.40 kPa (44.585 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 1.4.1). 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 cans 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.

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).

Stress locations shown in Fig. 2.1	Thermal condition 10 CFR 71.73 (c)(4) containment boundary stress @206.05 kPa (29.89 psi) gauge & 123.85°C (254.93°F) kPa (psi)		Immersion 10 CFR 71 containment bo @-150 kPa (-2 & -2.22°C kPa (Allowable stress (AS)	
	kPa (psi)	M.S.	kPa (psi)	M.S.	kPa (psi)
Top flat portion of sealing lid (center of head)	2.030 × 10 ³ (294.5)	64.2	1.478 × 10 ³ (214.4)	88.6	1.324 × 10 ⁵ (19,200) ^b
Closure nut ring (away from threaded portion)	5.734 × 10 ⁴ (8315.8)	7	4.246 × 10 ^{4 f} (6158)	9.8	4.571 × 10 ^s (66,300) ^c
Top flat head (sealing surface region)	2.070 × 10 ⁴ (3002.3)	11.8	1.665 × 10 ^{4 f} (2415)	14.9	2.648 × 10 ⁵ (38,400) ^c
Cylindrical section (middle)	5.886 × 10 ³ (853.7)	14	4.285 × 10 ¹ (621.5)	19.6	8.825 × 10⁴ (12,800) ^d
Cylindrical section (shell-to-flange interface)	1.432 × 10 ⁴ (2076.9)	17.5	1.238 × 10 ⁴ (1795.3)	20.4	2.648 × 10 ⁵ (38,400) ^c
Cylindrical section (shell-to-bottom interface)	1.510 × 10⁴ (2190)	16.5	1.099 × 10 ⁴ (1594.2)	23.1	2.648 × 10 ⁵ (38,400) ^c
Body flange threads load, kg (lb)	1.244 × 10 ³ (2742)	15.5	9.072 × 10 ² ^f (2000)	21.6	2.053 × 10⁴ (45266)⁵
Body flange thread region (under cut region)	3.514 × 10 ⁴ (5096.2)	6.5	2.397 × 10 ^{4 f} (3476)	10	2.648 × 10 ⁵ (38,400) ^c
Flat bottom head (center)	1.421 × 10 ⁴ (2061.4)	8.3	1.035 × 10⁴ (1500.7)	11.8	1.324 × 10 ⁵ (19,200) ^b
Closure nut thread load, kg (lb)	1.244 × 10 ³ (2742)	27.5	9.072 × 10 ^{2 f} (2000)	38.1	3.545 × 10⁴ (78154) [¢]

Table 2.51. HAC ES-3100 containment boundary stress compared to the allowable stress *

* 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 $P_1 + P_b$; allowable stress intensity value is $1.5 \times S_m$. ^c Stress interpreted as the sum of $P_1 + P_b + Q$; 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 .

⁶ 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). ⁶ Stress and shear load in these areas are dominated by the 162.7 ± 6.8 N·m (120 ± 5 ft-lb) preload.

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. After examination for damage (distortion, warpage, heating), the volume between the O-rings was pressurized, and the O-ring seals were leak checked in accordance with the CALT5 manufacturer's instructions manual using the CALT5 leak tester. Following the O-ring cavity check, the containment vessel lids were drilled and tapped for a fullbody helium leak check. The seals remained functional on all vessels, and the integrity of the containment vessel structure was maintained (indicated by a helium leak rate $\leq 2.0 \times 10^{-7}$ cm³/s). Following these leak tests, each unit was then submerged under a 0.9-m (3-ft) head of water for at least 8 h. No water leakage into the vessel was seen in any of the test units. The results of this test for each unit are recorded on the data sheet of Procedure TTG-PRF-14 shown in the test report. (ORNL/NTRC-013, Vol. 3) It should be noted that the criticality analysis does assume water leakage into the ES-3100 containment vessel; however, the 0.9-m (3-ft) immersion tests were performed anyway.

2.7.6 Immersion—All Packages

Requirement. A separate, undamaged specimen must be immersed under water at a pressure equivalent to a 15-m (50-ft) head of water, as required by 10 CFR 71.73(c)(6). This requirement may be satisfied by an external pressure of 150 kPa (21.7 psi) gauge.

Analysis. Immersion under a 15-m (50-ft) head of water would result in water entering the drum because the plastic plugs covering the four ventilation holes could fail, and the drum/lid flange is not gasketed. The ES-3100 containment boundary has been designed and tested for an external pressure of 150 kPa (21.7 psi) gauge and an internal gauge pressure of 699.82 kPa (101.5 psi), using nominal dimensions for all boundary components. Each containment vessel design incorporates an O-ring seal of verified integrity to provide assurance that no water will penetrate the containment boundary. The containment boundary of Test Unit-6 was subjected to this 15-m (50-ft) water immersion test. No visual signs of water leakage into the containment boundary were recorded.

2.7.7 Deep Water Immersion Test (for Type B Packages Containing More than 10⁵ A₂)

The amount of A_2 s proposed for transport is ~290.26. Therefore, the deep water immersion test is not applicable.

2.7.8 Summary of Damage

After testing five full scale ES-3100 test packages under HAC, the drum, drum lid, and top plug were damaged as expected. The containment boundary flange, O-ring grooves, and closure nut were not damaged. Plastic deformation occurred in the five drum assemblies in the impact areas from the 1.2-m and 9-m (30-ft) drop, crush and subsequent puncture tests. No breaks were noted in the drum assembly, and no insulation was exposed. The resultant damage did not reduce the effective center-to-center package spacing to a point of criticality concern (Sect. 6).

The full scale test units were fabricated in accordance with drawings created for production hardware. During the procurement process for the full scale test units, several small changes were suggested by the manufacturer to improve the efficiency and to reduce the cost of fabrication. These changes were incorporated and tested. However, following compliance testing, the following changes have been made to the proposed production hardware. First, a change in the neutron poison from BoroBond4 to Cat 277-4 has been adopted; second, the mid liner design has been changed to a continuous shell by reducing the diameter of the step in the inner liner for the containment vessel flange from 22.35 cm (8.8 in.) to 21.84 cm (8.6 in.);

and third, the silicone rubber pad thickness on the drum assembly bottom liner was increased by ~0.15 cm (0.06 in.). The second change increased the amount of Kaolite 1600 around the containment vessel flange, increased the final volume of the neutron poison, and slightly decreased the volume of the Kaolite 1600 adjacent to the neutron poison. The third change was made to stiffen the rubber pad so it would remain in place during vibration normally incurred during transport. In order to evaluate the impact of these changes, analytical drop simulations were conducted and documented in Appendix 2.10.2. The drop simulations were conducted in the same attitude and temperature regime as those conducted during the compliance testing phase for certification. Temperature dependent material properties were used in the analysis. The results of the structural deformation from compliance testing, drop simulation using BoroBond4 and drop simulations using Cat 277-4 material are presented in the following tables and figures. The analytical structural deformation results shown in Tables 2.52 through 2.61 are nearly identical for the two neutron poisons. The analytical results are also well representative of the results recorded during compliance testing as depicted in Figs. 2.25 through 2.30. Analytical strain prediction in the structural components are also compared for the two neutron poisons. Although there are minor differences between the compliance testing and drop simulations, the overall magnitude of the strains is very similar. The thermal aspects of these changes are addressed in Sect. 3. NCT and HAC results predicted for an undamaged package show that the change in neutron poison actually reduces the final temperature of the containment vessel components. Therefore, the substitution of Cat 277-4 material and the minor changes in the inner and mid liners for production hardware should not reduce the effectiveness of the packaging when subjected to the regulatory requirements of 10 CFR 71.71 and 71.73, and the results of compliance testing would be analogous. Some of the test units lost approximately 0.45 kg (1 lb) of their gross weight due to boiling off of the water trapped in the refractory and BoroBond4 materials (Table 2.62).

Assuming all water loss is from the neutron poison, the BoroBond4 material lost ~ 9.4% of its water content. Using the temperature data recorded during HAC testing shown in Table 2.50 and applying the temperature adjustments discussed in Sect. 3.5.3, the average temperature of the neutron poison would be ~150°C (302°F). Since the ES-3100 test units were not fabricated packages with Cat 277-4, thermogravimetric analysis (TGA) was used to compare the neutron poison's propensity to lose water. The results of this analysis are shown in Appendix 2.10.4 (Thompson, *Summary of TGA Testing*). Samples of both BoroBond4 and Cat 277-4 were TGA tested, and the results were compared at 150°C (302°F). The BoroBond4 samples lost ~ 61.6% of their original water content. The dry Cat 277-4 lost a maximum of only 6.61%. The BoroBond4 TGA samples lost ~6.5 times the amount of water lost by the ES-3100 test units during HAC compliance testing. Assuming comparable results would be expected for the Cat 277-4 material due to similarity in the structural configuration, installation methodology, and LS-Dyna drop simulation structural deformation results, the Cat 277-4 water loss would be only 1.02%. Criticality safety analysis assumes a greater percent loss; therefore, additional conservatism is being applied in this SAR.

The maximum blackout temperature recorded adjacent to the O-rings during testing was $127.22^{\circ}C$ (241°F) [Table 2.50]. Using the adjustments discussed in Sect. 3.5.3, the maximum adjusted temperature at the containment boundary O-rings during shipment under HAC was calculated to be $141.22^{\circ}C$ (286.2°F). The normal operating temperature for these O-rings is -40 to $150^{\circ}C$ (-40 to $302^{\circ}F$) as shown in Table 2.15. Therefore, containment will be maintained during HAC.

Following the thermal test, all five containment boundaries were subjected to leak testing of the O-ring cavity as well as the full-body helium leak check. To verify the entire containment boundary, all test units were drilled and tapped for a helium leak check using the procedure documented in the test report. (ORNL/NTRC-013, Vol. 3) The procedure consisted of creating a near vacuum inside the containment vessel and supplying a helium environment around the exterior of the assembly. The maximum recorded helium leak rate for any of these containment vessels was 2.0×10^{-7} cm³/s as documented after 20 min of leak checking. This procedure measures leakage in the opposite direction to leakage from the vessel. It

		0 to 180°			90 to 270°	
Axial measurement location	Test results	Analytical results with BoroBond	Analytical results with Cat 277–4	Test results	Analytical results with BoroBond	Analytical results with Cat 277-4
Top false wire	15.63	15	14.9	20.63	20.7	20.7
Top rolling hoop	16	15.3	15.1	20.44	20.8	20.8
CG & top rolling hoop	16.25	15.9	15.7	20.25	20.6	20.7
CG rolling hoop	16.5	16.4	16.2	19.88	20.1	20.4
Bottom rolling hoop	18.25	18.3	18.1	19.5	19.6	19.8
Bottom false wire	17.81	18.1	18	19.25	19.4	19.4

Table 2.52. Diametrical damage comparison of Test Unit-1 with analytical predictions [Diameter (in.)]

Table 2.53. Flat contour damage comparison of Test Unit-1 with analytical results

Axial measurement location	Flats width @ 0° (in.)			Flats width @ 180° (in.)		
	Test results	Analytical results with BoroBond	Analytical results with Cat 277-4	Test results	Analytical results with BoroBond	Analytical results with Cat 277-4
Top false wire	9	10.5	10.5	8.5	10.5	10.9
Top rolling hoop	10	11	11	10	11	11
CG & top rolling hoop	10	10.1	10.1	10.13	10.1	10.1
CG rolling hoop	9	8.4	8.4	10.63	10.1	10.1
Bottom rolling hoop	8.25	7.6	7.6		0	0
Bottom false wire	9.88	10.1	10.1		0	0



		Effective plastic strain (in./in.)					
Component	Component material	Offset	crush	Centere	d crush		
		Model with BoroBond	Model with Cat 277-4	Model with BoroBond	Model with Cat 277–4		
CV body	Type 304L stainless steel	0.0457	0.0564	0.0741	0.0643		
CV lid	Type 304L stainless steel	0.0005	0.0013	0.0006	0.0018		
CV closure nut	A-479 nitronic 60	0.0000	0.0001	0.0003	0.0000		
Angle	Type 304 stainless steel	0.1045	0.1070	0.0917	0.0944		
Drum	Type 304 stainless steel	0.3972	0.3920	0.3537	0.3443		
Drum bottom	Type 304 stainless steel	0.2877	0.2879	0.2919	0.3000		
Liner	Type 304 stainless steel	0.2702	0.2060	0.2363	0.2846		
Lid	Type 304 stainless steel	1.0797	0.9689	1.0795	0.5828		
Lid stiffener	Type 304 stainless steel	0.0838	0.0894	0.0303	0.0288		
Drum lid studs	Type 304 stainless steel	>0.57	0.4018	0.3174	0.2390		
Lid hex nut	Silicon bronze - C65100	0.0086	0.0028	0.0000	0.0000		
Drum washer	300 series stainless steel	0.1003	0.0790	0.0597	0.0775		
Top plug weldment	Type 304 stainless steel	0.2715	0.2665	0.1636	0.1644		

Table 2.54. Cumulative analytical 12° slapdown drop tests maximum effective plastic strain results

Axial measurement location	0 to 180°			90 to 270°			
	Test results	Analytical results with BoroBond	Analytical results with Cat 277-4	Test results	Analytical results with BoroBond	Analytical results with Cat 277-4	
Top false wire	17.63	18.1	18	19.81	19.6	19.6	
Top rolling hoop	17.38	16.6	16.6	19.75	19.75	20.1	
CG & top rolling hoop	17	16.5	16.5	20	20	20.4	
CG rolling hoop	16	16.3	16.3	20.25	20.25	20.5	
Bottom rolling hoop	15.5	16.1	16.1	20.13	20.13	20	
Bottom false wire	18	17.6	17.6	19.25	19.38	19.4	

Table 2.55. Diametrical damage comparison of Test Unit-2 with analytical predictions [Diameter (in.)]

Table 2.56. Flat contour damage comparison of Test Unit-2 with analytical predictions

Axial measurement location		Flats width @ (in.)) 0°	Flats width @ 180° (in.)			
	Test results	Analytical results with BoroBond	Analytical results with Cat 277-4	Test results	Analytical results with BoroBond	Analytical results with Cat 277-4	
Top false wire	8	9.2	9.2	6.25	0	0	
Top rolling hoop	9	8.4	9.3	8.88	10.1	10.1	
CG & top rolling hoop	10.13	8.4	8.4	9.63	8.4	9.3	
CG rolling hoop	9.88	9.3	9.3	12	9.3	9.3	
Bottom rolling hoop	9.88	9.3	9.3	14.88	10.1	10.1	
Bottom false wire	9.38	10.1	10.1	0	0	0	



Fig. 2.26. Visual comparison of the cumulative damage on the rigid surface side after the four drop tests (from left to right: Test Unit-2, analytical results with BoroBond, analytical results with Cat 277-4).



Fig. 2.27. Visual comparison of the cumulative damage on the crush plate side after the three drop tests (from left to right: Test Unit-2, analytical results with BoroBond, analytical results with Cat 277-4).



. Component	Component material	Effective plastic strain (in./in.)		
		Model with BoroBond	Model with Cat 277-4	
CV body	Type 304L stainless steel	0.0462	0.0525	
CV lid	Type 304L stainless steel	0.0004	0.0004	
CV closure nut	A-479 nitronic 60	0.0000	0.0005	
Angle	Type 304 stainless steel	0.0816	0.0845	
Drum	Type 304 stainless steel	0.2623	0.2814	
Drum bottom	Type 304 stainless steel	0.2807	0.2827	
Liner	Type 304 stainless steel	0.2005	0.2022	
Lid	Type 304 stainless steel	0.6411	0.6413	
Lid stiffener	Type 304 stainless steel	0.0217	0.0171	
Drum studs	Type 304 stainless steel	0.1753	0.2364	
Drum hex nut	Silicon bronze - C65100	0.0000	0.0018	
Drum washer	300 series stainless steel	0.1034	0.0439	
Top plug weldment	Type 304 stainless steel	0.1258	0.1286	

Table 2.57. Cumulative analytical side drop test maximum effective plastic strain results

Axial measurement location		0 to 180°		90 to 270°		
	Test results	Analytical results with BoroBond	Analytical results with Cat 277-4	Test results	Analytical results with BoroBond	Analytical results with Cat 277-4
Top false wire	19.25	19	19	19.06	19	19
Top rolling hoop	18.75	18.9	18.9	20.25	20.6	20.6
CG & top rolling hoop	19.25	19.4	19.4	19.75	19.9	19.8
CG rolling hoop	19.13	19.3	19.3	19.25	19.4	19.4
Bottom rolling hoop	19.13	19.3	19.3	19.75	20.4	20.4
Bottom false wire	18	18.6	18.6	19.38	19.4	19.4

Table 2.58. Diametrical damage comparison of Test Unit-3 with analytical predictions [Diameter (in.)]



Fig. 2.28. Visual comparison of the cumulative bottom damage after the three drop tests (from left to right: Test Unit-3, analytical results with BoroBond, analytical results with Cat 277-4).

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Fig. 2.29. Visual comparison of the cumulative lid damage after the three drop tests (from top to bottom: Test Unit-3, analytical results with BoroBond, analytical results with Cat 277-4).

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Component	Component material	Effective plastic strain (in./in.)		
•		Model with BoroBond	Model with Cat 277-4	
CV body	Type 304L stainless steel	0.0364	0.0371	
CV lid	Type 304L stainless steel	0.0024	0.0051	
CV closure nut	A-479 nitronic 60	0.0000	0.0002	
Angle	Type 304 stainless steel	0.0464	0.0462	
Drum	Type 304 stainless steel	0.3787	0.3830	
Drum bottom	Type 304 stainless steel	0.0731	0.0761	
Liner	Type 304 stainless steel	0.5507	0.5254	
Lid	Type 304 stainless steel	0.3579	0.3622	
Lid stiffener	Type 304 stainless steel	0.0272	0.0272	
Drum studs	Type 304 stainless steel	0.5578	0.5598	
Drum hex nut	Silicon bronze - C65100	0.2258	0.2266	
Drum washer	300 series stainless steel	0.1111	0.1528	
Top plug weldment	Type 304 stainless steel	0.1170	0.1166	

	Table 2.59.	Cumulative analyti	cal corner droj	p test maximum	effective	plastic strain	results
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Axial measurement location	0 to 180°			90 to 270°		
	Test results	Analytical results with BoroBond	Analytical results with Cat 277-4	Test results	Analytical results with BoroBond	Analytical results with Cat 277-4
Top false wire	19.25	19.3	19.3	19.38	19.3	19.3
Top rolling hoop	20.00	20.2	20.1	20.13	20.2	20.1
CG & top rolling hoop	20.00	20.2	20.2	20.06	20.2	20.2
CG rolling hoop	19.44	20.1	20.1	19.5	20.1	20.1
Bottom rolling hoop	19.94	20.5	20.5	20	20.5	20.5
Bottom false wire	19.25	19.4	19.4	19.25	19.4	19.4

Table 2.60. Diametrical damage comparison of Test Unit-4 with analytical predictions [Diameter (in.)]



Fig. 2.30. Visual comparison of the cumulative damage after the three drop tests (from left to right: Test Unit-4, analytical results with BoroBond, analytical results with Cat 277-4).

Component	Component material	Effective plastic strain (in./in.)		
_		Model with BoroBond	Model with Cat 277-4	
CV body	Type 304L stainless steel	0.0053	0.0083	
CV lid	Type 304L stainless steel	0.0034	0.0072	
CV closure nut	A-479 nitronic 60	0.0000	0.0011	
Angle	Type 304 stainless steel	0.0304	0.0308	
Drum	Type 304 stainless steel	0.1258	0.1237	
Drum bottom	Type 304 stainless steel	0.0312	0.0267	
Liner	Type 304 stainless steel	0.3585	0.3812	
Lid	Type 304 stainless steel	0.1415	0.1389	
Lid stiffener	Type 304 stainless steel	0.0098	0.0100	
Drum studs	Type 304 stainless steel	0.1541	0.1535	
Drum hex nuts	Silicon bronze - C65100	0.0170	0.0173	
Drum washer	300 series stainless steel	0.0510	0.0506	
Top plug weldment	Type 304 stainless steel	0.0944	0.0960	

Table 2.61. Cumulative analytical top drop test maximum effective plastic strain results

Table 2.62. ES-3100 test package weights before and after 10 CFR 71.73(c)(4) HAC thermal testing

Test Unit	Pre-test * weight kg (lb)	Post-test * weight kg (lb)	Thermal test weight loss kg (lb)	BoroBond4 original weight ^b kg (lb)	Water weight in BoroBond4 ^c kg (lb)	Water loss percent ^d (%)
1	202.3 (446)	202.3 (446)	0.0 (0)	20.7 (45.64)	4.91 (10.82)	0.00
2	202.8 (447)	202.8 (447)	0.0 (0)	20.5 (45.19)	4.86 (10.72)	0
3	203.7 (449)	203.2 (448)	0.45 (1)	20.5 (45.19)	4.87 (10.74)	9.31
4	201.8 (445)	201.4 (444)	0.45 (1)	20.4 (44.97)	4.84 (10.66)	9.38
5	157.4 (347)	156.9 (346)	0.45 (1)	20.6 (45.42)	4.89 (10.77)	9.29

* Data from the test report. (ORNL/NTRC-013)

^b Weight of BoroBond4 and water obtained from casting data. (ES-3100 Weldments)
^c This weight is based on TGA measurements and calculation showing that the minimum water percent is 23.71%.

⁴ All weight loss attributed to loss of water in BoroBond4.

could be postulated that the additional pressure differential (ambient on the exterior and a near vacuum inside) would help to further compress the O-rings during this test. However, since the containment vessel closure nut is screwed down, the additional pressure does not compress the O-ring more than a few ten thousands of an inch based on mismatch between the internal and external threaded joint. Only rotation of the closure nut will alter O-ring compression significantly. Pictures taken of all containment vessel tops following testing showed that the closure nut had rotated a maximum of 0.15 cm (0.060 in.) [Fig. 2.31] from its original radial position obtained during assembly (Fig. 2.32) except for Test Unit-4, which showed no rotation. Based on the pitch of the closure nut, this rotation translates into only 0.0009 cm (0.00035 in.) decompression of the O-rings. This compares to the original nominal compression of 0.064 cm (0.025 in.). According to the Parker O-Ring Handbook, the minimum squeeze for all seals, regardless of cross section should be about 0.018 cm (0.007 in.). Using the nominal compression of 0.064 cm (0.025 in.) and subtracting the decompression from rotation and the minimal pressure differential compression, there is ample O-ring compression. Therefore, the leak test in either direction for this containment vessel arrangement is valid. As required in 10 CFR 71.73(c)(5), the containment vessels were submerged under a 0.9-m (3-ft) head of water following the leakage tests, with no water in-leakage permitted. Following this immersion test, the containment vessels were opened. The lid assembly, with the O-rings in place on the body, are joined together by torquing the closure nut and sealing lid assembly to 162.7 ± 6.8 N·m (120 ± 5 ft-lb). The lowest break-loose torque value of 40.7 N·m (30 ft-lb) was recorded for Test Unit-4. Visual inspection following the testing indicated that neither the vessel bodies, the O-rings, the seal areas, nor the vessel lid assemblies were damaged during the tests. In Test Unit-5, the convenience cans had buckled from the pressure differential caused during the leak testing operation. However, the containment vessel wall showed little or no signs of impact. Therefore, based on the success of these six test units (including the containment vessel of Test Unit-6) and the analytical drop simulation effort, the structural integrity of the ES-3100 package, with the previously mentioned modifications, meets all the applicable requirements of 10 CFR 71.73 for transport of the proposed contents.



Fig. 2.31. Containment vessel markings at assembly (swivel hoist ring removed prior to testing).



Fig. 2.32. Containment vessel marking after compliance testing.

2.8 ACCIDENT CONDITIONS FOR AIR TRANSPORT OF PLUTONIUM

The proposed contents are not shipped by air; therefore, this section is not applicable.

2.9 ACCIDENT CONDITIONS FOR FISSILE MATERIAL PACKAGES FOR AIR TRANSPORT

The proposed contents are not shipped by air; therefore, this section is not applicable.

2.10 SPECIAL FORM

The package does not include any special form of radioactive material. Hence, the requirements of 10 CFR 71.75 and 71.77 are not applicable.

2.11 FUEL RODS

The contents do not utilize cladding for the containment of radioactive materials. Therefore, this requirement is not applicable.

2.10 APPENDICES

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Appendix	Description
2.10.1	ES-3100 CONTAINMENT VESSEL ASME CODE EVALUATION (DAC-EA-900000-A006 and DAC-EA-900000-A007)
2.10.2	IMPACT ANALYSES OF ES-3100 DESIGN CONCEPTS USING BOROBOND AND CAT 277-4 NEUTRON ABSORBERS
2.10.3	KAOLITE PROPERTIES
2.10.4	CATALOG 277-4 PROPERTIES
2.10.5	BOROBOND4 PROPERTIES
2.10.6	RECOMMENDED RANDOM VIBRATION AND SHOCK TEST SPECIFICATIONS FOR CARGO TRANSPORTED ON SST AND SGT TRAILERS

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Y/LF-717/Ch-2/ES-3100 HEU SAR/pc/02-25-05

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APPENDIX 2.10.1

ES-3100 CONTAINMENT VESSEL ASME CODE EVALUATION (DAC-EA-900000-A006 and DAC-EA-900000-A007)

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Y/LF-717/Ch-2/ES-3100 HEU SAR/pc/02-25-05

Y/LF-717/Ch-2/ES-3100 HEU SAR/pc/02-25-05

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^{JOB} ASME Code Subsection NB Stress Analysis of ES-3100 Containment Vessel		DATE 3 January 2005	SHEET 1 of 26	
DAC NO. DAC-EA-900000-A006	REVISION NO. 1	COMPUTED C. R. Hammond	CHECKED BY R. M. Jessee	

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OBJECTIVE

The design for the ES-3100 Containment Vessel is evaluated for compliance with ASME Code, Section III structural design rules using bounding loads taken from the U. S. Code of Federal Register and International Atomic Energy Agency Requirements.

EVALUATION INPUT (CRITERIA) AND SOURCE

REFERENCES USED

BWXT Y-12 drawings (Project: ES-3100 Shipping Package, all dated 10/29/03):

M2E801580A011, Rev. C, "Containment Vessel Assembly"

M2E801580A012, Rev. C, "Containment Vessel Body Assembly"

M2E801580A013, Rev. B, "Containment Vessel O-ring Details"

M2E801580A014, Rev. B, "Containment Vessel Lid Assembly"

M2E801580A015, Rev. C, "Containment Vessel Sealing Lid"

M2E801580A016, Rev. B, "Containment Vessel Closure Nut"

Texts

(B1.1) Unified Inch Screw Threads, ASME B1.1-1989, The American Society of Mechanical Engineers, 1989.

(B1.9) Buttress Inch Screw Threads, ANSI B1.9 – 1973, The American Society of Mechanical Engineers, 1973.

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(Roark) R. J. Roark and W. C. Young, *Formulas for Stress and Strain*, 5th Ed., McGraw-Hill Book Company, 1975, p. 363.

(Section II) Section II, Materials, Part D – Properties, 2001 Edition with 2003 Addenda, The American Society of Mechanical Engineers, 2003.

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ASSUMPTIONS MADE

Calculations are based on geometry and specifications from referenced drawings.

Results are rounded to significant figures although more digits may be retained in intermediate calculations.

IDENTIFICATION OF COMPUTER CALCULATION

<u>Computer Type:</u> Dell PC x86 Family processor Family 6 Model 8 Stepping 1 using the Microsoft Windows 2000 operating system level 5.00.2195 with Service Pack 4.

<u>Computer Program Name, Revision, Verification, Applicability:</u> Programs used were Algor (R) Linear Static Stress Version 12.26-WIN 28-OCT-2002, ALG.DLL VERSION:13180000 and FEMPRO Version 13.26-WIN 22-NOV-2002. Verification was by running example programs with known solutions on the same computer used for final calculations. The expected results were produced exactly. Hand calculations are used here to confirm results. The program is applicable to linear elastic solutions for bodies of revolution as needed here.

METHODS TO BE USED

The Finite Element Method is used to determine the response of the CV components to internal pressure and gasket seating loads. External pressure resistance of the cylindrical shell is evaluated following Code rules. The finite element results also serve to demonstrate the external pressure resistance of the lid and bottom of the CV. Buttress threads used to restrain the lid are evaluated by a method derived from an accepted way of determining the strength of standard threads.

ANALYSES AND/OR CALCULATIONS

DESIGN CONDITIONS

Internal Pressure: 101.5 psig at 300 F. per IAEA.

External Pressure: 21.7 psig at 300 F. per 10CFR71.73.

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ALLOWABLE STRESS INTENSITIES

From Section II.

PART	SPECIFICATION	ALLOWABLE STRESS INTENSITY
Containment vessel	ASME SA-182, Type F304L forging or bar (<5 in. thick)	12,800 @ 300 F.*
Containment lid	ASME SA-479, 304 bar	12,800 @ 300 F.*
Closure nut	ASME SA-479, UNS-S21800 bar	22,100 @ 300 F.

* The lower of two allowable values was chosen to limit deflection of the flange.

NB-3133 COMPONENTS UNDER EXTERNAL PRESSURE

The design internal pressure is higher than the external pressure across the bottom of the vessel and the lid. Since stability or buckling was not an issue, these flat heads were evaluated for resistance to internal pressure only. They can resist the external pressure by linearity.

NB-3133.3 Cylindrical Shells and Tubular Products

Data: Outside diameter of cylindrical shell, $D_o = 5.04" + 2(0.100") = 5.24"$ Shell thickness, T = 0.100"Total length, L = 32.40" - (0.25")/2 - 1.10" = 31.18" $D_o/T = 52.4$ $L/D_o = 5.95$ From ASME Section II, Fig. G, A = 0.00053

From ASME Section II, Fig. HA-3, conservatively using the 400 F. curve, B(400 F.) = 4900.

The maximum acceptable external pressure in this case is $P_a = 4B/3(D_o/T) = 125$ psig.

This allowable value exceeds the design external pressure and the shell is acceptable.

NB-3133.6 Cylinders Under Axial Compression

Data: Inside radius, R = 5.04"/2 = 2.52"

A = 0.125/(R/T) = 0.0050

From ASME Section II, Fig. HA-3, conservatively using the 400 F. curve, B(400 F.) = 7100.

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This is the maximum acceptable compressive stress limited by axial buckling. The maximum external pressure applied to the axial cross section of the cylinder at 400°F. can be derived using nominal values from:

$$7100\,\mathrm{psi} = \frac{\mathrm{p_e}\,\frac{\pi}{4}(5.24\,\mathrm{in.})^2}{\frac{\pi}{4}\left[(5.24\,\mathrm{in.})^2 - (5.04\,\mathrm{in.})^2\right]}$$

 $p_e = 532$ psi. This is less than the design external pressure and the shell is still acceptable.

NB-3200 DESIGN BY ANALYSIS

Individual axisymmetric finite element models were constructed of the CV body, the lid, and the closure nut and identified es5100, es3100lid, and es3100nut, respectively. Two loading conditions were applied to each model per Section III requirements: internal pressure and gasket seating. Load Case 1 is internal pressure including gasket load and Load Case 2 is gasket load alone.

The material properties at 300 F. obtained from Section II are as follows:

MATERIAL	MODULUS OF ELASTICITY	POISSON'S RATIO*
304 or 304L stainless steel	27,000,000 psi	0.3
UNS-S21800 stainless steel	27,000,000 psi**	0.3

* Typical values. Stress distributions are not sensitive to Poisson's ratios near 0.3.

** Not in Tables. Based on principal constituents same as 304 stainless (18% Cr, 8% Ni).

Gasket load

Two concentric O-rings are specified to provide a redundant and testable seal. Per normal ASME practice, the O-ring grooves were not included in the finite element model. Elements reasonably close to the actual O-ring locations were chosen and elements representing the O-rings were added to the model of the CV. The gasket force was applied by displacing the top surface by 0.139 in. -0.114 in. = 0.025 in. This way a reduction in gasket load will be caused by deformation of the CV from application of pressure.

Each O-ring has a 0.139 inch cross section diameter and is specified to have a 70 +/- 5 Shore A durometer reading. The O-ring manufacturer's catalog (Parker) gives ranges of distributed force required to compress O-rings. The O-ring grooves cut into the flange surface are specified to be 0.114 inch deep. The lid is expected to be pressed down so contact is metal-to-metal. Then the O-rings will be compressed

$$\frac{0.025 \text{ in.}}{0.139 \text{ in.}} \times 100 ^{\circ}/_{\circ} = 18.0 ^{\circ}/_{\circ}$$

This is equivalent to a strain of 0.18 in./in.

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Attachment A shows the effective distributed compression force for different amounts of compression based on values of distributed force averaged between high and low values for the highest allowed durometer reading, 75. The distributed force for 18% compression was about 20 lb/in. The stress-strain relationship for a thin annular shell t thick of average radius r loaded axially by the force F=20 lb/in(2 r) and an elastic modulus E is approximately

$$\frac{20 \text{ lb/in}(2\pi r)}{2\pi r t} = E\varepsilon = E(0.18 \text{ in/in}). \text{ So}$$
$$E = \frac{20 \text{ lb/in}}{0.18 t}.$$

For the outer O-ring, the thickness is 3.04584 in. -2.96172 in. and $E_0 = 1321$ psi. For the inner O-ring, the thickness is 2.817 in. -2.718 in. and $E_i = 1122$ psi.

These moduli were applied to the respective O-ring elements in the CV model.

Pressure was applied over the inner surface of the CV model up to the outer edge of the inner O-ring groove per Code rules. Two nodal forces had to be applied at the inner corner of the flange area since the program could not apply pressure to two faces of one element. The pressure and gasket seating forces were resisted by stiff elastic boundary elements canted 7 degrees out from the axis of symmetry to simulate the effect of the 7 degree surface on the threads to meet Code rules to consider radial forces and resulting hoop stress at the threads.

Results from the O-ring elements and the boundary element restraint are collected in Attachment B. The local 2-axes of the O-ring elements are parallel to the CV axis of symmetry, the global Z-axis. The values from load case 2 are -237.1 psi for the first set of elements representing the outer O-ring and -201.3 psi for the inner O-ring. These stresses were achieved by applying a displacement of 0.025 inches. The equivalent distributed loads in the O-ring elements are -237.1 psi (3.04584 in. -2.96172 in.) = -19.94 lb/in. and -201.3 psi (2.817 in. -2.718 in.) = -19.93 lb/in. which are within 1% of the target, 20 lb/in.

The gasket reaction forces and internal pressure were applied to a model of the lid. The nodal forces are shown in Attachment C. The lid was restrained by a portion of the surface under the nut. The contact area was moved radially inward until there was no tension developed during Load Case 1. The dimensions of the contact area may not be exact but the Code requirement to maintain equilibrium of forces and moments is met. One of the contact nodes for Load Case 2 was in tension but equilibrium of force and moment were still maintained by the force distribution applied to the model of the nut. Also Load Case 2 produces such low stresses that optimizing the model for it is unnecessary.

The interface forces were applied to a model of the nut. The force magnitude and moment of the distributed forces was maintained using small added nodal forces as shown in Attachment D.

The distribution of stress intensity is shown on Figs. 1 - 10. Stress intensities are very low relative to the basic allowable stress for the material. Code compliance is trivial since the Code tests subdivide the computer results but the sum is less than the allowable for any of the subsets. By the numbers.

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NB-3221.1 General Primary Membrane Stress Intensity

General primary membrane stress intensity is limited to the basic allowable stress intensity at temperature. That is 12,800 psi in the CV. The general primary membrane stress intensity is based on stresses averaged across the thickness of a section. The highest calculated stress intensities (called 2 times Tresca Stress by the program) were 7436 psi for Load Case 1 and 1203 psi for Load Case 2. Average stress is always less than peak stress so the CV is acceptable.

Fig. 4 is a close look at the cylindrical section. The stress intensity away from thickened sections appears to be less than 3000 psi. As a check the average elastic stresses in the middle of the cylindrical side of the vessel are easily calculated from equilibrium. Section III of the ASME Code provides values in Nonmandatory Appendix A. The tolerance on critical dimensions is ± 0.01 in. and is taken into consideration to calculate maximum values of stress intensity.

A-2221 General Primary Membrane Stress Intensity

$$S = (pR/t) + (p/2) = 101.5 psig\left(\frac{5.04 in. + 0.01 in.}{2(0.10 in. - 0.01 in.)}\right) + \frac{101.5 psig}{2} = 2898 psi.$$

A-2222 Maximum Value of Primary Plus Secondary Stress Intensity

$$S = 2pY^{2}/(Y^{2}-1) = \frac{2(101.5 \text{ psig}) \left(\frac{5.04 \text{ in.} + 0.01 \text{ in.}}{5.04 \text{ in.} + 0.01 \text{ in.} - 2(0.10 \text{ in.} - 0.01 \text{ in.})}\right)^{2}}{\left(\frac{5.04 \text{ in.} + 0.01 \text{ in.}}{5.04 \text{ in.} + 0.01 \text{ in.} - 2(0.10 \text{ in.} - 0.01 \text{ in.})}\right)^{2} - 1} = 2899 \text{ psi.}$$

This confirms the computer solution for the cylindrical section.

There is a small radial membrane stress in the CV bottom but there is no need to calculate it since the sum of all order stresses is less than the allowable for the membrane stress.

The highest calculated stress intensity in the lid was 2398 psi for Load Case 1 and 872 psi for Load Case 2. The general primary membrane radial stress in the lid is zero from equilibrium so the highest average membrane stress is p/2 = 200 psi/2 = 100 psi. The allowable stress intensity is also 12,800 psi so the lid is acceptable.

NB-3221.2 Local Membrane Stress Intensity

Local membrane stress intensity is the average stress across the thickness of a cross section at the junction between the side and bottom of the CV. The allowable value of this stress component is 1.5 times the basic allowable stress. Figs. 4 and 5 show that the peak values of stress at this junction are below the basic allowable so the average must also be below the allowable and the CV is acceptable.

NB-3221.3 Primary Membrane plus Primary Bending Stress Intensity

Primary membrane plus primary bending stress intensity in the CV bottom and the lid.

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Fig. 3 shows the stress intensity at the center of the CV bottom. The distribution is primarily due to bending and the peak value is less than 1.5 times the basic allowable stress intensity.

The stress in the bottom cover is complicated by attachment to the side but bending stress at the center can be checked by bounding stress by assuming both simple support and fixed support around the outside edge. From the Code Appendix:

A-5212

Radial bending stress at center (r = 0) and outside surface (x = t/2)

$$\sigma_{r} = p \frac{3(x)}{4t^{3}} \left[(3+v)(R^{2}-r^{2}) \right] = 101.5 \operatorname{psig} \frac{3(t/2)}{4t^{3}} \left[(3+0.3) \left(\frac{5.04 \operatorname{in.}}{2} \right)^{2} \right]$$

= 101.5 psig $\frac{3}{8(0.25 \operatorname{in.})^{2}} \left[3.3(2.52 \operatorname{in.})^{2} \right] = 12,762 \operatorname{psi.}$

This equation is based on a simply supported outer edge. For a fixed edge, the stress at the same point using Roark (Table 24, Case 10b) is:

$$\sigma_{\rm r} = p \frac{6}{16(0.25\,{\rm in.})^2} \left[(1+\nu) R^2 \right] = 101.5 \,{\rm psig} \frac{3}{8(0.25\,{\rm in.})^2} \left[1.3(2.52\,{\rm in.})^2 \right] = 5,028 \,{\rm psi}.$$

From Fig. 3 it is seen that the peak stress intensity at the center of the CV bottom is about 7,000 psi. This value is between the bending stresses for the simply supported and fixed edge cases as expected.

The pattern of stress intensity in the lid is also primarily bending of the relatively thin outboard edge with bearing under the restraining nut and some intensification at a fillet. The bending stress appears to be less than 300 psi which is far below the allowable.

NB-3222.3 Expansion Stress Intensity

Expansion stress intensity is undefined but can be bounded. The largest temperature range possible for the CV is between -40 F. which is the minimum temperature specified in 10CFR71 and 300 F. defined here. Suppose a tendril maintains a temperature of -14 F. while the surrounding material is heated to 300 F. The result is a 340 F. temperature difference across a sharp boundary – an infinite gradient. The stress in the tendril would be $\sigma = E \alpha_{(-40)-300} 340^{\circ}$. *E* is the cold modulus of elasticity – 28,800,000 psi by interpolation from Table TM-1 in Section II. The temperature at the midpoint of the range is 170 F. and the instantaneous α at that temperature is 9.1 × 10⁻⁶ in/in/° F. from Table TE-1 in Section II. The bounding expansion stress is 89,000 psi. This is a fictitious elastic stress per the Code. Add to this the highest stress from the CV and lid models multiplied by an intensification factor of 2 since the finite element program may extrapolate to the surface too simplistically. That is 89,000 psi + 2 (7436 psi) = 100,000 psi. The alternating stress is half this value or 50,000 psi. The allowable number of cycles for this stress per Fig. I-9.2.1 in Code Mandatory Appendix I is 30,000. The vessel should acceptable for a few hundred years although a severe transportation accident should be counted as two cycles, one for impact and one for fire.

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NB-3230 STRESS LIMITS FOR BOLTS

NB-3232.1 Average Stress

Average stress across a bolt cross section has a different allowable value. Since the CV is threaded to retain the lid special consideration is given to the neck above the lid. Allowable stress on bolts per Appendix III, Article III-2000, of Section III is one-third of the minimum specified yield strength of the material. This is half of the basic allowable but the service stress may be twice the allowable so we are back to an allowable service stress of 12,800 psi. Fig. 5 shows that the peak stress intensity in the neck region is under 6000 psi and the average service stress is much less so the CV is acceptable.

NB-3232.2 Maximum Stress

Maximum service stress in a bolt including bending stress may be three times the basic allowable bolt stress and since the bending component is included in the calculated stress the CV is clearly acceptable.

NB-3227.2 Pure Shear

Pure shear across threads on CV and Closure Nut. These threads are 7.0 inch 8 threads per inch push buttress threads Class 2A fit per ANSI B1.9-1973. The 7 degree slope of the mating surface was accounted for in the finite element models. The threads were not modeled in detail and they are evaluated using a traditional method (B1.1). Internal threads are limiting because the allowable stress for the CV material is about half the allowable stress for the nut material. The appropriate shear area on internal threads is the cylindrical area at the tip of the external thread with minimum height. That is the area at the minimum major diameter of the external thread called $MIN D_s$ in B1.9. $MIN D_s$ is the nominal D_s , D - G, where D is the nominal diameter and G is the allowance for easy assembly minus the tolerance on D. The minimum width of the internal thread at this radius, say t_e , is a function of the theoretical sharp thread form, H, defined as 0.89064p where p is the thread pitch, the crest truncation, f (=0.14532p), and the sum of radial allowance and tolerances (the gap). The gap based on thread tolerances is half the tolerance on the pitch diameter and half the tolerance on the major diameter of the thread. The gap should also include any outward radial deformation of the threads. Fig. 11 shows that due to rotation of the flange, the threads in the CV actually mode inward and do not increase the gap. In any case the calculated displacements are smaller than the thread tolerances. So, limited to thread properties

$$gap = \frac{PD \text{ tol}}{2} + \frac{G}{2} + \frac{D \text{ tol}}{2} = \frac{0.0101 \text{ in.}}{2} + \frac{0.0067}{2} + \frac{0.0101 \text{ in.}}{2} = 0.0134 \text{ in.}$$
$$t_e = (0.89064 \ p - 0.14532 \ p - gap)(\tan(7^\circ) + \tan(45^\circ))$$
$$= ((0.89064 - 0.14532)(0.125 \ \text{in.}) - 0.0134 \ \text{in.})(1.1228)$$
$$= 0.08956 \ \text{in.}$$

$$MIND_s = 7in. - 0.0067 - 0.0101in. = 6.9832in.$$

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Three threads are fully engaged so the shear area is at least

 $A_{i} = 3(0.08956in)\pi(6.9832in) = 5.894in^2$.

The shear capacity given the Code limit on shear stress of 0.6 S_m is 0.6 (12,800 psi)(5.894 in.²) = 45,300 lb.

The load due to pressure to the outer edge of the inner O-ring groove is

$$W_{m1} = \pi \frac{101.5 \operatorname{psi}(5.624 \operatorname{in.})^2}{4} = 2521 \ lb.$$

The force due to gasket seating is

$$W_{m2} = 20 lb./in.\pi [(5.359 in. + 0.139 in.) + (5.859 in. + 0.139 in.)] = 722.3 lb.$$

The combined force is 3244 lb. This is much less than the shear capacity so the threads are acceptable for shear.

NB-3232.3 Fatigue Analysis of Bolts

Fatigue analysis of bolts is contained in Section 2 of the Safety Analysis Report for Packaging

CONCLUSIONS

The ES-3100 Containment Vessel meets ASME Code, Section III, requirements for structural design except for fatigue analysis of the threaded closure which was not evaluated. Fatigue analysis of the threaded closure is contained in Section 2 of the Safety Analysis Report for Packaging.
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Load Case: 1 of 2 Maximum Value: 7436.43 lbf/(in^2) Minimum Value: 34.3304 lbf/(in^2)

Fig. 1 – Stress Intensity in Containment Vessel due to Load Case 1

Stress Tresca * 2 Ibf/(in^2)

7436.433 5956.012 4475.592 2995.171 1514.751 34.33044

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Load Case: 2 of 2 Maximum Value: 1202.6 lbf/(in^2) Minimum Value: 4.68536e-009 lbf/(in^2)

Fig. 2 – Stress Intensity in Containment Vessel due to Load Case 2

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Load Case: 1 of 2 Maximum Value: 7436.43 lbf/(in²) Minimum Value: 34.3304 lbf/(in²)

Fig. 3 - Stress Intensity in the Bottom of the Containment Vessel due to Load Case 1



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Minimum Value: 34.3304 lbf/(in^2)

Fig. 4 - Stress Intensity at Junction of Bottom and Side of Containment Vessel due to Load Case 1

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Fig. 5 - Stress Intensity in Flange Region of Containment Vessel due to Load Case 1



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Load Case: 2 of 2 Maximum Value: 1202.6 lbf/(in*2) Minimum Value: 4.68536e-009 lbf/(in*2)

Fig. 6 - Stress Intensity in Flange Region of Containment Vessel due to Load Case 2

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Load Case: 1 of 2 Maximum Value: 2398.09 lbf/(in*2) Minimum Value: 3.73138 lbf/(in*2)

Fig. 7 – Stress Intensity in CV Lid due to Load Case 1



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Load Case: 2 of 2 Maximum Value: 871.919 lbf/(in^2) Minimum Value: 1.23938 lbf/(in^2)

Fig. 8 – Stress Intensity in CV Lid due to Load Case 2

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Load Case: 1 of 2 Maximum Value: 8569.75 lbf/(in^2) Minimum Value: 70.7862 lbf/(in^2)

Fig. 9 – Stress Intensity in Nut due to Load Case 1

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Load Case: 2 of 2 Maximum Value: 2223.51 lbf/(in^2) Minimum Value: 36.9021 lbf/(in^2)

Fig. 10 – Stress Intensity in Nut due to Load Case 2

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Fig. 11 - Radial Strain in the Flange Region of the Containment Vessel due to Load Case 1 (Distortion is Exaggerated)

Load Case: 1 of 2

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ATTACHMENT A – O-RING SPRING CONSTANT

Compression	n of 0.139) in. dia. O-r	ing (Parker	Seals, "O-Ri	ng Handbo	ook," ORD-8	5700, Dec 1	977)
Diameter =	0.139	D =	70	D =	80			
		Force						
% compress	sion	Min	Max			Ave	Del	К
5	0.00695	0.93	6.1	2.5	10	4.8825	0.00695	702.518
10	0.0139	2	14	4.5	20	10.125	0.0139	728.4173
20	0.0278	4.5	30	9	45	22.125	0.0278	795.8633
30	0.0417	11	72	20	90	48.25	0.0417	1157.074
40	0.0556	19	160	40	180	99.75	0.0556	1794.065



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ATTACHMENT B – RESULTS FOR O-RING ELEMENTS FROM FINITE ELEMENT ANALYSIS OF CONTAINMENT VESSEL

**** Nodal stresses for 2-D elasticity elements:

E1.	#	LC	ND	Sigma-11 Sigma-Int	Sigma-22	Sigma-33	Tau-12	Sigma-Max	Sigma-Min
	1	1	I	7.151E-03 -3.629E-02	-2.347E+02	-3.629E-02	1.115E-02	7.152E-03	-2.347E+02
	1	1	J	6.460E-03 -3.564E-02	-2.348E+02	-3.564E-02	1.099E-02	6.460E-03	-2.348E+02
	1	1	ĸ	7.565E-04 -4.589E-02	-2.348E+02	-4.589E-02	9.078E-03	7.568E-04	-2.348E+02
	1	1	L	1.448E-03 -4.662E-02	-2.347E+02	-4.662E-02	9.233E-03	1.448E-03	-2.347E+02
	1	2	I	-3.586E-03 -6.498E-03	-2.371E+02	-6.498E-03	8.397E-03	-3.586E-03	-2.371E+02
	1	2	J	-3.713E-03 -6.454E-03	-2.371E+02	-6.454E-03	8.271E-03	-3.713E-03	-2.371E+02
	1	2	ĸ	5.712E-03 -7.804E-03	-2.371E+02	-7.804E-03	7.936E-03	5.712E-03	-2.371E+02
	1	2	L	5.839E-03 -8.014E-03	-2.371E+02	-8.014E-03	8.062E-03	5.839E-03	-2.371E+02
	2	1	I	8.755E-03 -3.608E-02	-2.348E+02	-3.608E-02	-8.886E-03	8.756E-03	-2.348E+02
	2	1	J	8.182E-03 -3.552E-02	-2.350E+02	-3.552E-02	-8.763E-03	8.183E-03	-2.350E+02
	2	1	K	-7.855E-05 -4.575E-02	-2.350E+02	-4.575E-02	-1.064E-02	-7.807E-05	-2.350E+02
	2	1	L	4.944E-04 -4.633E-02	-2.348E+02	-4.633E-02	-1.077E-02	4.949E-04	-2.348E+02
	2	2	I	-3.637E-03 -6.900E-03	-2.371E+02	-6.900E-03	-9.129E-03	-3.636E-03	-2.371E+02
	2	2	J	-3.745E-03 -6.860E-03	-2.371E+02	-6.860E-03	-9.012E-03	-3.745E-03	-2.371E+02
	2	2	ĸ	5.687E-03 -8.074E-03	-2.371E+02	-8.074E-03	-9.358E-03	5.687E-03	-2.371E+02
	2	2	L	5.795E-03 -8.250E-03	-2.371E+02	-8.250E-03	-9.475E-03	5.796E-03	-2.371E+02

**** 2-D Elasticity elements:

```
Number of elements
                               2
                         =
Number of materials
                         =
                              5
Maximum temperature pts =
                              1
Analysis code
                              0
                         =
  0 : axisymmetric
  1 : plane strain
  2 : plane stress
Incompatible modes
                               0
  0 : included
  1 : not included
```

**** Nodal stresses for 2-D elasticity elements:

El. # LC ND Sigma-11 Sigma-22 Sigma-33 Tau-12 Sigma-Max Sigma-Min Sigma-Int 1 1 I 1.838E-03 -1.987E+02 -3.397E-02 7.582E-03 1.838E-03 -1.987E+02 -3.397E-02 1 J 1.110E-03 -1.988E+02 -3.334E-02 7.464E-03 1.111E-03 -1.988E+02 -3.334E-02

.12.

DB AS	^B ASME Code Subsection NB Stress Analysis of ES-3100 Containment Vessel					DATE 3 Jan	uary 2005	sheet 24	SHEET 24 of 26	
AC NO.	DAC	C-E.	A-900000-A00	6 REVIS	ION NO. 1	COMPUTED	C. R. Hammo	ond CHECKED BY	R. M. Jessee	
1	1	ĸ	1.855E-03 - -4.282E-02	·1.988E+02	-4.282E-02	5.515E-03	1.856E-03	-1.988E+02		
1	1	L	2.583E-03 - -4.364E-02	-1.987E+02	-4.364E-02	5.634E-03	2.583E-03	-1.987E+02		
1	2	I	-1.419E-03 -	-2.013E+02	-5.945E-03	6.027E-03	-1.419E-03	-2.013E+02		
1	2	J	-1.558E-03 - -5.865E-03	-2.013E+02	-5.865E-03	5.923E-03	-1.558E-03	-2.013E+02		
1	2	к	3.687E-03 - -7.071E-03	-2.013E+02	-7.071E-03	5.591E-03	3.687E-03	-2.013E+02		
1	2	L	3.825E-03 - -7.268E-03	-2.013E+02	-7.268E-03	5.696E-03	3.825E-03	-2.013E+02		
2	1	I	1.931E-03 -	1.988E+02	-3.367E-02	-3.542E-03	1.931E-03	-1.988E+02		
2	1	J	1.223E-03 - -3.305E-02	1.990E+02	-3.305E-02	-3.463E-03	1.223E-03	-1.990E+02		
2	1	ĸ	1.761E-03 - -4.236E-02	-1.990E+02	-4.236E-02	-5.358E-03	1.762E-03	-1.990E+02		
2	1	L	2.469E-03 - -4.316E-02	1.988E+02	-4.316E-02	-5.436E-03	2.469E-03	-1.988E+02		
2	2	I	-1.833E-03 - -6.185E-03	2.013E+02	-6.185E-03	-5.2472-03	-1.833E-03	-2.013E+02		
2	2	J	-1.970E-03 - -6.110E-03	-2.013E+02	-6.110E-03	-5.152E-03	-1.969E-03	-2.013E+02		
2	2	к	3.840E-03 - -7.192E-03	-2.013E+02	-7.192E-03	-5.486E-03	3.841E-03	-2.013E+02		
2	2	L	3.977E-03 - -7.391E-03	-2.013E+02	-7.391E-03	-5.581E-03	3.978E-03	-2.013E+02		

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.

ATTACHMENT C - O-RING INTERFACE LOADS

Axisymm Inner O-r	netric nodal ring	forces on lie	d from O-ring pres	sure			
Node	Node	Mean radius	Force/pressure	Load case 1	Load case 1	Load case 2	Load case 2
143	2.69812	2.717935	0.053659565	198.825	10.66886299	201.3	10.80167042
144	2.73775	2.75756	0.108483245	198.825	21.56918112	201.3	21.83767716
145	2.77737	2.797185	0.110053385	198.825	21.88136433	201.3	22.15374646
146	2.817		0.055622538	198.825	11.0591511	201.3	11.19681688
Outer O-	ring						
149	2.942	2.962835	0.061513619	234.825	14.44493549	237.1	14.58487897
150	2.98367	3.0045	0.124314506	234.825	29.19215396	237.1	29.47496946
151	3.02533	3.046165	0.126050479	234.825	29.59980364	237.1	29.88656848
152	3.067		0.063683896	234.825	14.95457097	237.1	15.09945183

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ATTACHMENT D - INTERFACE LOADS ON NUT

Matchin	າg in	terface pre	ssure loads	5						
Load C	ase	1								
	Side 1							Sic	le 2	
Index		Radius	Szz.	FORCEz	Force/Rad	Index	Radius	Szz	FORCEZ	Force/Rad
	0	2.50507	0				2.50964	0		
	1	2.54629	-3300.16	-136.0161	-346.3364		2.53798	-800	-22.668	-57.53093
	2	2.5875	-1230.75	-50.71921	-131.2359		2.56631	-3300.16	-97.27222	-249.6307
	3	2.62871	-662.77	-27.31275	-71.7973		2.59693	-1230.75	-37.67941	-97.85079
	4	2.66992	-65.6015	-2.703438	-7.217963		2.62754	-1230.75	-37.67941	-99.00416
	5	2.71113	0				2.65816	-662.77	-20.2907	-53.93594
Sum				-216.7515	-556.5876		2.68877	-65.6015	-2.00839	-5.400099
							2.71939	0		



Load Case 2

LUau	ase.	2								
Side 1			le 1				Side 2			
Index	l	Radius	Szz	FORCEz	Force/Rad Index	Radius	Szz	FORCEz	Force/Rad	
	0	2.50507	0			2.50964	0			
	1	2.54629	301.824	12.43968	31.67502	2.53798	301.824	8.552183	21.70527	
	2	2.5875	-132.484	-5.459666	-14.12688	2.56631	100	2.9475	7.564199	
	3	2.62871	-398.673	-16.42931	-43.1879	2.59693	-132.484	-4.055998	-10.53314	
	4	2.66992	-1240.54	-51.12265	-136.4934	2.62754	-398.673	-12.20537	-32.07011	
	5	2.71113	0	I.		2.65816	-1240.54	-37.97913	-100.9546	
Sum				-60.57196	-162.1332	2.68877	-600	-18.369	-49.39002	
						2.71939	0			



-61.10982 -163.6784

.



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2.0 OBJECTIVE

The 7°/45° Buttress threads, specified per ANSI B1.9-1973 7.0-8 Push, used to secure the lid of the ES-3100 Containment Vessel are evaluated for fatigue resistance under normal conditions of use. The evaluation is based on rules in NB-3232.3 from ASME B&PV Code, Section III.

3.0 EVALUATION INPUT (CRITERIA) AND SOURCE

3.1 REFERENCES USED

(B1.9) Buttress Inch Screw Threads, ANSI B1.9 – 1973, The American Society of Mechanical Engineers, 1973.

(Code) Class 1 Components, Section III, Rules for Construction of Nuclear Power Plant Components, Division 1, 2001 Edition with 2003 Addenda, The American Society of Mechanical Engineers, 2003.

(Drawing) "Containment Vessel Assembly," M2E801580A011, Rev. A, BWXT Y-12, 2003.

(Hammond) "ASME Code Subsection NB Stress Analysis of ES-3100 Containment Vessel," DAC-EA-900000-A006, Rev. 1, BWXT Y-12, 2004.

(Laughner & Hargan) Handbook of Fastening and Joining of Metal Parts, McGraw-Hill Book Company, 1956, pp. 167-168.

(Section II) Section II, Materials, Part D – Properties, 2001 Edition with 2003 Addenda, The American Society of Mechanical Engineers, 2003.

(SST/SGT) J. S. Cap, "Recommended Random Vibration and Shock Test Specifications for Cargo Transported on SST and SGT Trailers," letter to distribution, Sandia National Laboratory, Albuquerque, New Mexico, 2002.

3.2 DESIGN CONDITIONS

Hot NCT: Internal pressure of 17.786 psia at 190.06° F.

Cold NCT: Internal pressure of 11.13 psia at -40° F.

3.3 METHODS TO BE USED

A finite element model described in DAC-EA-900000-A006 by Hammond was used. The program was verified by running problems with known solutions. The file name for the model is ES3100CV1. Properties used in the model are shown in Appendix 2.

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4.0 ANALYSES AND/OR CALCULATIONS

The previous analysis (Hammond) followed ASME Code rules to validate the vessel design under a bounding internal pressure of 101.5 psi. The design margin of the vessel, including the vessel body, the lid, and the retaining nut but not including threads on the nut or vessel body, was limited by stress intensity calculated at the side wall to bottom transition of the vessel. The actual maximum expected internal pressure is 17.786 psia or 17.786 psia – 14.7 psia = 3.1 psig. Away from the contact region between the lid and vessel body, stresses are proportional to pressure so the stress in the body and at the center of the lid will be reduced to 3.1 psi/101.5 psi = 0.0305 or 3.05% of values calculated previously. The design margin in the vessel becomes limited by stresses in the clamping region primarily due to gasket seating load or the load produced by tightening the nut. These calculations determine the load from torquing the nut and their effects on stress in the vessel components in the contact or clamping region.

4.1 TIGHTENING TORQUE

The specified nut torque is 120 +/- 5 ft.-lb. From Laughtner & Hargan, the ratio of axial force, P (lb.), to torque, T (in.-lb.) is

$$P_{T}^{P} = 2(D_{v} + d_{p} m)$$
, where

D = mean bearing diameter of nut (in.),

dp = pitch diameter of screw thread (in.),

v = coefficient of friction between nut and bearing surface,

$$m = \frac{\tan(\beta + \phi)}{\cos \alpha}$$
, where

 α = one-half of thread profile angle (degrees),

 β = helix angle (degrees), and

 ϕ = friction angle the tangent of which is the friction coefficient.

The threads are 7 inch nominal diameter with 8 threads per inch or having a pitch of 0.125 in. From B1.9 the pitch diameter is

$$d_p = 7 \text{ in.} - 0.6 (0.125 \text{ in.}) = 6.93 \text{ in.}$$

The helix angle on the pitch diameter is

$$\beta = \arctan \frac{0.125 \text{ in.}}{\pi (6.93 \text{ in.})} = 0.329^{\circ}$$

The thread profile angle at the mating surfaces is 7° so $\alpha = 3.5^{\circ}$.

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The mean effective bearing diameter of the nut is about 5.8 inches. That is D = 5.8 in.

The referenced drawing has the note: "During installation of container vessel lid assembly, apply a light coat of Krytox grease to the threads and under the nut." A typical value for coefficient of friction for lubricated threads is 0.11. In this case

$$\phi = \arctan(0.11) = 6.3$$
.

$$m = \frac{\tan (0.329^\circ + 6.3^\circ)}{\cos (3.5^\circ)} = 0.12.$$

$$P_T = \frac{2}{(5.8 \text{ in.} (0.11) + 6.93 \text{ in.} (0.12))} = 1.36$$

The maximum and the minimum force, assuming that the friction coefficient 0.11 is correct are

Pmax = 1.36 T = 1.36 (125 ft.-lb)(12 in./ft.) = 2,000 lb., rounding to 2 significant figures, and

Pmin = 1.36 (115 ft.-lb.)(12 in./ft.) = 1,900 lb.

According to Hammond the force required to seat the gaskets is $W_{m2} = 20 \text{ lb./in.} \pi [(5.359 \text{ in.} + 0.139 \text{ in.}) + (5.859 \text{ in.} + 0.139 \text{ in.})] = 722.3 \text{ lb}$ and

the load due to the maximum allowable pressure, 101.5 psig, to the outer edge of the inner O-ring groove is

$$W_{m1} = \pi \frac{101.5 \operatorname{psig}(5.624 \operatorname{in.})^2}{4} = 2521 \operatorname{lb}.$$

The sum of gasket seating and pressure forces is 3,244 lb. so the specified torque is not adequate for the bounding pressure. However, the highest expected internal pressure is 17.786 psia which is (17.786 psia - 14.7 psia =) 3.1 psig so

$$W_{m1} = \pi \frac{3.1 \operatorname{psig}(5.624 \operatorname{in.})^2}{4} = 77 \operatorname{lb}.$$

The sum of gasket seating force and actual pressure force is 799 lb and there is a large margin on torque required to maintain a tight gasket and consequently the required torque is not sensitive to the coefficient of friction.

The minimum cross section area of the CV subject to the axial force from torquing the nut is at the undercut just below the threads. The inside diameter at the undercut is 6.85 in. +2(0.09 in.) = 7.03 in. The outside diameter in the same plane is 7.50 in. The minimum cross section area considering the tolerances listed on the drawing is $\pi((7.50 \text{ in.} - 0.01 \text{ in.})^2 - (7.03 \text{ in.} + 0.01 \text{ in.})^2))/4 = 5.14 \text{ in}^2$.

The average axial stress due to the force due to maximum torque at this section is

 $\overline{\sigma}_{torque} = 2,000 \text{ lb.} / 5.14 \text{ in}^2 = 389 \text{ psi.}$

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The maximum diameter at the root of a thread on the CV is 7.04 in. That is called the maximum major diameter of the internal thread which per B1.9 is D - h + PDtol. + 0.80803 p, where D is the major diameter (7 in.), h is the basic height of thread engagement (0.6 p), PDtol. is tolerance on pitch diameter (0.0101 in.), and p is pitch (0.125 in.). The cross section area at the root of the thread is the same as the minimum area at the undercut (i.e. 7.03 in. + 0.01 in. including tolerance) and the average stress is the same.

The finite element model used by Hammond to evaluate pressure resistance was modified to simulate the effect of the axial force due to torquing the nut. The section of the vessel between the flange surface and the threads was forced to shrink in the axial direction by applying an artificial temperature drop of 100° F. and manipulating the axial coefficient of thermal expansion to produce an axial force of 2,000 lb. Fig. 1 shows the effected region of the vessel with dots at the locations where axial stresses were recorded. The O-ring elements were removed and the entire flange surface was held in place by stiff axial spring elements. Nodal axial stresses were obtained across the two horizontal sections. There were two stresses calculated at each point, one above and one below the section boundary. The stress in the section without the temperature-dependent properties was recorded to avoid including thermal strain in the stress calculated at each point across the two sections in Appendix 1.

The net axial forces across each section were calculated by multiplying the axial stress over the tributary area. There was a slight but acceptable difference (4%) between the upper and lower sections attributed to model coarseness. The net force across the section with the highest axial stress was about 2% greater than 2000 lb.

The plot of axial stress shown in Appendix 1 clearly indicates that the peak stress at the left edge is higher than an extrapolated equivalent linear bending stress. The value of peak stress due to preload from torque, 3,476 psi, is so low that we can substitute this peak stress for the sum of membrane and bending stress in combination with axial stress from other loads.

The gasket seating force between the lid and CV body is the sum of gasket seating forces at both O-rings or 722.3 lb. total. The pressure force due to the 101.5 psig from the earlier calculation over the area to the back side of the inner O-ring groove is

 $F_{\rm P} = 101.5 \, {\rm psi} \, \pi (2.817 \, {\rm in.})^2 = 2530 \, {\rm lb.}$

In general, stress intensities are not linear functions of applied force but in our case of the axial force due to torque on the nut alone, stress intensities will increase by the ratio 2000 lb./722.3 lb. = 2.77. The calculated peak stress intensity due to gasket seating load alone (Load Case 2) were highest near points of high compression that would be affected by the applied torque. The peak values were 872 psi in the lid and 2224 psi in the nut (Hammond, pp. 18, 20). The stresses in these components due to torque would be 2.77(872 psi) = 2415 psi in the lid and 2.77(2224 psi) = 6158 psi in the nut.

Bending or radial stress near the center of the lid and stresses in the vessel body away from the contact region will be reduced to about 3.05% of previously calculated values.

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The effect of an internal 3.1 psig pressure plus the torque is shown in Fig. 3. Maximum stress intensity is 3501 psi. This is in the same location as for the pressure plus gasket seat case, in the transition between the side and bottom of the vessel. The axial stress in this region due to 3.1 psi pressure and torque is shown on Fig. 4. The peak axial stress is 3714 psi. The slight pressure causes just a slight increase in stress over the case with torque alone. The stress intensities in the clamping regions of the lid and nut will become about (3714 psi/3476 psi) 2415 psi = 2580 psi and (3714 psi/3476 psi) 6158 psi = 6580 psi, respectively.

4.2 DIFFERENTIAL THERMAL EXPANSION

The range of temperatures to which the CV may be exposed is -40° F. to 190.06° F. The average thermal expansion coefficient for the 304 material of the CV between 70 and 200 F. is 8.9 10⁻⁶ in./in./° F. and greater for higher upper temperatures per Section II. From the HP Alloys web site the average thermal expansion coefficient of the Nitronic 60 material of the nut between 75 and 200 F. is 8.8 10⁻⁶ in./in./° F. and greater for higher upper temperatures. Since the temperatures on opposite sides of the thread mating surface are expected to be the same an upper bound on the stress due to differential thermal expansion is

 $\sigma_t = E_c \Delta T (\alpha_{CV} - \alpha_N)$, where E_c is the cold elastic modulus of either part, T is temperature, and α is average thermal expansion coefficient.

In the CV the stress, using a modulus interpolated from Table TM-1 in Section II, is

$$\sigma_{tCV} = 28.8 \times 10^{6} \text{ psi}(190.06^{\circ} - (-40^{\circ}))(8.9 \times 10^{-6} \text{ in./in./o} - 8.8 \times 10^{-6} \text{ in./in/o})$$

- 663 nci

= 663 psi.

The nut material has a slightly lower modulus listed so the stress in the nut will be slightly less. The room temperature modulus of the nut material is 26.2×10^6 psi per the HP Alloy website. The cold temperature modulus is not available but an approximation is obtained by comparing the modulus of Nitronic 60 at room temperature with the modulus of 304 at room temperature. From Table TM-1, the modulus of 304 at 70F. is 28.3×106 psi. Stress in the nut at the threads is about

$$\sigma_{tN} = \frac{26.2 \times 10^6 \text{ psi}}{28.3 \times 10^6 \text{ psi}} 663 \text{ psi} = 613 \text{ psi}.$$

The CV material has the higher thermal expansion coefficient so the effect of temperature increase is to reduce preload on the lid. Consider the mid-height of the threads to be fixed. The fixed plane is 1.100 in. -0.55 in. /2 = 0.825 in. above the mating plane. The lid is 0.5 in. thick under the nut and the lid will grow the same amount as the CV. The nut has 0.325 in. of material below the fixed plane and the difference in growth between the CV and the nut is

$$0.325 \text{ in.} (190.06^\circ - (-40^\circ))(8.9 \times 10^{-6} \text{ in.}/\text{in.}/\circ - 8.8 \times 10^{-6} \text{ in.}/\text{in.}/\circ) = 0.0000075 \text{ in.}$$

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Even if the torque load in the metal is ignored, the O-rings are compressed at least

Comp. = (0.139 in. - 0.004 in.) - (0.114 in. + 0.001 in.) = 0.020 in.

and a reduction in compression of 0.004% due to temperature change is insufficient to unload the O-rings enough to allow leakage.

4.3 TANSPORTATION LOADS

The highest shock acceleration expected during transport is 11g in the vertical direction compared to a maximum horizontal acceleration of 5g per SST/SGT. The contents of the CV are specified to not exceed 90 lbs. The lid can be viewed as three disks, the volumes of which are:

Disk	Volume Formula	Volume, in ³
Тор	π (3.98in.) ² (0.56in.)/4	6.97
Middle	π (6.741in.) ² (0.500in.)/4	17.84
Bottom	$\pi (5.00 \text{ in.})^2 (0.05 \text{ in.})/4$	0.98
Sum		25.8

The weight density of the lid material is about 0.29 lb./cu. in. so the weight of the lid is about 7.5 lb. Assume the threads must restrain 100 lbs. as the package is transported. Assuming the CV is upright, gravity provides 1g downward acceleration so the nut must restrain at most a net of 100 lbm. (11g - 1g) = 1,000 lbf. The average stress at the minimum cross section due to shock load is 1,000 lb. / 5.14 in² = 195 psi.

4.4 FATIGUE ANALYSIS

For each use of the vessel, the part of the CV equivalent to a bolt is loaded in tension by a torque producing a maximum axial load of 2,000 lb., an average stress of 389 psi and a peak stress (including bending) of 3,563 psi. When the vessel is pressurized to 3.1 psi the peak axial stress is 3,714 psi. This is the peak stress at the undercut which has a stress concentration factor of about 3. Per the Code, paragraph NB-3232.3 (c), the fatigue strength reduction factor for the threads shall not be less than 4 so the fatigue stress on the threads is 3,714 psi. (4/3) = 4,952 psi.

Conservatively ignoring the interplay between the CV and the nut and lid, the stress due to impact during transportation is added to produce a maximum tensile stress of 4,952 psi + 195 psi = 5,147 psi. The thermal expansion reduces the preload so it will not extend the stress range. The range is zero to 5,175 psi and the alternating stress is half of the range or 5,147 psi / 2 = 2,574 psi.

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The threads are evaluated for cyclic service by comparison with the design Curve A on Table I—9.2.2. For alternating stresses below 23,700 psi the allowable number of cycles exceeds 10^{11} . In every case the stress in the nut has been less than in the CV and since the nut material is also austenitic it does not limit fatigue design.

5.0 CONCLUSIONS

Force due to torquing the nut on the vessel was determined. The actual maximum expected internal pressure is low so the torque load produces much higher stresses in the vessel than pressure but the combined effect of torque and actual pressure was less than the conditions including bounding pressure used in the previous evaluation of the vessel design.

Thermal loads were evaluated relative to gasket compression it was shown that gaskets would remain seated through the maximum expected temperature change.

The threaded components of the ES-3100 Containment Vessel were evaluated per ASME Section III requirements and were found to have an allowable fatigue life in excess of 10¹¹ cycles. Since the allowable life of the vessel is limited to a mere 30,000 cycles, the threads do not limit the life of the vessel.

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Load Case: 3 of 4 Maximum Value: 3562.71 lbf/(in*2) Minimum Value: -1243.74 lbf/(in*2)



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Fig. 2 - Axial Stress below the Threads in the Containment Vessel due to Gasket Seating Load

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Fig. 3 –Stress Intensity below the Threads in the Containment Vessel due to 3.1 psi Pressure and Torque Loads

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Appendix 1 - Axial Stresses across Neck of ES-3100 due to Torque

```
Top Section
Current Load Case = 3
Node # 1894 ( X = 0, Y = 3.515, Z = 9.45 )
   Displaced Position : X = 0, Y = 3.51496, Z = 9.44997
   Displacement = DX: 0, DY: -4.55757e-005, DZ: -2.7064e-005, Magnitude: 5.30057e-005
   appears in 2 Elements
   Part: 8
            Element: 1
   Current Result Value: 3476.397428 lbf/(in^2)
   Part: 6 Element: 152
   Current Result Value: 3562.710297 lbf/(in^2)
Node # 1895 ( X = 0, Y = 3.53702, Z = 9.45 )
   Displaced Position : X = 0, Y = 3.53697, Z = 9.44998
   Displacement = DX: 0, DY: -4.64674e-005, DZ: -1.54912e-005, Magnitude: 4.89816e-005
   appears in 4 Elements
   Part: 8
             Element: 1
   Part: 8
            Element: 2
   Current Result Value: 2076.571725 1bf/(in^2)
   Part: 6
             Element: 151
   Part: 6 Element: 152
   Current Result Value: 2150.404851 1bf/(in^2)
Node # 1896 ( X = 0, Y = 3.55903, Z = 9.45 )
   Displaced Position : X = 0, Y = 3.55898, Z = 9.44998
   Displacement = DX: 0, DY: -4.70825e-005, DZ: -1.69066e-005, Magnitude: 5.0026e-005
   appears in 4 Elements
   Part: 8
             Element: 2
   Part: 8
              Element: 3
   Current Result Value: 1338.334401 1bf/(in^2)
```

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Part: 6 Element: 150				
Part: 6 Element: 151				
Current Result Value: 1388	1.726762 lbf/(in^2)			
Node # 1897 ($x = 0, y = 3.58$	545, Z = 9.45)			
Displaced Position : $X = ($), Y = 3.5854, Z =	9.44998		
Displacement = DX: 0, DY:	-4.7175e-005, DZ:	-1.82265e-005, Magnitude:	5.05735e-005	
appears in 4 Elements				
Part: 8 Element: 3				
Part: 8 Element: 4				
Current Result Value: 815.	1134205 lbf/(in^2)			
Part: 6 Element: 149				
Part: 6 Element: 150				
Current Result Value: 856.	.9278605 lbf/(in^2)			
Node # 1898 ($X = 0, Y = 3.61$	186, Z = 9.45)			
Displaced Position : $X = 0$), Y = 3.61182, Z =	9.44998		
Displacement = DX: 0, DY:	-4.7039e-005, DZ:	-1.97662e-005, Magnitude:	5.10232e-005	
appears in 4 Elements				
Part: 8 Element: 4				
Part: 8 Element: 5				
Current Result Value: 422	.3549006 lbf/(in^2)	i de la construcción de la constru		
Part: 6 Element: 148				
Part: 6 Element: 149				
Current Result Value: 454	.1958936 lbf/(in^2))		
Nođe # 1899 (X = 0, Y = 3.64	356, Z = 9.45)			
Displaced Position : $X = 0$), Y = 3.64352, Z =	9.44998		
Displacement = DX: 0, DY:	-4.6803e-005, DZ:	-2.12778e-005, Magnitude:	5.14127e-005	
appears in 4 Elements				
Part: 8 Element: 5				
Part: 8 Element: 6				

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DAC NO. DAC-EA-900000-A007	REVISION NO. 0	COMPUTED C. R. Hammond	CHECKED BY M. L. Goins
Current Result Value: 60.9	2361234 lbf/(in*2)		
Part: 6 Element: 147			
Part: 6 Element: 148			
Current Result Value: 92.8	7579812 lbf/(in^2)		
Node # 1900 ($X = 0$, $Y = 3.675$	26, Z = 9.45)		
Displaced Position : $X = 0$, Y = 3.67522, Z =	9.44998	
Displacement = DX: 0, DY:	-4.64719e-005, DZ:	-2.30637e-005, Magnitude	: 5.18804e-005
appears in 4 Elements			
Part: 6 Element: 145		•	
Part: 6 Element: 147			
Current Result Value: -276	.2872177 lbf/(in^2	•)	
Part: 8 Element: 6			
Part: 8 Element: 7			
Current Result Value: -291	.8618414 lbf/(in^2)	
Node # 1901 (X = 0, Y = 3.712	263, Z = 9.45)		
Displaced Position : $X = 0$, Y = 3.71258, Z =	9.44997	
Displacement = DX: 0, DY:	-4.6099e-005, DZ:	-2.48703e-005, Magnitude:	5.23798e-005
appears in 4 Elements			
Part: 8 Element: 7			
Part: 8 Element: 8			
Current Result Value: -690	.1878235 1bf/(in^2	:)	
Part: 6 Element: 145			
Part: 6 Element: 146			
Current Result Value: -699	.5449043 lbf/(in^2	:	
Node # 1902 ($X = 0$. $Y = 3.75$.	z = 9.45		
Displaced Position : $X = 0$, Y = 3.74996, Z =	9.44997	
Displacement = DY: 0. DV.	-4.48856e-005 DZ-	-2.93433e-005. Magnitude	: 5.3626-005
annears in 2 Flements			. 5150206-005
appears in 4 Stements			

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Current Result Value: -1189.038154 lbf/(in^2)

Part: 6 Element: 146

Current Result Value: -1243.744425 lbf/(in*2)

Lower Section

Current Load Case = 3

```
Node # 1718 ( X = 0, Y = 3.4065, Z = 8.96 )
```

Displaced Position : X = 0, Y = 3.40646, Z = 9.03102

```
Displacement = DX: 0, DY: -3.86154e-005, DZ: 0.0710243, Magnitude: 0.0710243
```

```
appears in 2 Elements
```

```
Part: 6 Element: 1
```

```
Current Result Value: 2381.970074 1bf/(in^2)
```

```
Part: 3 Element: 713
```

Current Result Value: 2573.760605 1bf/(in^2)

```
Node # 1719 ( X = 0, Y = 3.43091, Z = 8.96 )
```

```
Displaced Position : X = 0, Y = 3.43087, Z = 9.03103
```

```
Displacement = DX: 0, DY: -3.82805e-005, DZ: 0.071027, Magnitude: 0.071027
```

```
appears in 4 Elements
```

```
Part: 6 Element: 1
```

```
Part: 6 Element: 2
```

Current Result Value: 1429.725908 lbf/(in^2)

Part: 3 Element: 712

Part: 3 Element: 713

Current Result Value: 1507.238598 1bf/(in^2)

```
Node # 1720 ( X = 0, Y = 3.45532, Z = 8.96 )
```

```
Displaced Position : X = 0, Y = 3.45529, Z = 9.03102
```

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DAC NO. DAC-EA-900000-A007	REVISION NO. 0	COMPUTED C. R. Hammond	CHECKED BY M. L. Goins
Displacement = DX: 0, DY:	-3.93058e-005, DZ	: 0.0710167, Magnitude: 0.	0710167
appears in 4 Elements			
Part: 3 Element: 711			
Part: 3 Element: 712			
Current Result Value: 1015	.779644 lbf/(in*2))	
Part: 6 Element: 2			
Part: 6 Element: 3			
Current Result Value: 1035	.108104 lbf/(in*2)	I	
Node # 1721 (X = 0, Y = 3.484	62, Z = 8.95)		
Displaced Position : $X = 0$, Y = 3.48458, Z =	= 9.03103	
Displacement = DX: 0, DY:	-3.78762e-005, DZ	: 0.0710297, Magnitude: 0.	0710297
appears in 4 Elements			
Part: 3 Element: 710			
Part: 3 Element: 711			
Current Result Value: 699.	5787633 lbf/(in^2))	
Part: 6 Element: 3			
Part: 6 Element: 4			
Current Result Value: 752.	6151572 lbf/(in*2))	
Node # 1722 (X = 0, Y = 3.513	91, Z = 8.96)		
Displaced Position : $X = 0$, Y = 3.51388, Z :	9.03103	
Displacement = DX: 0, DY:	-3.73704e-005, DZ	: 0.0710323, Magnitude: 0.	0710323
appears in 4 Elements			
Part: 3 Element: 707			
Part: 3 Element: 710			
Current Result Value: 479.	8616501 lbf/(in*2))	
Part: 6 Element: 4			
Part: 6 Element: 5			
Current Result Value: 524.	8054716 lbf/(in*2))	
Node # 1723 (X = 0, Y = 3.549	907, z = 8.96		

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DAC NO. DAC-EA-900000-A007	REVISION NO. 0	COMPUTED C. R. Hammond	CHECKED BY M. L. Goins	
Displaced Position : X = 0,	, Y = 3.54903, Z =	9.03101		
Displacement = DX: 0, DY: •	-3.89625e-005, DZ:	0.0710096, Magnitude: 0.	0710096	
appears in 4 Elements				
Part: 3 Element: 704				
Part: 3 Element: 707				
Current Result Value: 286.3	7099034 lbf/(in*2)			
Part: 6 Element: 5				
Part: 6 Element: 6				
Current Result Value: 319.4	4018001 lbf/(in^2)			
Node # 1724 ($X = 0$, $Y = 3.584$	22, Z = 8.96)			
Displaced Position : $X = 0$,	, Y = 3.58418, Z =	9.03101		
Displacement = DX: 0, DY: •	-3.94127e-005, DZ:	0.071011, Magnitude: 0.0	71011	
appears in 4 Elements				
Part: 3 Element: 704				\subseteq
Part: 3 Element: 705				
Current Result Value: 104.2	2072763 lbf/(in*2)			
Part: 6 Element: 6				
Part: 6 Element: 7				
Current Result Value: 126.(0936862 lbf/(in^2)			
Node # 1725 ($X = 0, Y = 3.625$	67, Z = 8.96)			
Displaced Position : $X = 0$,	, Y = 3.62563, Z =	9.03101		
Displacement ≈ DX: 0, DY: -	-3.94951e-005, DZ:	0.0710126, Magnitude: 0.	0710126	
appears in 4 Elements				
Part: 6 Element: 7				
Part: 6 Element: 8				
Current Result Value: -69.6	55167919 lbf/(in^2)		
Part: 3 Element: 705				
Part: 3 Element: 706				
Current Result Value: -87.3	34285327 1bf/(in^?)		2

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```
Node # 1726 ( X = 0, Y = 3.66711, Z = 8.96 )
```

```
Displaced Position : X = 0, Y = 3.66707, Z = 9.03101
   Displacement = DX: 0, DY: -3.94338e-005, DZ: 0.0710146, Magnitude: 0.0710146
   appears in 4 Elements
   Part: 6 Element: 8
   Part: 6 Element: 9
   Current Result Value: -274.1379622 lbf/(in^2)
   Part: 3
             Element: 706
   Part: 3 Element: 708
   Current Result Value: -286.8211743 lbf/(in^2)
Node # 1727 ( X = 0, Y = 3.70856, Z = 8.96 )
   Displaced Position : X = 0, Y = 3.70852, Z = 9.03102
   Displacement = DX: 0, DY: -3.91153e-005, DZ: 0.0710191, Magnitude: 0.0710191
   appears in 4 Elements
   Part: 6
            Element: 9
   Part: 6 Element: 10
   Current Result Value: -489.6421277 1bf/(in*2)
   Part: 3 Element: 708
   Part: 3
            Element: 709
   Current Result Value: -498.9915546 lbf/(in^2)
Node # 1728 ( X = 0, Y = 3.75, Z = 8.96 )
   Displaced Position : X = 0, Y = 3.74996, Z = 9.03102
   Displacement = DX: 0, DY: -3.89012e-005, DZ: 0.0710215, Magnitude: 0.0710215
   appears in 2 Elements
   Part: 6
            Element: 10
   Current Result Value: -726.5076374 lbf/(in*2)
   Part: 3 Element: 709
   Current Result Value: -737.209287 1bf/(in*2)
```

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Appendix 1 - Axial stress across neck of ES-3100 CV due to torque

Top section - Part 8

Y, in.	Sigma ZZ, psi	Delta R, in.	Force, lb.	Force (hard way), lb.
3.515	3476.397428	0.01101	845.3215421	846.6454383
3.53702	2076.571725	0.022015	1015.974973	1015.974255
3.55903	1338.334401	0.024215	724.7039558	724.9284512
3.58545	815.1134205	0.026415	485.0563535	485.0560153
3.61186	422.3549006	0.029055	278.4897363	278.5917067
3.64356	60.92361234	0.0317	44.21307309	44.21307309
3.67526	-291.8618414	0.034535	-232.7580525	-232.8478243
3.71263	-690.1878235	0.03737	-601.6610939	-601.6610939
3.75	-1189.038154	0.018685	-523.4799217	-522.1757588
		Sum	2035.860566	2038.724263
Lower section - Part 3				
3.4065	2573.760605	0.012205	672.3481194	673.5525828
3.43091	1507.238598	0.02441	793.1201445	793.1201445
3.45532	1015.779644	0.026855	592.2332744	592.4428079
3.48462	699.5787633	0.029295	448.7096535	448.7093316
3.51391	479.8616501	0.032225	341.4125422	341.5551249
3.54907	286.7099034	0.035155	224.7626947	224.7625364
3.58422	104.2072763	0.0383	89.88171407	89.92121045
3.62567	-87.34285327	0.041445	-82.46461971	-82.46456285
3.66711	-286.8211743	0.041445	-273.8969268	-273.8971135
3.70856	-498.9915546	0.041445	-481.8928886	-481.8925638
3.75	-737.209287	0.02072	-359.9081529	-358.9138467
		Sum	1964.305555	1966.895652

Section difference =

0.036518771


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Appendix 2 – Finite Element Data

Summary

Description

Thread Analysis

Model Information

Analysis Type - Static Stress with Linear Material Models Units - English (in) - (lbf, in, s, deg F, deg R, V, ohm, A, in*lbf) Model location - C:\ALGOR12\es3100CV1

Analysis Parameters Information

Load Case Multipliers

Static Stress with Linear Material Models may have multiple load cases. This allows a model to be analyzed with multiple loads while solving the equations a single time. The following is a list of load case multipliers that were analyzed with this model.

Load Case	Pressure/ Surface Forces	Acceleration/ Gravity	Displaced Boundary	Thermal	Voltage
1	1	0	1	0	0
2	0	0	1	0	0
3	0	0	0	1	0
4	0.0305	0	0	1	0

Multiphysics Information

Default Nodal Temperature	70°F
Source of Nodal Temperature	None
Time step from Heat Transfer Analysis	Last

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Processor Information

Type of Solver	Sparse
Disable Calculation and Output of Strains	No
Calculate Reaction Forces	Yes
Invoke Banded Solver	Yes
Avoid Bandwidth Minimization	No
Stop After Stiffness Calculations	No
Displacement Data in Output File	No
Stress Data in Output File	No
Equation Numbers Data in Output File	No
Element Input Data in Output File	No
Nodal Input Data in Output File	No
Centrifugal Load Data in Output File	No

Part Information

Part ID	Part Name	Element Type	Material Name
1	Plate & shell	2-D	[Customer Defined] (Part 1)
2	Bottom corner	2-D	[Customer Defined] (Part 2)
3	Top transition	2-D	[Customer Defined] (Part 3)
4	Outer O-ring	2-D	[Customer Defined] (Part 4)
<u>5</u>	Inner O-ring	2-D	[Customer Defined] (Part 5)
<u>6</u>	Top flange neck	2-D	[Customer Defined] (Part 6)
<u>8</u>	Thread region	2-D	[Customer Defined] (Part 8)

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Element Properties used for:

- Plate & shell
- Bottom corner
- Top transition
- Thread region

Element Type	2-D
Geometry Type	Axisymmetric
Material Model	Isotropic
Thickness	1 in
Stress Free Reference Temperature	70°F
Principle Axes Transformational Angle	0°
Nodal Order Method	Default
Nodal Order Y Coordinate	0 in
Nodal Order Z Coordinate	0 in

Element Properties used for:

- Outer O-ring
- Inner O-ring

Element Type	2-D
Geometry Type	Axisymmetric
Material Model	Isotropic
Thickness	1 in
Stress Free Reference Temperature	0°F
Principle Axes Transformational Angle	0°
Nodal Order Method	Default
Nodal Order Y Coordinate	0 in
Nodal Order Z Coordinate	0 in

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Element Properties used for:

• Top flange neck

Element Type	2-D
Geometry Type	Axisymmetric
Material Model	Orthotropic
Thickness	1 in
Stress Free Reference Temperature	170°F
Principle Axes Transformational Angle	0°
Nodal Order Method	Default
Nodal Order Y Coordinate	0 in
Nodal Order Z Coordinate	0 in

Material Information

[Customer Defined] (Part 1) - 2-D

Material Model	Standard
Material Source	Not Applicable
Material Source File	
Date Last Updated	2004/09/28-14:35:06
Material Description	Customer defined material properties
Mass Density	7.50e-4 lbf*s^2/in/in ³
Modulus of Elasticity	27e6 lbf/in ²
Poisson's Ratio	0.3
Thermal Coefficient of Expansion	9.2e-6 1/°F
Shear Modulus of Elasticity	10384615 lbf/in ²

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[Customer Defined] (Part 2) - 2-D

Material Model	Standard
Material Source	Not Applicable
Material Source File	
Date Last Updated	2004/09/28-14:36:43
Material Description	Customer defined material properties
Mass Density	7.50e-4 lbf*s^2/in/in ³
Modulus of Elasticity	27e6 lbf/in ²
Poisson's Ratio	0.3
Thermal Coefficient of Expansion	9.2e-6 1/°F
Shear Modulus of Elasticity	10384615 lbf/in ²

[Customer Defined] (Part 3) - 2-D

Material Model	Standard
Material Source	Not Applicable
Material Source File	
Date Last Updated	2004/09/28-14:38:39
Material Description	Customer defined material properties
Mass Density	7.50e-4 lbf*s^2/in/in ³
Modulus of Elasticity	27e6 lbf/in ²
Poisson's Ratio	0.30
Thermal Coefficient of Expansion	9.2e-6 1/°F
Shear Modulus of Elasticity	10384615 lbf/in ²

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[Customer Defined] (Part 4) - 2-D

Material Model	Standard
Material Source	Not Applicable
Material Source File	
Date Last Updated	2004/09/28-14:39:52
Material Description	Customer defined material properties
Mass Density	0 lbf*s^2/in/in ³
Modulus of Elasticity	1321 lbf/in²
Poisson's Ratio	0
Thermal Coefficient of Expansion	0 1/°F
Shear Modulus of Elasticity	660.5 /²

[Customer Defined] (Part 5) - 2-D

Material Model	Standard
Material Source	Not Applicable
Material Source File	
Date Last Updated	2004/09/28-14:40:41
Material Description	Customer defined material properties
Mass Density	0 lbf*s^2/in/in ³
Modulus of Elasticity	1122 lbf/in ²
Poisson's Ratio	0
Thermal Coefficient of Expansion	0 1/°F
Shear Modulus of Elasticity	561. /2

^{JOB} Fatigue Analysis of ES-3100 C Normal Conditions of Use	V Threads under	DATE 16 February 2005	SHEET 27 of 29
DAC NO. DAC-EA-900000-A007	REVISION NO. 0	COMPUTED C. R. Hammond	CHECKED BY M. L. Goins

[Customer Defined] (Part 6) - 2-D

Material Model	OrthotropicTempDep
Material Source	Not Applicable
Material Source File	
Date Last Updated	2004/10/14-14:27:16
Material Description	Customer defined material properties
Mass Density	7.50e-4 lbf*s^2/in/in ³
Index 1 - Temperature	170 °F
Index 1 - E1	27e6 lbf/in ²
Index 1 - E2	27e6 lbf/in ²
Index 1 - E3	27e6 lbf/in ²
Index 1 - V12	.3
Index 1 - V13	.3
Index 1 - V23	.3
Index 1 - G12	10384615 lbf/in ²
Index 1 - G13	10384615 lbf/in ²
Index 1 - G23	10384615 lbf/in ²
Index 1 - Alpha 1	0 1/°F
Index 1 - Alpha 2	1.45e-3 1/°F
Index 1 - Alpha 3	0 1/°F

^{JOB} Fatigue Analysis of ES-3100 C Normal Conditions of Use	V Threads under	DATE 16 February 2005	SHEET 28 of 29	\smile
DAC NO. DAC-EA-900000-A007	REVISION NO. 0	COMPUTED C. R. Hammond	CHECKED BY M. L. Goins	

[Customer Defined] (Part 8) - 2-D

Material Model	Standard
Material Source	Not Applicable
Material Source File	
Date Last Updated	2004/09/28-14:43:25
Material Description	Customer defined material properties
Mass Density	7.50e-4 lbf*s^2/in/in ³
Modulus of Elasticity	27e6 lbf/in ²
Poisson's Ratio	0.30
Thermal Coefficient of Expansion	9.2e-6 1/°F
Shear Modulus of Elasticity	10384615 lbf/in ²

Processor Output

Processor Summary

```
ALGOR (R) Static Stress with Linear Material Models
Version 16.00-WIN 29-SEP-2004
Copyright (c) 1984-2004 ALGOR, Inc. All rights reserved.
```

```
DATE: FEBRUARY 16, 2005
TIME: 07:55 AM
```

INPUT MODEL: C:\ALGOR12\es3100CV1

```
PROGRAM VERSION: 16000001
ALG.DLL VERSION: 13240000
AlgConfig.DLL VERSION: 15000000
agsdb_ar.DLL VERSION: 14000004
amgsolve.DLL VERSION: 03220000
```

Linear Stress

1**** CONTROL INFORMATION

number	of	node points	(NUMNP)	=	2061
number	of	element types	(NELTYP)	=	8
number	of	load cases	(LL)	=	4

No	tigue Analysi ormal Conditi	is of ES-3100 C ions of Use	V Threads une	der DATE	^E 16 F	February 2005	5	SHEET	29 of 29	
DAC NO.	DAC-EA-9	00000-A007	REVISION NO.	0 сом	PUTED	C. R. Hammo	ond	CHECKED	^{BY} M. L. Goin	;
	number o	f fremencie	25	(NF)	-	· · · · · · · · · · · · · · · · · · ·				
	analycic	type code		(NE)	_		ň			
	analysis	s per block		(KEOB)	-		0			
	bandwidt	b minimizati	ion flag	(MINEND)	_		õ			
	gravitat	ional consta	ont Ling	(GRAV)	_	3 86401	FTU2			
	number o	f equations		(NEQ)	=	5.0040	4092			
****	PRINT OF	NODAL DATA	SUPPRESSE	D						
****	PRINT OF	EQUATION N	MBERS SUP	PRESSED						
****	PRINT OF	TYPE-4 ELEN	IENT DATA	SUPPRESSEI	2					
****	PRINT OF	TYPE-4 ELEN	IENT DATA	SUPPRESSEI)					
****	PRINT OF	TYPE-4 ELEN	IENT DATA	SUPPRESSEI)					
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****	PRINT OF	TYPE-7 ELEN	IENT DATA	SUDDBESSEI	•					
				0011100000	,					
****	Hard dis	k file size	informati	on for pro	cess	or:				
****	Hard dis Availabl	k file size e hard disk	informationspace on the space o	on for pro	cess	or: = 3849.8	848 m	legabyt	es	
**** 1****	Hard dis Availabl NODAL LO	k file size e hard disk ADS (STATIC)	informations space on of OR MASSE	on for pro current dr S (DYNAMIC	cess ive : 2)	or: = 3849.8	848 n	negabyt	es	
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**** 1**** NO NUM	Hard dis Availabl NODAL LO DE LOAD BER CASE	k file size e hard disk ADS (STATIC) X-AXIS FORCE	informations space on of OR MASSE Y-AXIS FORCE	on for pro current dr S (DYNAMIC Z-AXI FORC	cess ive : C) CS CE	or: = 3849.8 X-AXIS MOMENT	848 m Y M	negabyt Z-AXIS IOMENT	es Z-AXIS MOMENT	
**** 1**** NO NUM 1	Hard dis Availabl NODAL LO DE LOAD BER CASE 685 1	k file size e hard disk ADS (STATIC) X-AXIS FORCE 0.000E+00	information space on of OR MASSE Y-AXIS FORCE 0.000E+00	on for pro current dr S (DYNAMIC Z-AXI FORC -6.362E+(cive cive c) cs cs cs cs cs cs cs cs cs cs cs cs cs	or: = 3849.8 X-AXIS MOMENT .000E+00	848 m Y M 0.00	negabyt Z-AXIS MOMENT 00E+00	z-AXIS MOMENT 0.000E+00	
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**** NO NUM 1 1 1 1	Hard dis Availabl NODAL LO DE LOAD BER CASE 685 1 685 4 686 1 686 4 ELEMENT load cas	k file size e hard disk ADS (STATIC) X-AXIS FORCE 0.000E+00 0.000E+00 0.000E+00 0.000E+00 LOAD MULTIPI e case 	informati space on OR MASSE Y-AXIS FORCE 0.000E+00 0.000E+00 0.000E+00 CLIERS A cas E+00 0.00	on for pro current dr S (DYNAMIC Z-AXI FORC -6.362E+(-1.943E-(-6.424E+(-1.962E-(e B ca 	cive : cive : c) cs cs cs cs cs cs cs cs cs cs cs cs cs	or: = 3849.1 X-AXIS MOMENT .000E+00 .000E+00 .000E+00 .000E+00 .000E+00	848 m Y 0.00 0.00 0.00 0.00 D E+00	-AXIS COMENT 00E+00 00E+00 00E+00 00E+00 00E+00 00E+00	Z-AXIS MOMENT 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00	
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