A AREVA

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435-B

TRANSPORT PACKAGE

Safety Analysis Report

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1.0 GENERAL INFORMATION

This section presents a general introduction and description of the 435-B package. The 435-B package is used to transport radioactive sources in the Long Term Storage Shield (LTSS) or shielded devices containing their sources. This application seeks authorization of the 435-B package as a Type B(U)–96 shipping container in accordance with the provisions of Title 10, Part 71 of the Code of Federal Regulations [1]. The packaging also meets the requirements of TS-R-1 [2].

The major components comprising the package are discussed in Section 1.2.1, *Packaging*, and illustrated in Figure 1.2-1 through Figure 1.2-8. A glossary of terms is presented in Appendix 1.3.2, *Glossary of Terms and Acronyms*. Detailed drawings of the package design are presented in Appendix 1.3.3, *Packaging General Arrangement Drawings.*

1.1 Introduction

The **Model No. 435-B** package has been developed to transport radioactive sealed sources in the LTSS, as well as shielded irradiation devices (shielded devices) containing sources. The LTSS may transport gamma sources (the majority of sources in the LTSS), beta sources, and very small neutron sources. Fissile materials such as Pu-239 are limited to quantities of less than 15 grams. Thus the payload is fissile exempt per the provisions of §71.15(b) [1]. All shielded devices contain gamma sources only. The 435-B package does not supply significant biological shielding. The primary shielding is provided by the lead shielding in the LTSS or in the shielded devices. All sources are sealed. The 435-B package provides leaktight containment of the radioactive contents under all NCT and HAC.[1]

The packaging consists of a base, a bell cover which is bolted to the base, and an internal lodgment which supports the LTSS. Shielded devices are placed in an inner container for shipment. The package uses conventional materials and metalworking techniques. When loaded and prepared for transport, the 435-B package is 83 inches tall, 70 inches in diameter (over the lower impact limiter), and weighs a maximum of 10,100 lb. The package is designed to be transported singly, with its longitudinal axis vertical, by ground, air, or by water in non-exclusive use.

Since all payloads transported in the 435-B are either non-fissile or fissile-exempt, the criticality safety index does not apply.

An isometric view of the 435-B packaging is shown in Figure 1.1-1. Cross sectional views of the package configured with a LTSS payload and a shielded device payload are shown in Figure 1.1-2 and 1.1-3, respectively.

[1] Leaktight is defined as a maximum of 1×10^{-7} reference–cm^3/sec, air leakage per ANSI N14.5–1997 [3].

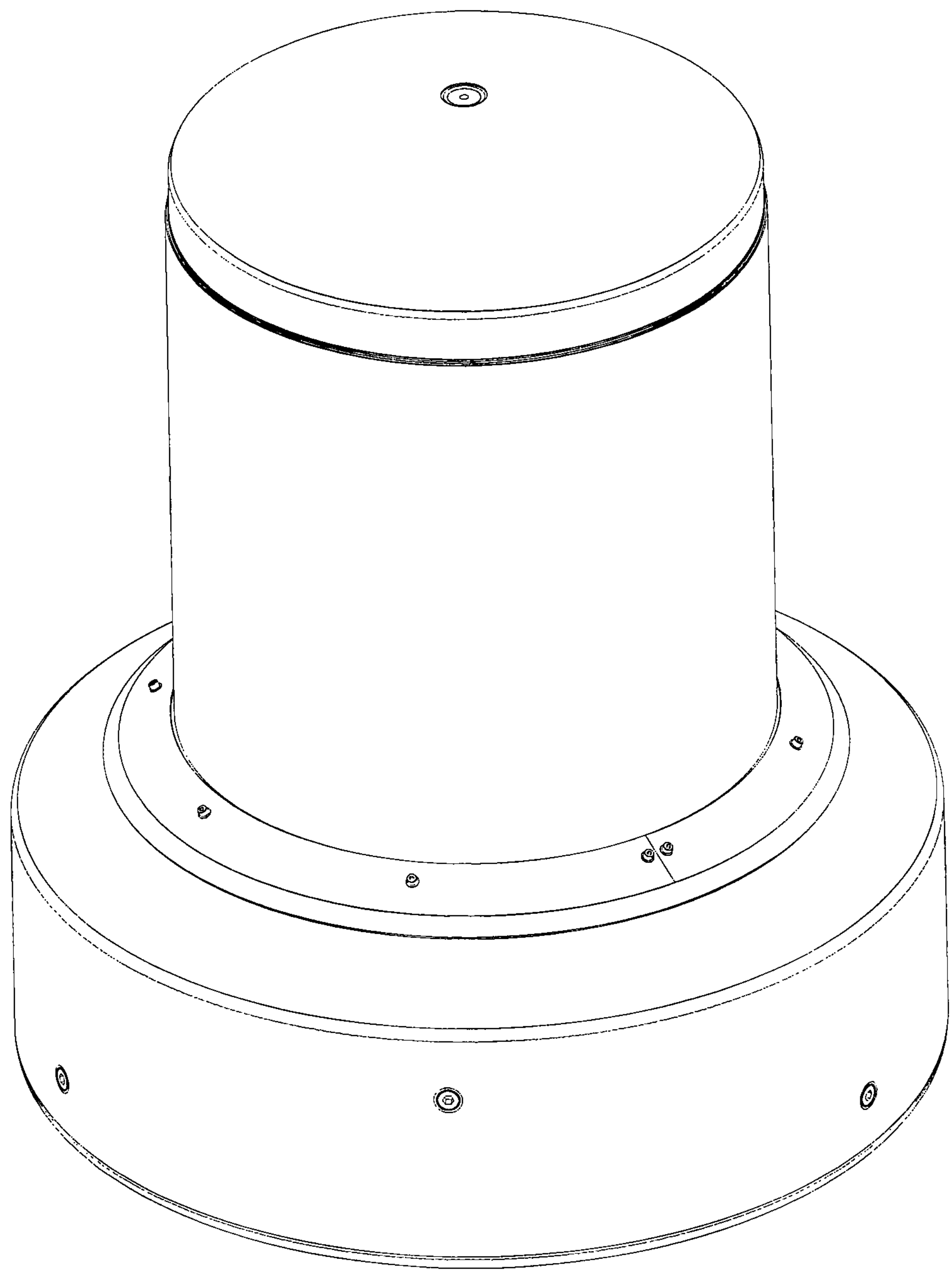

Figure 1.1-1 – 435-B Packaging

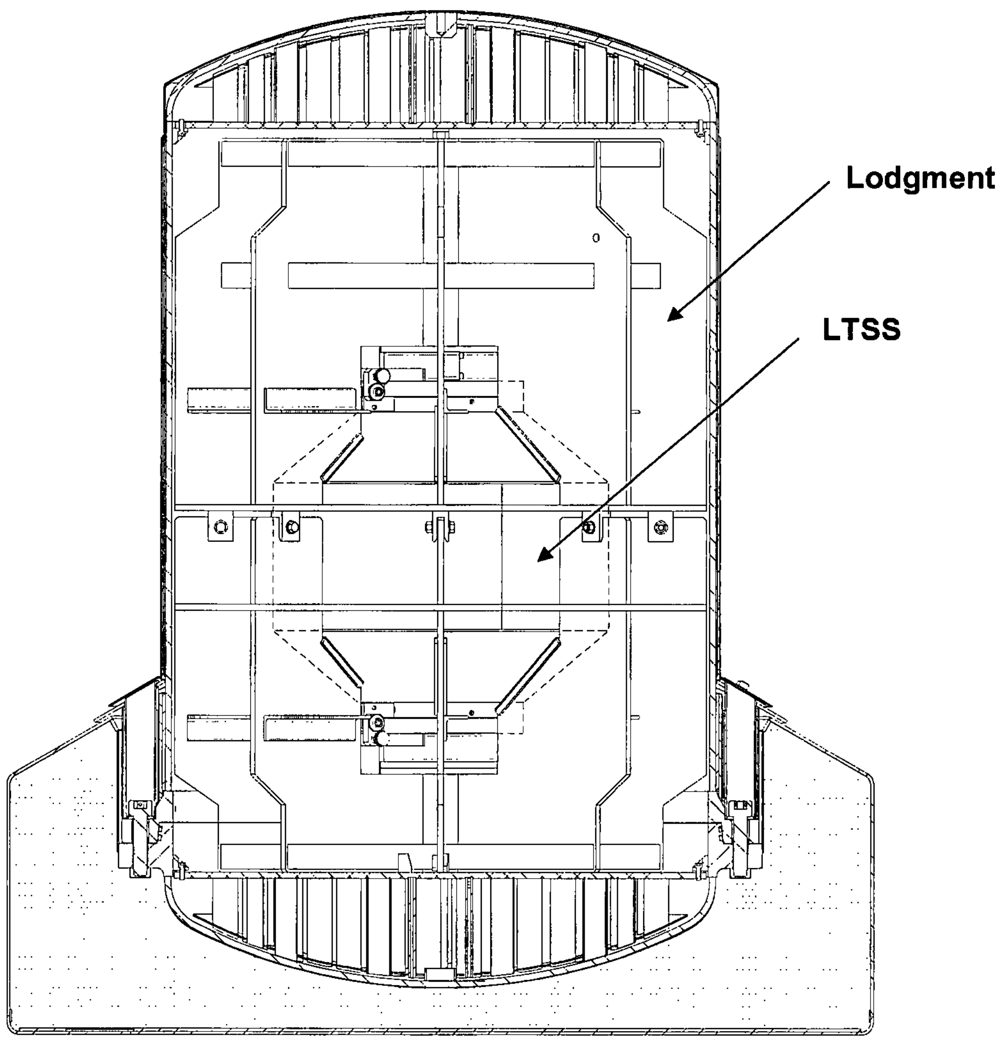

Figure 1.1-2 – 435-B Package With LTSS

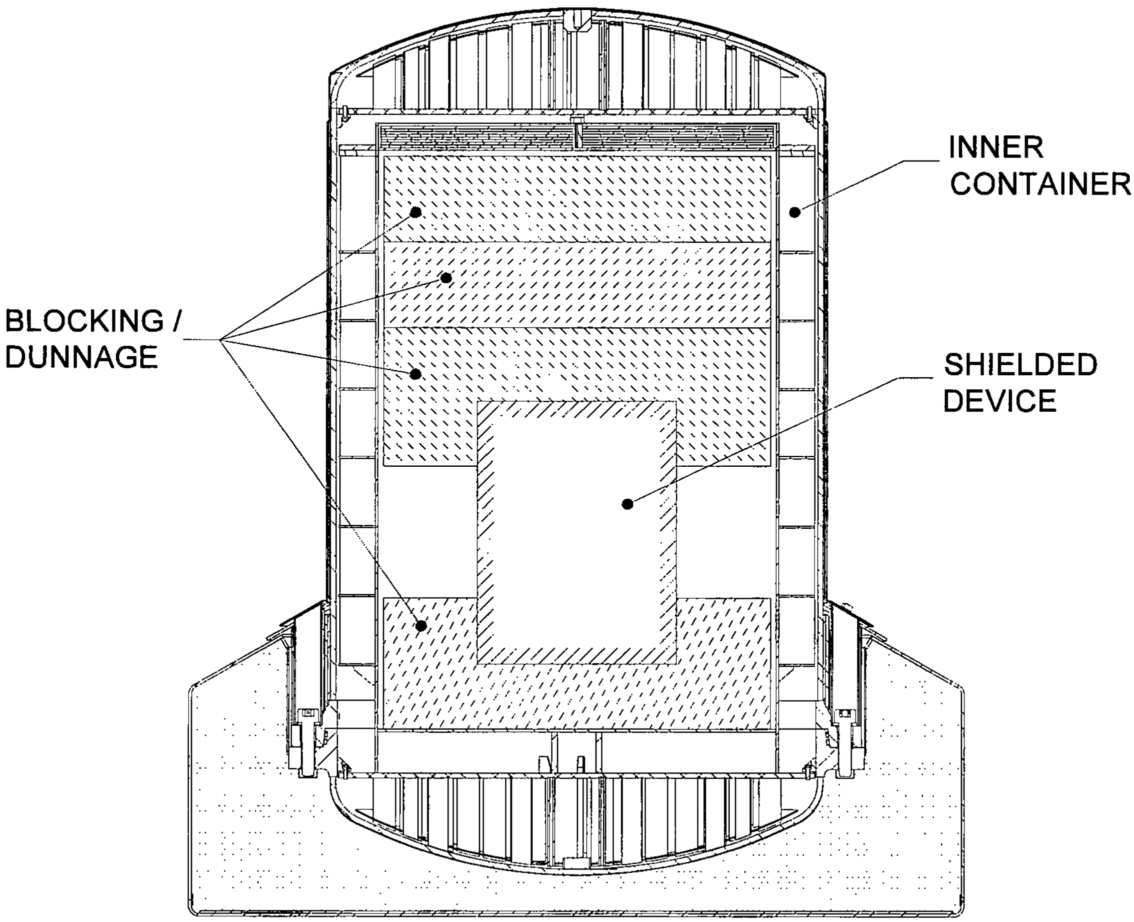

Figure 1.1-3 – 435-B Package With Shielded Device

1.2 Package Description

This section presents a basic description of the 435-B package components and construction. In the following, drawing references are to the general arrangement drawings provided in Appendix 1.3.3, *Packaging General Arrangement Drawings*.

1.2.1 Packaging

The 435-B package (drawing 1916-01-01-SAR) consists of a lower body assembly or base, including the impact limiter containing polyurethane foam, an upper body assembly or bell, two internal impact limiter assemblies, 24 closure bolts, the LTSS payload with a lodgment (drawing 1916-01-02-SAR) to support the LTSS within the package, or a shielded device payload inside an inner container (drawing 1916-01-03-SAR). The package is primarily of welded construction, using Type 304 austenitic stainless steel. The lodgment is made from welded structural aluminum. The LTSS is made from Type 304 stainless steel and lead. The inner container is made of Type 304 stainless steel. These components will now be discussed in detail.

1.2.1.1 Containment Vessel

The 435-B containment vessel consists of a cylindrical body shell with an inner diameter of 43.5 inches and two torispherical heads, all ½ inches thick. The torispherical inner radius is equal to 43.5 inches, and the knuckle radius is equal to 3.5 inches. The vessel is made from ASTM Type 304 stainless steel and includes a brass vent port plug. The upper and lower portions of the vessel connect at a heavy flange joint, located at the lower end of the cylindrical shell. The flanges are 2 inches thick and are connected using 24, 1-1/4-7 UNC bolts made of ASTM A320, L43 material. Each of these components (not including the bolts) may be made from separate pieces of material and joined using full penetration welds. All butt welds in the containment boundary are full-penetration and radiograph inspected.

The closure seal is a 3/8-inch cross-sectional diameter O-ring made of butyl rubber. A vent port, sealed with a butyl sealing washer and threaded brass plug, is located in a block welded to the upper flange (see Section M-M on sheet 6). The block is attached using a circumferential 3/16-inch (non-containment) fillet weld, and the containment is made by a circumferential 1/8-inch fillet weld. The machined opening on the lower flange face (containment) is closed using a full depth groove weld of minimum 0.25-inch thickness. Both of these containment welds are liquid penetrant inspected on the final pass. The seal test port block (not part of containment) is identically configured. The elastomer material of the containment seal and test seal O-rings, and the vent port and seal test port sealing washers, is made from Rainier Rubber R-0405-70, and subject to the tests given in Section 8.1.5.2, *Butyl Rubber O-rings*. The 435-B containment boundary consists of the following components:

- The upper torispherical head and upper body assembly lifting boss
- The cylindrical side shell
- The upper flange (attached to the upper body assembly)
- The lower flange (attached to the lower body assembly)
- The lower torispherical head
- The containment elastomer O-ring seal

- The vent port block in the upper flange including brass plug and elastomer sealing washer

A sketch of the containment vessel is shown in Figure 1.2-1. Additional detail on the containment vessel and other packaging components is given below, and depicted in Figure 1.2-2 through Figure 1.2-7.

1.2.1.2 Lower Body Assembly (Base)

The lower body assembly consists of the lower torispherical head, lower flange, lower internal impact limiter, and integral external impact limiter, and is depicted as Assembly A2 on drawing 1916-01-01-SAR. All material conforms to ASTM A240, Type 304 stainless steel unless otherwise specified.

The lower torispherical head is formed from ½-inch thick plate, and is connected to the lower flange using a full penetration weld. The lower flange is made from ASTM A182, Grade F304 forging, or ASTM A240, Type 304 plate material. The flange has an inner diameter of 43-1/4 inches, an outer diameter of 52.0 inches, and is 2.0 inches thick. An extension of the flange supports the containment closure and test O-ring grooves. The O-rings are arranged on a 5° taper, are bore-type seals, and interface with a recess in the upper flange.

The external impact limiter is integral with, and permanently connected to the lower body. The inner cylindrical shell of the impact limiter is 0.12 inches thick and is welded to the outer edge of the lower flange. The outer shell (tapered top, outer cylinder, and flat bottom) is ¼ inches thick. The top plate of the impact limiter is tapered at 30° from the horizontal, and includes a short lead-in chamfer to guide the upper body assembly into place. The outer cylindrical shell is 70 inches in diameter and approximately 21 inches tall and features six fire-consumable plastic plugs designed to relieve pressure in the HAC fire event. The inside surface of the bottom shell is covered with a ¼-inch thick layer of refractory insulation paper to reduce heat flow into the flat bottom from the HAC fire event. The cavity of the limiter is filled with 15 lb/ft^3 polyurethane foam. The foam is rigid, closed–cell, and is poured in place.

The lower flange features threaded holes for the closure bolts and two alignment pins. These holes may be optionally fitted with alloy steel thread inserts or helically coiled stainless steel thread inserts. On the underside (foam side) of the flange, each hole is covered with a thin cross-section stainless steel cup, tack welded in place and sealed using RTV sealant. The cups provide clearance for the ends of the closure bolts and seal the foam cavity.

The lower internal impact limiter is described in Section 1.2.1.4, *Internal Impact Limiters*.

1.2.1.3 Upper Body Assembly (Bell)

The upper body assembly consists of the upper torispherical head, cylindrical shell, upper flange, vent and test port blocks, upper internal impact limiter, dual side thermal shield, head thermal shield, and the closure bolt access tube structure, and is depicted as Assembly A3 on drawing 1916-01-01-SAR. All material conforms to ASTM A240, Type 304 stainless steel unless otherwise specified.

The upper torispherical head and cylindrical shell are formed from ½-inch thick plate, having a minimum yield strength of 40 ksi and a minimum ultimate tensile strength of 80 ksi. The upper flange is made from ASTM A182, Grade F304 forging, or ASTM A240, Type 304 plate material. The flange has an inner diameter of 43-1/4 inches, an outer diameter of 51.5 inches, and is 2.0 inches thick. The inner diameter of the cylindrical shell is 43.5 inches. A 2.5-inch diameter, 2-inch thick lifting boss, containing a 3/4-10 UNC threaded hole, is located in the center of the torispherical head. This hole may be optionally fitted with an alloy steel thread insert or with a helically coiled stainless steel thread insert. The head, lifting boss, cylindrical shell, and flange are connected using full penetration welds. The vent and test port blocks are made from A276 or A479, Type 304 stainless steel.' Their configuration is discussed in Section 1.2.1.1, *Containment Vessel*.

At the lower end of the upper body assembly is a structure consisting of tubes and shells which provides access to the closure bolts and the vent port and seal test port while also protecting these components from HAC puncture bar impact or excessive heat input from the HAC fire event. A detail view of this area is shown in Detail D, Section B-B, and Section C-C on sheet 6. An isometric cut-away view is given on sheet 7. There are 24 evenly spaced, 2.5-inch O.D. × 0.12-inch wall thickness bolt access tubes made from ASTM A249 or A269, Type TP304 stainless steel. In addition, there are two more tubes, 90° apart, and located halfway between bolt access tubes, which provide access to the vent port and seal test port. Both ports are closed with threaded plugs made of ASTM B16 brass and sealed with butyl rubber sealing washers. A port insulation cylinder (Assembly A5 on sheet 6) is used in each port access tube to prevent excessive heat input from the HAC fire event. Detail views of the vent port and test port are given in Section M-M and Section N-N, respectively, on sheet 6.

The top ends of the tubes are held in place by a ¼-inch thick tube sheet, oriented at a slope to match the upper surface of the external impact limiter. The outside edge of the tube sheet forms a skirt to cover the gap between the upper and lower body assemblies. This prevents the entry of precipitation and, in the HAC fire event, the entry of excessive heat. The tubes pass through the tube sheet and are fillet welded to the sheet all around each tube. The lower ends of the tubes are partially welded to the flange, and the remaining joint which is inaccessible for welding is sealed with RTV sealant. The upper end of the sloped tube sheet is connected to the cylindrical side wall of the package using a partial penetration weld as shown in Detail U on sheet 5. The outer shell of the tube region consists of a 0.12-inch thick sheet, welded to the outer top edge of the flange on the lower end, and to the underside of the tube sheet on the upper end. The area of the containment wall adjacent to the tubes is covered with two, ¼-inch thick layers of refractory insulation paper. The paper is retained using a formed sheet of 0.048-inch thick stainless steel, which is held in place using tack welds. Machined blocks of 30 lb/ft^3 polyurethane foam are located between the tubes.

The top openings of the tubes are covered by a 0.12-inch thick stainless steel rain shield cover. The rain shield is formed in two halves and attached to bolting bosses located in the tube sheet using 5, ½-13 UNC stainless steel bolts (total of 10 bolts). These holes may be optionally fitted with alloy steel thread inserts or helically coiled stainless steel thread inserts. The rain shield also retains the port insulation cylinders used in the vent and seal test ports.

Between the top of the tube sheet and approximately the location of the weld between the torispherical head and sidewall, is located a dual side thermal shield consisting of two gaps and two sheets, as depicted in Detail R and Detail U on sheet 5. The inner sheet is 0.060 inches thick, and the outer sheet is 0.105 inches thick. The gaps are formed by a spiral wrap of stainless steel wire, 0.105 inches in nominal diameter, wrapped on a 3-inch pitch and tack welded in place. At each end of the shield, small spacer strips are used to locate the sheets, which are fully welded in place to seal the gaps. Covering the upper torispherical head is a single thermal shield, 0.105 inches thick, using 0.105-inch nominal diameter wire, spiral wrapped on a 3-inch pitch, as depicted in Detail T on sheet 6. The inner edge of the head thermal shield is welded to a circular spacer strip, and the lower edge is welded to the top end of the side shield. In order to maintain a low thermal emissivity across the shields, the outer surface of the ½-inch thick containment shell, the inner and outer faces of the 0.060-inch thick sheet, and the inner surface of the 0.105-inch thick sheet are brightened per flag note 42 on sheet 2.

The upper body and lower body assemblies are connected using 24, 1-1/4-7 UNC bolts made of ASTM A320, L43 material, with hardened stainless steel washers. The bolts are plated with electroless nickel per SAE-AMS 2404, Revision F, Class 1, or MIL-DTL-26074 Rev. F Class 1 Grade B, and tightened to a torque of 300 ± 30 ft-lb.

The upper internal impact limiter is described in Section 1.2.1.4, *Internal Impact Limiters*.

1.2.1.4 Internal Impact Limiters

The internal impact limiters located at each end of the payload cavity are depicted as Assembly A4 on drawing 1916-01-01-SAR, sheet 7. They are made from an array of 130, 2-inch diameter × 0.035-inch wall thickness, ASTM A249 or A269, Type TP304 stainless steel tubes. The limiters are curved on one side to match the inside of the torispherical head, and flat on the other, so that when fully assembled, the payload cavity is a right circular cylinder 60.3 inches long.

The flat side of the impact limiters is made from a ½-inch thick, ASTM B209, 6061-T651 aluminum plate. The tubes are located in shallow grooves machined into one side of the plate, which stabilizes one end of the tubes. The other end of the tubes is stabilized by passing through a 0.105-inch thick stainless steel tube stabilizer sheet which is spherically curved to match the torispherical heads. Each of the 130 tubes is tack welded in three places to the tube sheet. The tube array is bolted to the aluminum plate using 10, 1/4-20 stainless steel bolts as shown in Section Y-Y on sheet 7. The limiters absorb energy in an impact by crippling deformation in an axial direction. The aluminum plate of the lower impact limiter has protrusions on the top surface that aid in proper placement of the payload during package use.

The internal impact limiters are held in place using four stainless steel clips welded to the inner surface of the containment boundary in the lower and upper position. There are four square notches in the 1/2-inch thick aluminum plate that match the four clips, which allow the limiter to pass beyond the clips. Then the limiter is turned about the package axis approximately 22.5° until smaller notches in the aluminum plate align with any two opposite (180° apart) clips. A 3/8-16 UNC, ASTM A574 bolt is installed in the two clips, which prevents the limiter from rotating. The lower internal impact limiter rests directly on the lower torispherical head, and the load path of the payload is directly into the head, not the clips. To ensure stability in normal use, the load path for the payload goes through a single row of tubes. The fifth row of tubes (consisting of 22 tubes at a radius of 12.5 inches) is slightly longer than the other rows, thus supporting the entire load under normal operation. The upper internal impact limiter rests on the upper clips.

1.2.1.5 Lodgment

The lodgment is designed to maintain the position of the LTSS within the package payload cavity during NCT and HAC, and is depicted as Assembly A1 on sheet 2 of drawing 1916-01-02-SAR. It is a weldment made from ASTM B209 or B221, 6061 T651 aluminum alloy. The LTSS is transported with its axis vertical and its lower end approximately 8 inches above the bottom surface of the lodgment. The main structural components of the lodgment are 8 equally spaced ribs running longitudinally and two circumferential ribs going around the body of the LTSS. All ribs are ½ inches thick. At the center of the longitudinal ribs is a "hub" made from MIL-P25995, 6061-T6, 4-inch, schedule 40 pipe. The longitudinal ribs are spaced and stiffened by 2-in. × 2-in. × ¼-in. thick angles made from ASTM B308, 6061-T651.

The lodgment is constructed with a lower half and an upper half. The two halves are connected using 8, ½-13 UNC bolts and nuts in double shear. When assembled, the lodgment is 42.75 inches in diameter and 59.5 inches tall. The LTSS rests on a ½-inch thick plate covered with a ½-inch thick layer of neoprene rubber. Rubber is also used on the tapered edges of the lower ribs, but there is nominally no contact between lodgment ribs and the LTSS. The top end of the LTSS is stabilized for transport using three toggle clamps which are bolted to three ribs. The lodgment is lifted using two opposite ribs. The lifting shackles may be placed in storage positions on the lodgment for transport.

1.2.1.6 LTSS

The LTSS consists of a central steel magazine, or barrel, surrounded by thick lead encased in a steel shell. All of the steel used in the LTSS is ASTM type 304 stainless steel. The barrel contains four longitudinal holes, each of which can accommodate one drawer assembly. The barrel is maintained axially in position using a support plate on each end, which is 20 mm thick and attached to the main body of the LTSS using eight, M10 socket head cap screws. A non-structural plate is attached to each support plate. Each end of the LTSS is closed using a lead-filled, hinged door which is attached using eight, M16 socket head cap screws. Four lift lugs are attached to the top lateral side for use in transporting the LTSS horizontally in a facility. On one end are located two threaded lifting blocks for upending and for transporting the LTSS with the axis vertical. Except for some minor operational differences in the support plates and index pins, and except for the axial lifting blocks, the LTSS is essentially radially symmetric and identical at each end. The LTSS is depicted in Figure 1.2-8 and Figure 1.2-9.

The drawer assemblies are 548 mm long and 63 mm in diameter. There are two types of drawer assembly. The Large Source Drawer has a cavity 508 mm long and a wall thickness of 5 mm. It contains the NLM-52 source capsule, which has an outer diameter of 52 mm, and two end shields made of tungsten having a minimum density of 17 g/cm^3. There are five different lengths of the NLM-52, as shown in the following table:

Capsule ID	Capsule Length, mm
NLM 52-74	74
NLM 52-150	150
NLM 52-200	200
NLM 52-250	250
NLM 52-325	325

Each NLM-52 source capsule may contain one or more sealed sources as described in Section 1.2.2, *Contents*. Other special form or non-special form capsules may be used that have the same length, diameter, and at least as much radiation attenuation as the NLM-52 capsule series. The Large Source Drawer is depicted in Figure 1.2-10.

The other drawer type is the T80/T780. The T80 and T780 drawers are physically identical. Like the large source drawer, they are 21.5 inches long and 2.5 inches in diameter. In the center is a 1.1-inch diameter cross-drilled hole which accepts a source capsule. The drawers are made of brass with a wall thickness of 0.2 inches and a stainless steel end thickness of 0.8 inches. For the T80 drawer, the shielding on each side of the source is 9.2 inches of lead. For the T780 drawer, the shielding may be either lead, tungsten, or depleted uranium. The T80/780 drawer is depicted in Figure 1.2-11.

1.2.1.7 Inner Container

The inner container (IC) is designed to hold a shielded device and provide support for the device and the blocking materials during transport. It is depicted as Assembly A1 on sheet 2 of drawing 1916-01-03-SAR. The IC is 59.5 inches tall and 42.75 inches in outer diameter, with an interior cavity of 36.0 inches in diameter and 53.0 inches long. The IC is a weldment made from ASTM A240, Type 304 stainless steel. The lid is attached using six, 1-8UNC hex bolts with flat washers and nuts. The shell, the base, and the inner sheet of the lid are made from 1/4-inch thick material; the bolting flanges, of 1/2-inch thick material; and the grid pattern of stiffening and energy-absorbing ribs on the outside are made from 3/16-inch thick material. The base structure is 4.0 inches high and is stiffened by 8 ribs made from 1/4-inch thick material. The lid is 2.5 inches thick, with three, 1/4-inch thick ribs and three threaded blocks near the outer diameter for lifting the entire IC. The open space in the lid is filled with eight layers of 1/4-inch thick refractory insulation paper. The top of the lid is sealed with 16 GA (0.06-inch thick) sheet metal.

1.2.1.8 Gross Weight

The gross weight of the 435-B package, including the empty packaging, and lodgment and LTSS or inner container and shielded device, is 10,100 lb. The empty weight is 4,940 lb. A summary of overall component weights is shown in Table 2.1-2 and discussed in Section 2.1.3, *Weights and Centers of Gravity*.

1.2.1.9 Neutron Moderation and Absorption

Since the 435-B package transports material which is either non-fissile or fissile exempt, no moderation or absorption of neutrons is necessary to control criticality.

1.2.1.10 Receptacles, Valves, Testing and Sampling Ports

The 435-B package upper body assembly contains a vent port and a containment seal test port. There are no valves or receptacles used in the 435-B package.

1.2.1.11 Heat Dissipation

The dissipation of heat from the 435-B package is entirely passive. A thermal shield is used on the upper body assembly and upper head to limit the heat flux into the package in the HAC fire event. A more detailed description of the package thermal design is given in Chapter 3, *Thermal Evaluation*.

1.2.1.12 Lifting and Tie–down Devices

The 435-B is lifted using a shipping skid and a fork lift truck. The threaded hole on the top of the upper package assembly is used only to lift the upper package assembly component. The package is tied down using straps or hold-down structures placed over the top of the impact limiter, and which are fastened to the shipping skid or to the conveyance. Thus, there are no lifting or tie-down devices that are a structural part of the package.

1.2.1.13 Pressure Relief System

There is no pressure relief system in the 435-B package.

1.2.1.14 Shielding

Biological shielding of gamma radiation is provided by lead located in the LTSS or in the shielded devices. No other components whose primary purpose is shielding are included in the 435-B. Details of the gamma shielding in the LTSS are provided in Section 1.2.1.6, *LTSS*. Gamma shielding in the shielded devices is described and evaluated in Chapter 5, *Shielding Evaluation*.

1.2.2 Contents

The 435-B package contains two payload types: the LTSS and shielded devices. The contents of the LTSS are subdivided into Content 1 and Content 2. The shielded device category is subdivided into Group 1 and Group 3 devices.

1.2.2.1 LTSS Contents

The LTSS contains sealed sources taken from shielded devices such as industrial irradiators, medical equipment, or research facilities. The sources are sealed and may be in special form, and may be present in the T80/T780 source drawer. Content 1 and Content 2 are defined in Section 7.1.4.1, *Qualifying a Payload for Transport*. The nuclides that will be transported in the LTSS are listed in Table 1.2-1. The maximum decay heat in the package is 200W or less. The quantity of Pu-239 is less than 15g. No other fissile isotopes are transported. Fissile exemption of the payload is discussed in Chapter 6, *Criticality Evaluation*. The 435-B, when containing isotopes of plutonium or greater than 200 curies of americium, will not be offered for transport by air. Allowable combinations of nuclides within a single LTSS is discussed in Chapter 5, *Shielding Evaluation*.

1.2.2.2 Shielded Devices

Shielded devices are units which were designed and manufactured to provide a safe source of radiation for industrial, medical, or research purposes. Each such device includes a sealed source (or a group of sources), shielding material, and a steel or cast iron shell to surround the shielding material and provide structure. All devices transported in the 435-B are found in the NRC Sealed Source Device Registry (SSDR). Each device was engineered to be safely used in a normally occupied environment (i.e., not requiring a hot cell environment), and was repeatedly surveyed for radiation dose over its lifetime. Conservatively, prior to transport, each device will be surveyed, with a surface dose rate limit of 200 mrem/hr and a dose rate at a distance of one meter from the surface of 10 mrem/hr. As noted in the SSDRs, the actual measured dose rate is as much as two orders of magnitude lower than this.

All shielded devices are placed into the inner container for shipment in the 435-B, described in Section 1.2.1.7, *Inner Container*, and blocked in position using dunnage materials.

Blocking/dunnage materials are metallic structures or polymeric foam. Cabinets, stands, or unnecessary appurtenances are not transported. Prior to loading, movable sources are placed in the safe shipping position, the structural integrity is evaluated, and a radiation survey is performed. More information is provided in Section 7.1.2.2, *Loading the Inner Container (IC).*

Group 1 shielded devices were manufactured by Radiation Machinery Corporation, Isomedix, Atomic Energy of Canada Limited, MDS Nordion, and Best Theratronics. All of the Group 1 devices feature a fixed-source design, that is, the source capsule(s) are located in a fixed position within the device, and the sample was moved (typically rotated) into or out of position using a shielded specimen holder. All Group 1 devices use Cs-137, with a maximum activity of 3,840 Ci and have a weight of approximately 3,300 lb. All of the devices are shielded with lead, which is contained within a thick steel shell weldment. The model types included in Group 1 are listed in Table 1.2-2. Photographs of the Group 1 devices are provided in Figure 1.2-12 through Figure 1.2-15.

Group 3 consists of the Gammacell-40 (a.k.a. GC-40 and Exactor), formerly manufactured by Atomic Energy of Canada Limited and MDS Nordion, and currently by Best Theratronics. The GC-40 features a telescoping source design, in which the source is contained in a source drawer which is moved along its axis through the shield. In the active position, the source is exposed to a lateral opening in the shield. In the storage position, the source is located near the center of the shield. The drawer contains shielding on each end of the source. All shielding material is lead. The GC-40 has two essentially identical shielded units (upper and lower). Each unit is transported singly. The maximum activity in any one unit is 2,250 Ci of Cs-137. The weight is approximately 2,650 lb. A figure of the GC-40 is provided in Figure 1.2-16.

1.2.3 Special Requirement for Plutonium

The 435-B package may contain plutonium in excess of 20 Ci, which is in solid form.

1.2.4 Operational Features

The 435-B package is of conventional design and is not complex to operate. Operational features are depicted on the drawings provided in Appendix 1.3.3, *Packaging General Arrangement Drawings*. Operating procedures and instructions for loading, unloading, and preparing an empty package for transport are provided in Chapter 7, *Package Operations*.

Table 1.2-1 – LTSS Payload Source Nuclides

Nuclide	Maximum Activity
Co-60	12,970 Ci
Cs-137	14,000 Ci
Sr-90	1,000 Ci
Ra-226 (no Be)[5]	20 Ci
Ra-226Be[5]	1.3 Ci
Am-241 (no Be) [6]	1000 Ci
Am-241Be[6]	6.6 Ci
Pu-238 (no Be) [7]	75 g Pu
Pu-239 (no Be) [7]	15 g Pu
Pu-239Be[7]	15 g Pu
Ir-192	200 Ci
Se-75	80 Ci

Notes:

1. Physical form of all nuclides is solid material in a sealed capsule.
2. The maximum decay heat limit for the 435-B package is 200W.
3. The maximum activity listed is the maximum for a single nuclide in the LTSS. For combinations of different nuclides, lower activity limits apply as discussed in Chapter 5, *Shielding Evaluation*.
4. The total activity in this table is 86,732 A_2. This value exceeds the maximum number of A_2 that could be transported.
5. Impurities may include oxygen, carbon, sulfur, bromine, and chlorine (hydrous and anhydrous).
6. Impurities may include oxygen and chlorine.
7. Impurities may include oxygen.

Table 1.2-2 – Shielded Devices

Model Name/Type	Maximum Activity, Ci	Weight, lb	SSDR No.[3]
Group 1 Devices			
Gammator 50B, B, B34, G-50-B	420	1800	NR-0880-D-802-S
Gammator M34	1,920	1,850	NR-0880-D-806-S
Gammator M38	3,840	2,250	NR-0880-D-806-S
Gammacell 1000 (GC-1000) -Models A through D -Elite A through D, Type I and Type II	3,840 (bounding value)	2,800	NR-0880-D-808-S, NR-1307-D-102-S
Gammacell 3000 (GC-3000) -Elan A through C, Type I and Type II[2]	3,048	3,300	NR-1307-D-102-S
Group 3 Devices			
Gammacell-40 (GC-40, Exactor)	2,250[4]	2,650	NR-1307-D-101-S

Notes:

1. Radionuclide in all cases is Cs-137.
2. Gammacell 3000 external secondary shielding is not credited in the shielding analysis.
3. Consult SSDR for design and safety features of each model.
4. Gammacell-40 activity is given for one of the two device components that make up a complete Gammacell-40. Only one device component may be shipped at one time.

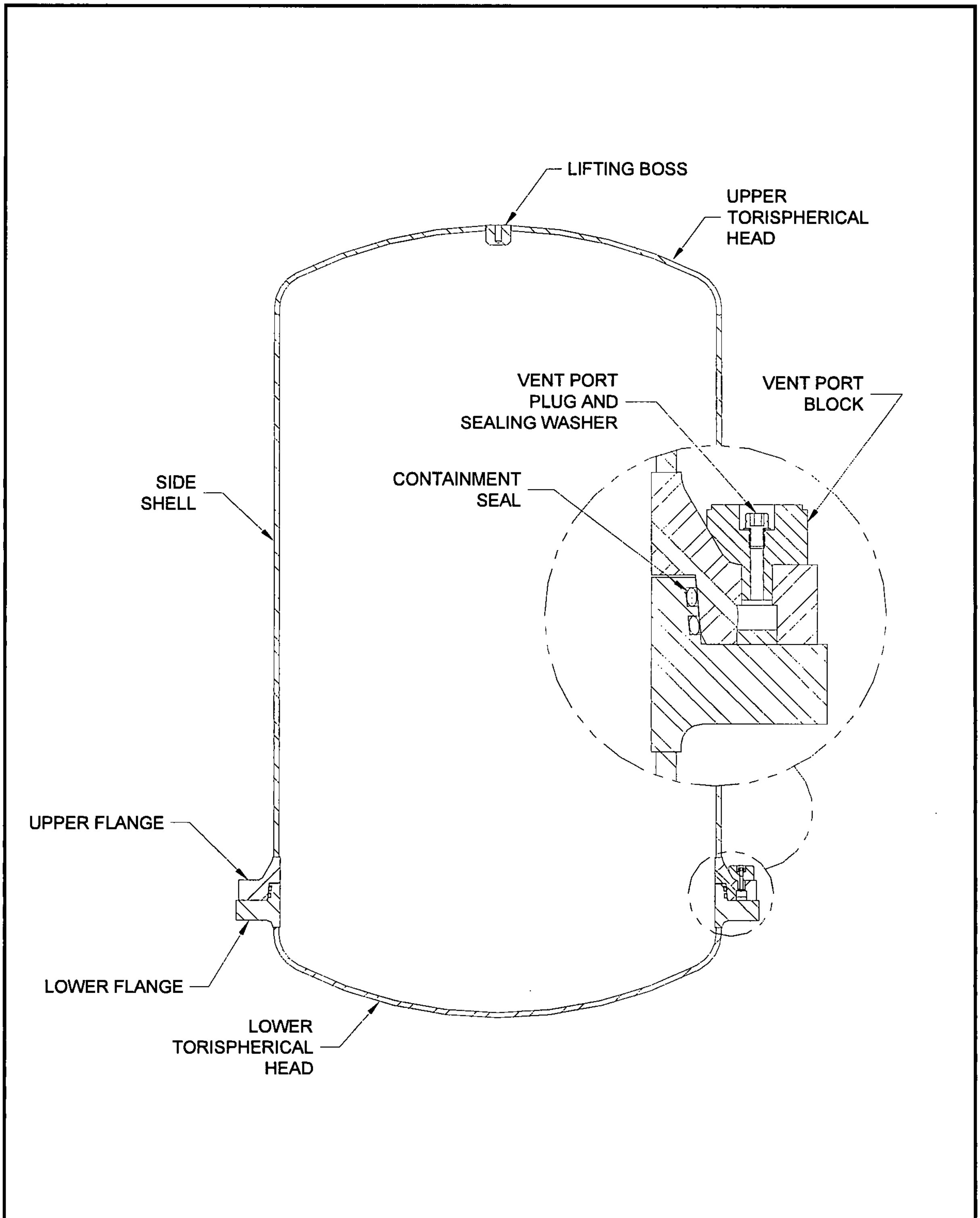

Figure 1.2-1 – 435-B Containment Boundary

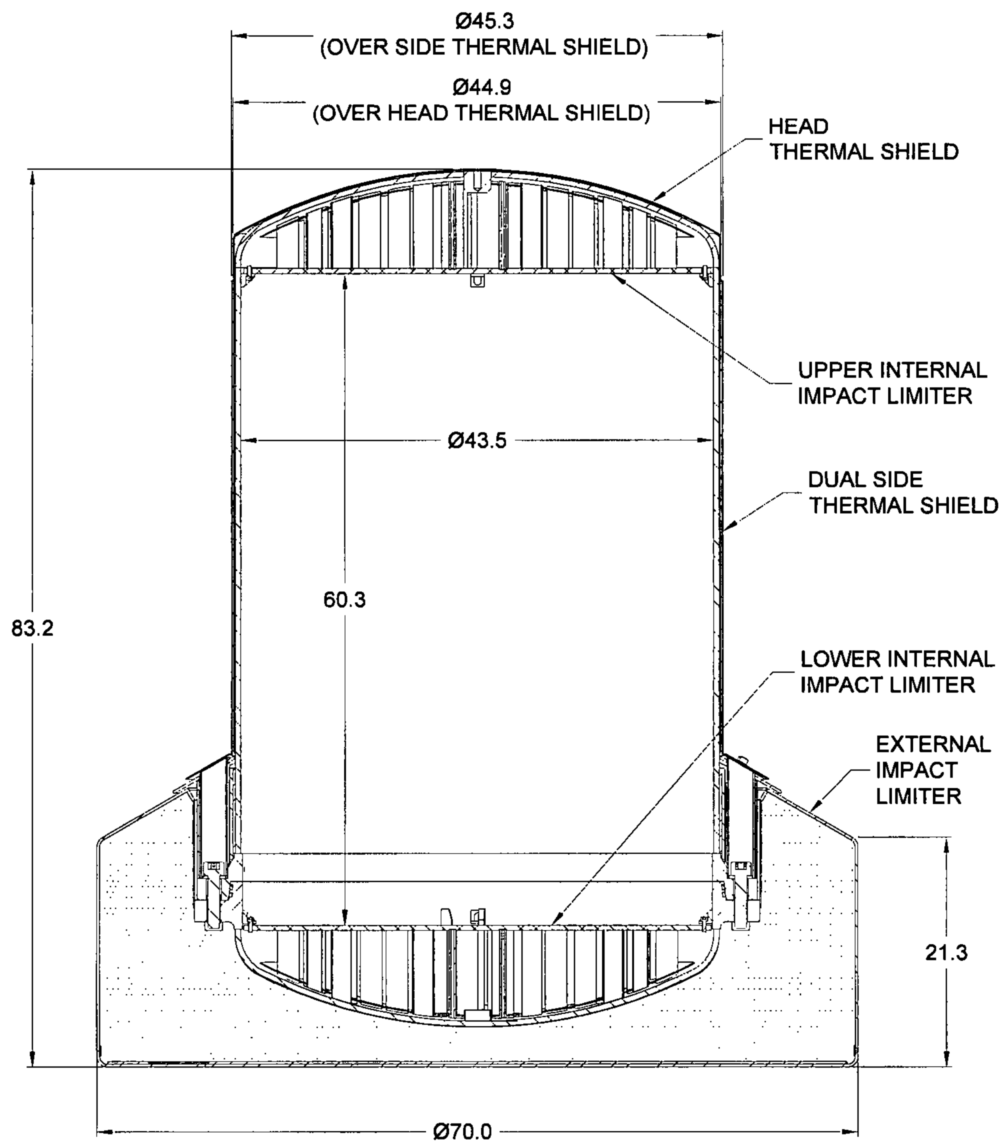

Figure 1.2-2 – 435-B Cross Sectional View

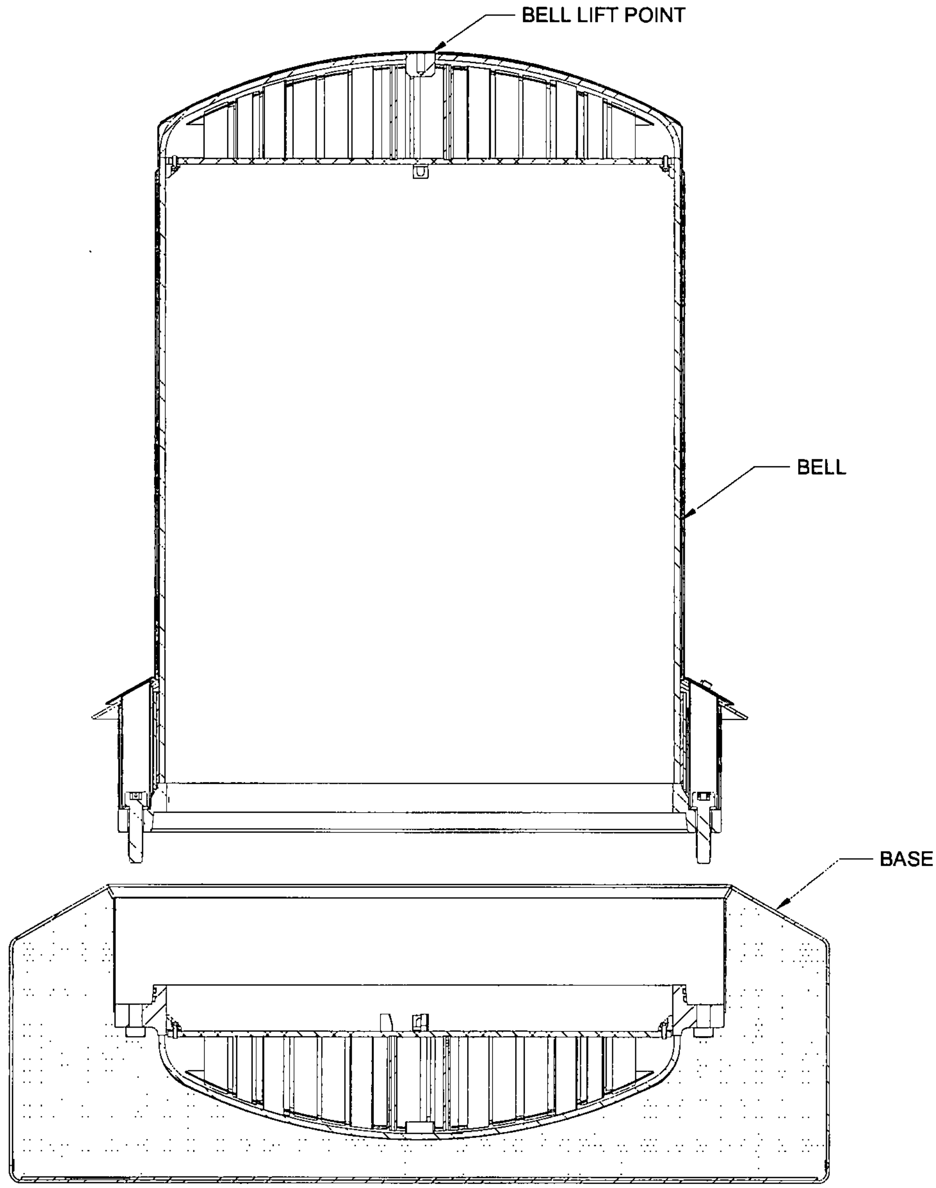

Figure 1.2-3 – Exploded View

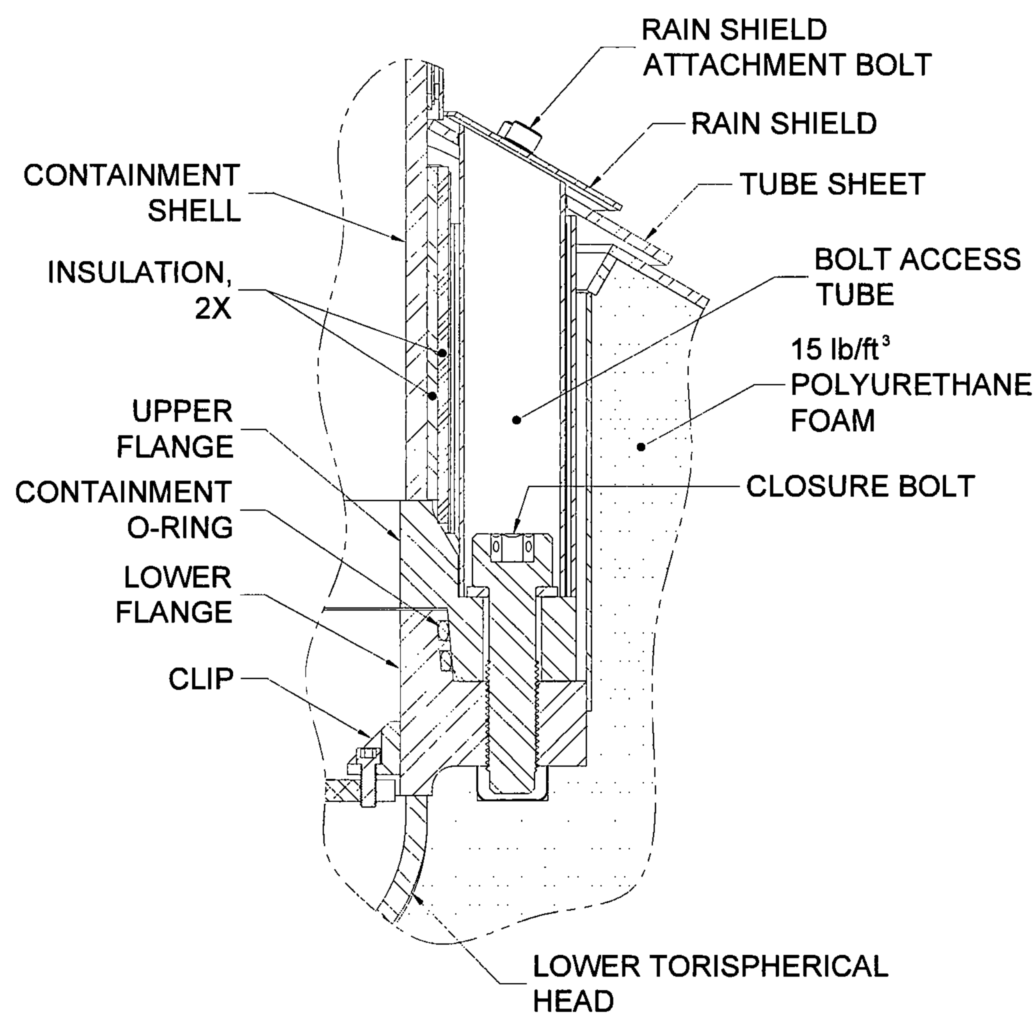

Figure 1.2-4 – Detail View of Flange Area

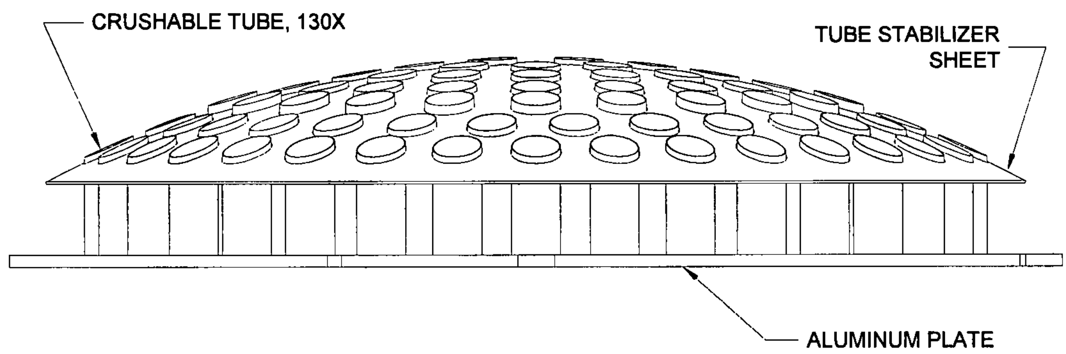

Figure 1.2-5 –Internal Impact Limiter

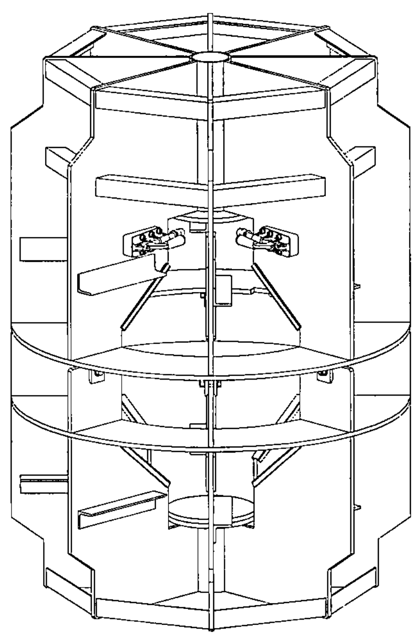

Figure 1.2-6 – LTSS Lodgment

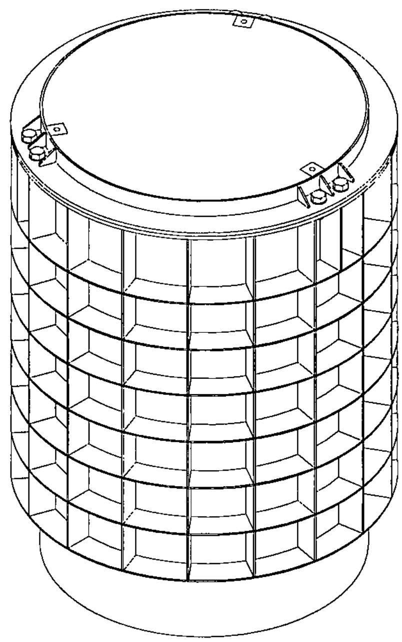

Figure 1.2-7 – Inner Container

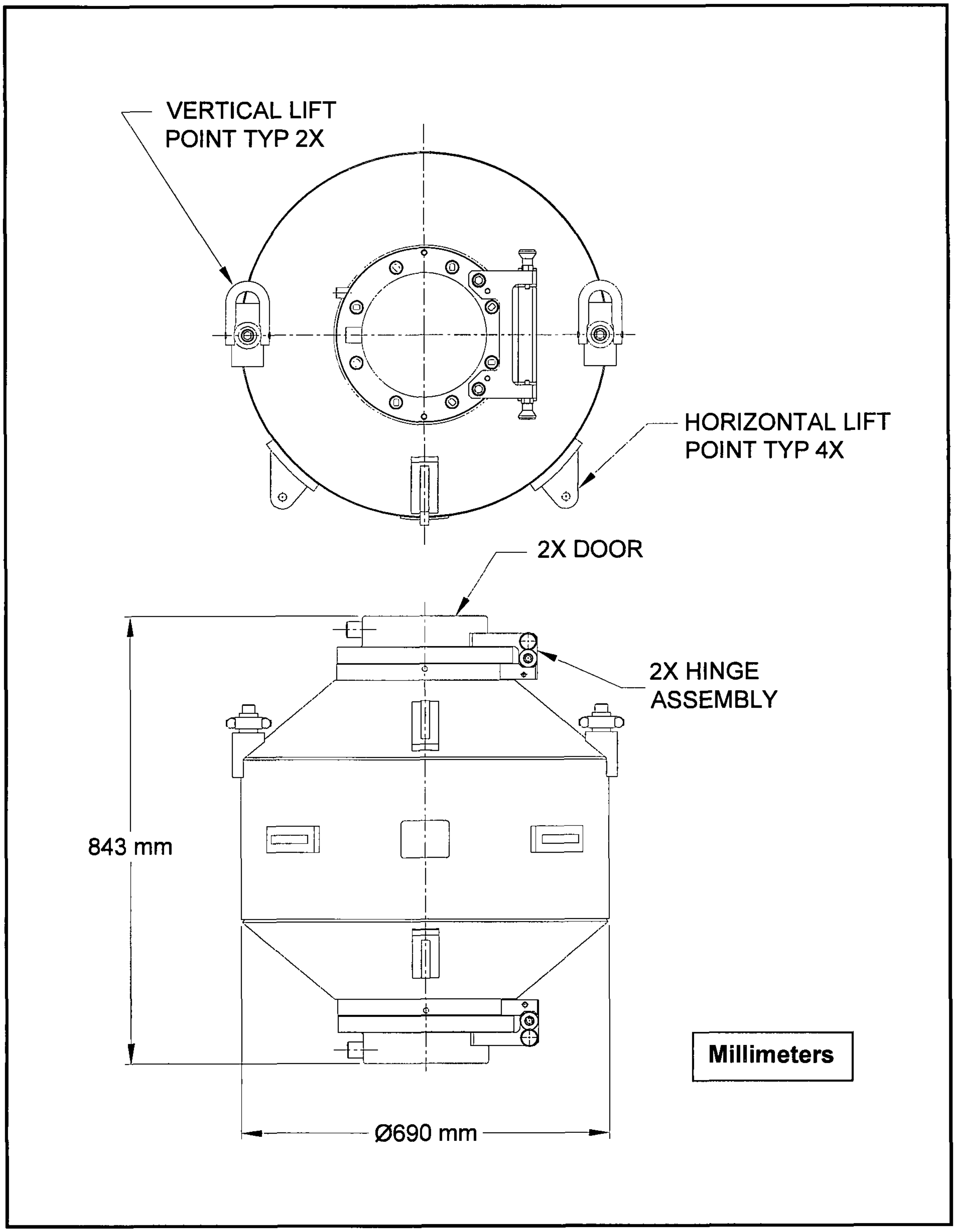

Figure 1.2-8 – LTSS Overview

Security Related Information
Figure Withheld Under 10 CFR 2.390

Millimeters

Figure 1.2-9 – LTSS Section View

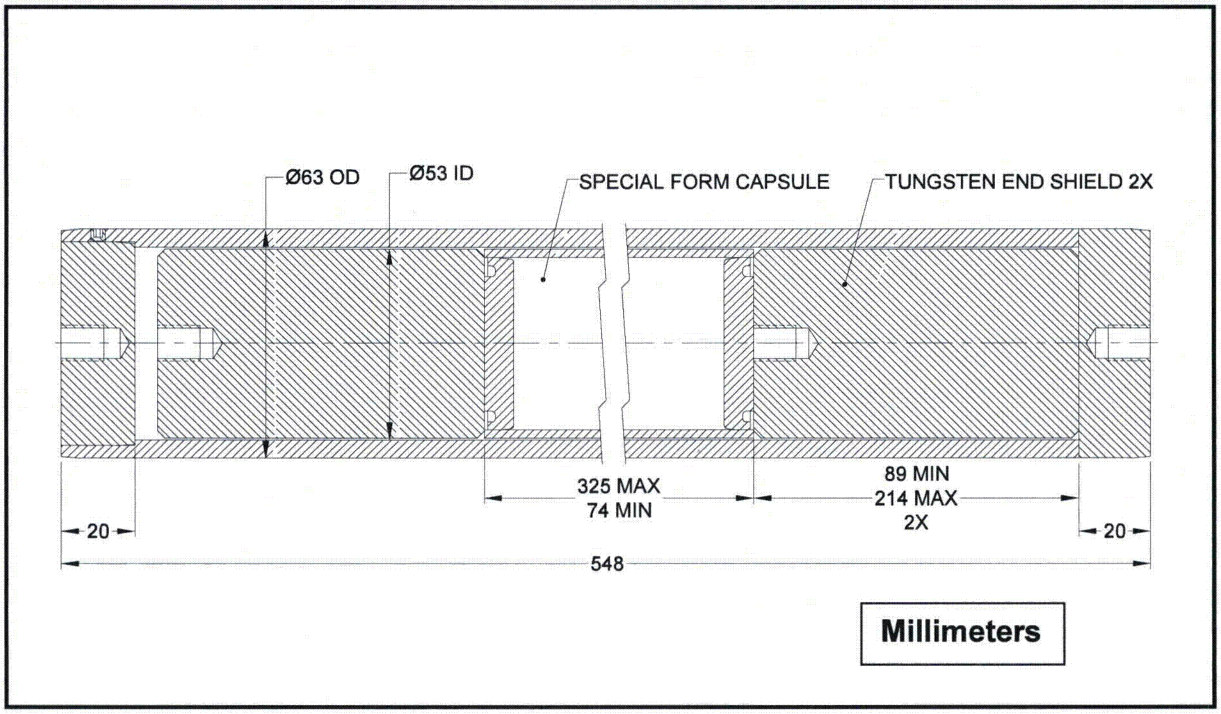

Figure 1.2-10 – LTSS Large Source Drawer

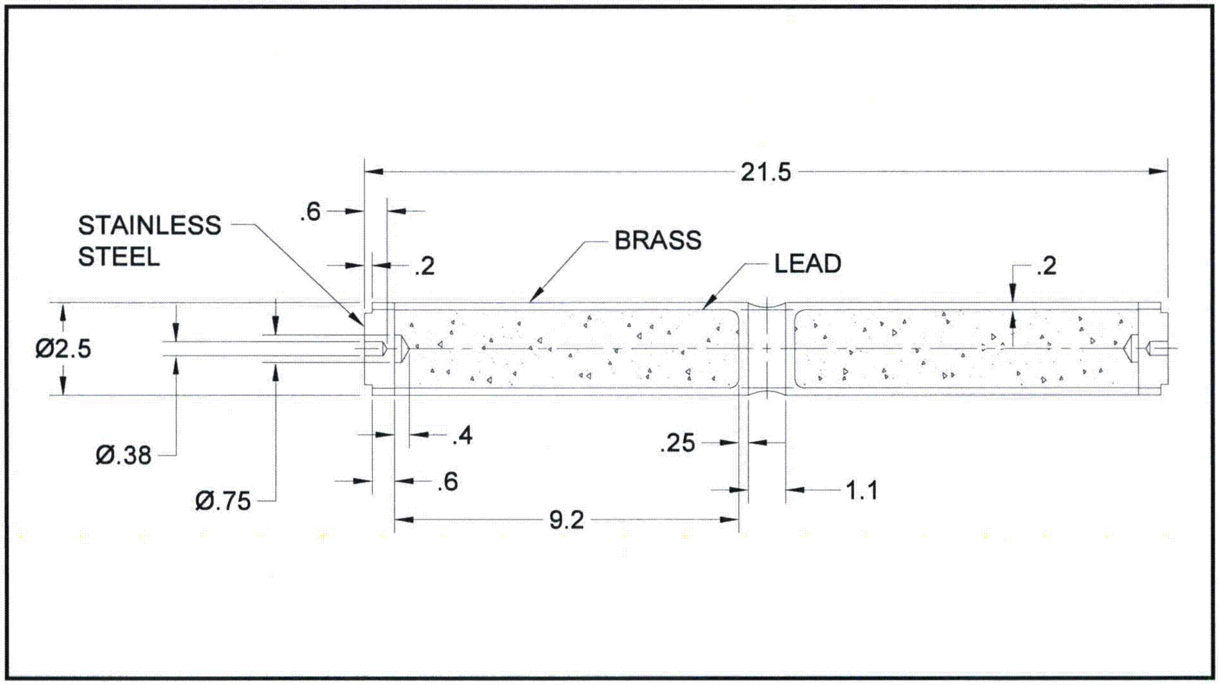

Figure 1.2-11 – T80/780 Source Drawer (inches)

Figure 1.2-12 – Gammator G-50-B Shielded Device

Figure 1.2-13 – Gammator M38 Shielded Device

Figure 1.2-14 – Gammacell 1000 Shielded Device

Figure 1.2-15 – Gammacell 3000 Shielded Device

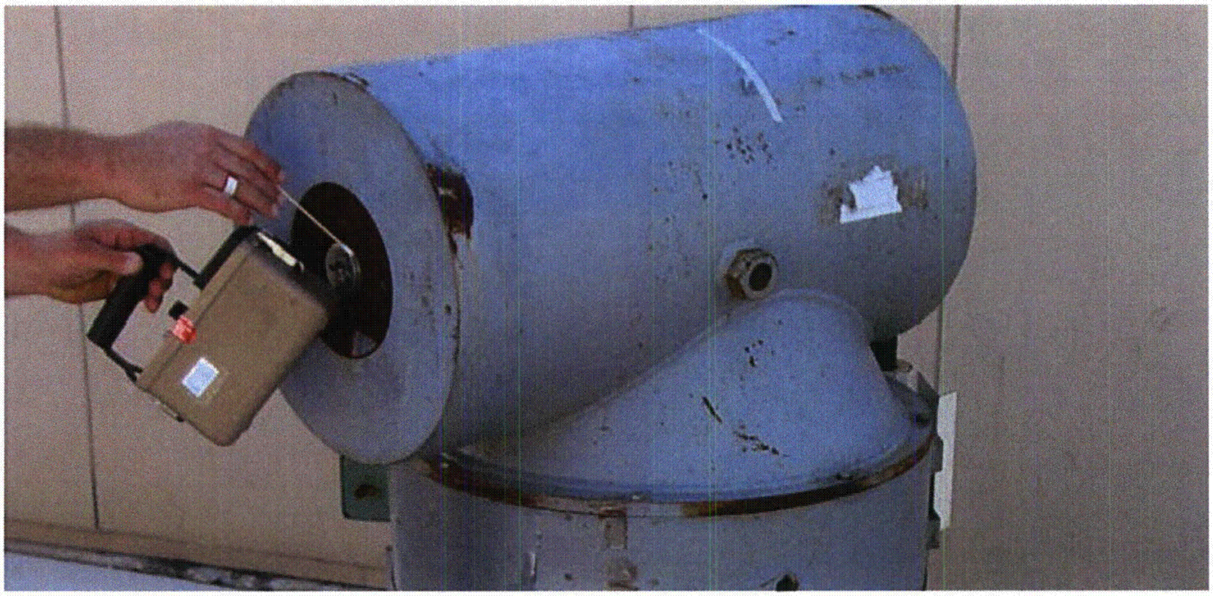

Figure 1.2-16 – Gammacell-40 Shielded Device (Upper Head Shown)

1.3 Appendices

1.3.1 References

1. Title 10, Code of Federal Regulations, Part 71 (10 CFR 71), *Packaging and Transportation of Radioactive Material*, 01–01–11 Edition.
2. International Atomic Energy Agency, *Regulations for the Safe Transport of Radioactive Material*, TS-R-1.
3. ANSI N14.5–1997, *American National Standard for Radioactive Materials – Leakage Tests on Packages for Shipment*, American National Standards Institute (ANSI), Inc.

1.3.2 Glossary of Terms and Acronyms

ANSI – American National Standards Institute.

ASME B&PV Code – American Society of Mechanical Engineers Boiler and Pressure Vessel Code.

ASTM – American Society for Testing and Materials.

AWS – American Welding Society.

Base – See *Lower Body Assembly*.

Bell – See *Upper Body Assembly*.

Clip – Eight brackets (four top and four bottom), welded to the inside of the containment boundary, supports and retains the *Internal Impact Limiters* in place.

Closure Bolts – Fasteners that secure the *Upper Body Assembly* to the *Lower Body Assembly*. Includes washers.

Closure Bolt Access Tube – 24, 2-¼ -inch inner diameter tubes that permit access to the *Closure Bolt* heads. See also *Port Access Tube*.

Containment O–ring Seal – Upper elastomeric seal, retained by the lower flange, which forms part of the containment boundary.

Crush Tubes – Tubes used with the *Internal Impact Limiter* to absorb free drop energy.

HAC – Hypothetical Accident Conditions.

Head Thermal Shield – Assembly of a sheet and a wire wrap attached to the outside of the upper torispherical head, forming a thin air gap that inhibits heat transfer into the package during the HAC fire event.

Inner Container – Steel container with a bolted lid used to house *Shielded Devices*, interfaces with the 435-B payload cavity.

Internal Impact Limiter – An energy absorbing component that is placed into each torispherical head. Forms flat ends for the payload cavity and absorbs payload kinetic energy in end drops.

Large Source Drawer – Shielded drawer used with the *LTSS*.

Lodgment – Aluminum weldment used to hold the *LTSS* inside the payload cavity.

Lower Body Assembly (Base) – Lower part of packaging, includes the lower torispherical head, lower flange, *Internal Impact Limiter*, and external impact limiter. Interfaces with the *Upper Body Assembly*.

Long Term Storage Shield (LTSS) – Lead-shielded container which holds source capsules.

MNOP – Maximum Normal Operating Pressure.

NCT – Normal Conditions of Transport.

Port Access Tube –	Two, 2-¼ -inch inner diameter tubes that permit access to the *Vent Port* and *Seal Test Port* plugs. Holds the *Port Insulation Cylinder*. See also *Closure Bolt Access Tube*.
Port Insulation Cylinder –	An insulated tube that fits within each *Port Access Tube* to provide additional thermal insulation for the port *Sealing Washers*.
Rain Shield –	Sheet, 0.120-inch thick, which covers the open ends of the *Closure Bolt Access Tubes* and *Port Access Tubes*.
Seal Test Port –	Opening located in a block welded to the upper flange, used to test the leakage rate of the *Containment O–ring Seal*. Closed with the *Seal Test Port* plug.
Sealed Source –	Sealed capsule containing source material.
Sealing Washers –	Integrated metal and elastomer seals that are used with the *Vent Port* and *Seal Test Ports*.
Side Thermal Shield –	Assembly of sheets and wire wraps attached to the outside of the outer shell, forming two thin air gaps that inhibit heat transfer into the package during the HAC fire event.
Shielded Device –	Industrial, medical, or research device for use in irradiating samples. Contains the source, shielding, and surrounding structure.
Special Form Capsule –	NLM 52, a welded capsule used in the *Large Source Drawer*.
T80/T780 Drawers –	Shielded source drawers used with the *LTSS*.
Test O–ring Seal –	Lower elastomeric O-ring seal, retained by the lower flange, used to allow leakage rate testing of the *Containment O-ring Seal*.
Tube Sheet –	The ¼-inch thick plate, inclined at 30° to the horizontal, that holds the upper end of the *Closure Bolt Access Tubes* in place.
Tube Stabilizer Sheet –	Bowl-shaped, 0.105-inch thick sheet that stabilizes the *Internal Impact Limiter* tubes.
Upper Body Assembly (Bell) –	Upper part of packaging, includes the upper torispherical head, cylindrical shell, upper flange, lifting boss, bolt tube structures, vent and test port blocks, access to closure bolts, and upper inner impact limiter. Interfaces with the *Lower Body Assembly*.
Vent Port –	Opening located in a block welded to the upper flange, used to vent the cavity and to introduce helium for leakage rate testing during operations. Closed with the vent port plug.

1.3.3 Packaging General Arrangement Drawings

The packaging general arrangement drawings consist of:

- 1916–01–01–SAR, 435-B Package Assembly SAR Drawing, 7 sheets
- 1916–01–02–SAR, 435-B LTSS Lodgment SAR Drawing, 2 sheets
- 1916–01–03–SAR, 435-B Inner Container SAR Drawing, 2 sheets

Security Related Information
Figure Withheld Under 10 CFR 2.390

REV	DESCRIPTION	DRAWN	CHECKER	VERIFIED
1	SEE ECN NO. 1916-01-01-SARR0-E1	P. PIKULIN 2/12/13	[signature] 2-14-13	[signature] 2/22/13

REVISION HISTORY

	NAME/SIGNATURE	DATE
APPD		
APPD	R BURNHAM	6/5/12
ENGR	P NOSS	6/4/12
QA	K. KING	6/4/12
CHECK	DL STEVENSON	6-4-12
DRAWN	P. PIKULIN	03/1/12

TOLERANCES:
FRACTIONS ± [illegible]
ANGLES ± 3°
3 PLACE DECIMALS AS SHOWN
2 PLACE DECIMALS ± .12
1 PLACE DECIMALS ± .4

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AREVA Federal Services LLC
Packaging Projects
Federal Way, WA 98003

DWG TITLE: 435-B PACKAGE ASSEMBLY SAR DRAWING

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REV: 1 | SHEET 1 OF 7
DWG SIZE: D | DWG NO. 1916-01-01-SAR
CADFILE: [illegible]
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Security Related Information
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Figure Withheld Under 10 CFR 2.390

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Figure Withheld Under 10 CFR 2.390

Security Related Information
Figure Withheld Under 10 CFR 2.390

DWG NO 1916-01-01-SAR REV 1 SH 6

Security Related Information
Figure Withheld Under 10 CFR 2.390

REV: 1 SHEET 6 OF 7
DWG NO.
1916-01-01-SAR

Security Related Information
Figure Withheld Under 10 CFR 2.390

Security Related Information
Figure Withheld Under 10 CFR 2.390

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REVISION HISTORY				

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APPD	R. BURNHAM	5/21/12
ENGR	P. NOSS	5-21-12
QA		5-17-12
CHECK	DL STEVENSON	5-18-12
DRAWN	P. PIKULIN	05/09/12

WELD & FORMED TOLERANCES:
FRACTIONS ± 1/2 ANGLES ± 3°
3 PLACE DECIMALS AS SHOWN
2 PLACE DECIMALS ± .12
1 PLACE DECIMALS ± .4

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Packaging Projects
Federal Way, WA 98003

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DWG NO 1916-01-02-SAR REV 0 SH 2

Security Related Information
Figure Withheld Under 10 CFR 2.390

REV: 0 SHEET 2 OF 2
DWG NO. 1916-01-02-SAR

Security Related Information
Figure Withheld Under 10 CFR 2.390

REV	DESCRIPTION	DRAWN	CHECKER	VERIFIED

REVISION HISTORY

	NAME/SIGNATURE	DATE
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ENGR	P. Nars [signature]	5-21-12
QA	[signature]	5-17-12
CHECK	L. STEVENSON [signature]	5-18-12
DRAWN	P PIKULIN	05/09/12

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Federal Way, WA 98003

DWG TITLE 435-B INNER CONTAINER SAR DRAWING

TOLERANCES:
FRACTIONS ± 1/2
ANGLES ± 3°
3 PLACE DECIMALS AS SHOWN
2 PLACE DECIMALS ± .12
1 PLACE DECIMALS ± .4

SCALE: NOTED | WT. -
REV: 0 | SHEET 1 OF 2
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CADFILE: 19160103SAR0.SLDDRW
DWG-3005281-000

Security Related Information
Figure Withheld Under 10 CFR 2.390

2.0 STRUCTURAL EVALUATION

This section presents evaluations demonstrating that the 435-B package meets all applicable structural criteria. The 435-B package, consisting of a lower and upper body assembly and lodgment or inner container, is evaluated and shown to provide adequate protection for the LTSS or shielded device payloads. Normal conditions of transport (NCT) and hypothetical accident condition (HAC) evaluations are performed to address 10 CFR 71 [1] performance requirements. The primary method of performance demonstration is by full-scale test. When analysis is used, demonstration techniques comply with the methodology presented in NRC Regulatory Guides 7.6 [2] and 7.8 [3]. NCT free drop and HAC free drop and puncture performance is evaluated by means of three full scale test units. A discussion of the tests performed is given in Appendix 2.12.2, *Certification Test Plan*, and results of the certification tests are provided in Appendix 2.12.3, *Certification Test Results*.

2.1 Structural Design

2.1.1 Discussion

The 435-B package is designed to transport radioactive sources contained in the LTSS or in shielded devices. An isometric view of the package is shown in Figure 1.1-1, with cross-sections of the package with the two payload types shown in Figure 1.1-2 and Figure 1.1-3. Other views of the packaging and of its internal components are shown Figure 1.2-1 through Figure 1.2-7. The 435-B package consists of a lower body assembly, an upper body assembly, two internal impact limiters, and a lodgment or an inner container (IC). The payload cavity is 43.5 inches in diameter and 60.3 inches long. Shielding of the radioactive sources is provided by the thick lead body of the LTSS or of the shielded devices. The 435-B containment boundary consists of ½-inch thick Type 304 stainless steel, and includes a cylindrical body, two torispherical ends, and heavy bolting flanges. A quantity of 24, 1-1/4-inch diameter alloy steel bolts are used to fasten the upper and lower assemblies together. The containment closure seal is a 3/8-inch cross-sectional diameter butyl O-ring seal. A test O-ring seal is used to provide a cavity for helium leak testing of the containment seal. Vent and test ports are located adjacent to the upper flange. A dual thermal shield is attached to the outside of the cylindrical shell and a single thermal shield is attached to the upper torispherical head.

An external impact limiter is located at the lower end of the package to protect the closure from impact loads and HAC fire heat. The impact limiter shell is ¼ inches thick and envelops nominally 15 lb/ft^3 polyurethane foam impact absorbing material. The impact limiter is integrally attached to the lower body assembly by welds. Two internal impact limiters, which absorb the energy of the payload using the crippling deformation of steel tubes, are used at each end of the payload cavity.

A lodgment consisting of an aluminum alloy weldment is used to maintain the LTSS in position. An inner container with internal blocking is used to hold the shielded devices. A comprehensive discussion of the 435-B package design and configuration is provided in Section 1.2, *Package Description*.

2.1.2 Design Criteria

Proof of performance for the 435-B package is achieved by a combination of full scale certification testing and analysis. The acceptance criteria for analytic assessments are in accordance with Regulatory Guide 7.6. The acceptance criterion for certification testing is a demonstration that the containment boundary remains leaktight [4] following the imposed loading conditions. Additionally, package deformations obtained from testing must be such that deformed geometry assumptions used in subsequent thermal evaluation is validated. These design criteria meet the following safety requirements of 10 CFR §71.51:

1. For normal conditions of transport, there shall be no loss or dispersal of radioactive contents, as demonstrated to a sensitivity of 10^{-6} A_2 per hour, no significant increase in external radiation levels, and no substantial reduction in the effectiveness of the packaging.
2. For hypothetical accident conditions, there shall be no escape of radioactive material exceeding a total amount A_2 in one week, and no external radiation dose rate exceeding one rem per hour at one meter from the external surface of the package.

The 435-B package qualifies as a Category I container, which is the highest and most stringent category [5]. Per NUREG/CR-3019 [6] and NUREG/CR-3854 [7], the cask components are classified as follows:

- Containment components are classified as ASME Code, Section III, Subsection NB [8].
- Non-containment structures such as the thermal shields, impact limiter shells, and internal impact limiter components are classified as ASME Code, Section III, Subsection NF [9].
- Lodgment and IC components are classified as ASME Code, Section III, Subsection ND [25].

The remainder of this section presents the detailed acceptance criteria used for analytic structural assessments of the 435-B package.

2.1.2.1 Containment Structures

A summary of allowable stresses used for containment structures is presented in Table 2.1-1. Containment structures include the cylindrical shell, the torispherical heads, and the flanges. The allowable stresses shown in Table 2.1-1 are consistent with Regulatory Guide 7.6, and the ASME Code, Section III, Subsection NB, and Appendix F [32]. Peak stresses are further discussed in Section 2.1.2.3.2, *Fatigue Assessment*, and buckling in Section 2.1.2.3.3, *Buckling Assessment*. Closure bolts are evaluated using the guidance of NUREG/CR-6007 [10]. Furthermore, stress intensity in the flanges which could affect compression of the containment O-ring seal is limited to the lesser of the value shown in Table 2.1-1, or the yield strength.

2.1.2.2 Other Structures

The external impact limiter, including the steel shells and energy-absorbing foam, is expected to permanently deform under NCT and HAC. The performance criteria are:

- Limit impact magnitude such that package component stress and deflection criteria are met.
- Prevent "hard" contact of a rigid part of the cask with the ground due to excessive deformation of the foam.

- Maintain sufficient structural integrity subsequent to the HAC free drop and puncture drop events that the containment O-ring seal is protected from excessive temperature in the subsequent HAC fire event.

The internal impact limiters contribute significantly to the absorption of the payload energy in a free drop event. They must limit the relative motion of the payload such that package component stress and deflection criteria are met.

The performance of the packaging is discussed in Sections 2.6, *Normal Conditions of Transport*, and 2.7, *Hypothetical Accident Conditions of Transport*. The thermal performance of the packaging is evaluated in Chapter 3, *Thermal Evaluation*.

Since the 435-B package is not lifted using any structural part of the package, lifting structural criteria are not required. Furthermore, since the 435-B package is not attached to the conveyance using any structural part of the package, tiedown structural criteria are not required.

2.1.2.3 Miscellaneous Structural Failure Modes

2.1.2.3.1 Brittle Fracture

With the exception of the closure bolts, all structural components of the 435-B package are fabricated of austenitic stainless steel or aluminum. These materials do not undergo a ductile-to-brittle transition in the temperature range of interest (i.e., down to -40 °F), and thus do not need to be evaluated for brittle fracture. The closure bolts are fabricated from ASTM A320, Grade L43 alloy steel bolting material. This material is specifically intended for low temperature service. In addition, per Section 5 of NUREG/CR-1815 [11], bolts are not considered as fracture-critical components because multiple load paths exist and bolting systems are generally redundant, as is the case with the 435-B package. Therefore, brittle fracture is not a failure mode of concern.

2.1.2.3.2 Fatigue Assessment

2.1.2.3.2.1 Normal Operating Cycles

Normal operating cycles do not present a fatigue concern for the 435-B package components over its service life. The basis for this conclusion is reached using the six criteria of Article NB-3222.4(d) of the ASME Boiler and Pressure Vessel Code. A summary of the six criteria and their application are discussed below. The service life of the package is 25 years with up to 50 shipments per year for a maximum of 1,250 shipments in the service life.

(1) Atmospheric to Service Pressure Cycle: The total number of atmospheric-to-operating pressure cycles during normal operations does not exceed the number of cycles on the fatigue curve corresponding to a value of $S_a = 3S_m$ for Type 304 stainless steel. From Section 2.2.1, *Material Properties and Specifications* at a bounding temperature of 200 °F per Section 2.6.1.1, *Summary of Pressures and Temperatures*, the S_m value for Type 304 stainless steel is 20 ksi, which corresponds to an alternating stress value of $S_a = 3S_m = 60$ ksi. The corresponding number of cycles for a value of $S_a = 60$ ksi is greater than 6,000 from Figure I-9.2 and Table I-9.2 of the ASME Code [12]. The package undergoes one atmospheric-to-operating pressure cycle per shipment, therefore the package will experience 1,250 atmospheric-to-operating pressure cycles in its life. Since the allowable number of cycles is greater than the maximum expected number of cycles, the first criterion is satisfied.

__(2) Normal Service Pressure Fluctuation:__ The specified full range of pressure fluctuations during normal service does not exceed the quantity 1/3 × Design Pressure × (S_a/S_m), where the Design Pressure is 25 psi, S_a is the value obtained from the Type 304 stainless steel design fatigue curve for the total specified number of significant pressure fluctuations (SPF), and S_m is the allowable stress intensity for the material at the service temperature. The total number of service cycles is based on the fill gas extreme temperature range as stated below. Conservatively, two complete temperature cycles are assumed to occur for each of the 1,250 lifetime shipments for a total quantity of 2,500 pressure fluctuation cycles. From Table I-9.2, S_a = 80,140 psi for 2,500 cycles. The value of S_m was defined above as 20 ksi at service temperature. The limiting full range of pressure fluctuation (FRF) becomes:

$$FRF_{LIMIT} = 1/3 \times \text{Design Pressure} \times (S_a/S_m) = 33.4 \text{ psi}$$

Next, the maximum pressure fluctuations in the package will be determined. Of note, the maximum pressure fluctuations will be conservatively assumed to be above the significance level, and therefore the value SPF does not need to be computed. The bulk average fill gas temperature varies between the extremes of T_1 = -40 °F and a conservative bounding temperature of T_2 = 200 °F. The maximum pressure (conservatively assuming that atmospheric pressure corresponds to -40 °F) is:

$$\frac{P_2}{P_1} = \frac{T_2}{T_1} \Rightarrow P_2 = P_1\left(\frac{T_2}{T_1}\right) = 14.7\left(\frac{200+460}{-40+460}\right) = 23.1 \text{ psia}$$

The resulting pressure fluctuation is FRF = 23.1 – 14.7 = 8.4 psi, which is less than FRF_{LIMIT} = 33.4 psi presented above and therefore, the second criterion is satisfied.

__(3) Temperature Difference — Startup and Shutdown:__ The temperature between adjacent points of a package component during normal service does not exceed $1/2(S_a/E\alpha)$, where S_a is the design fatigue curve value taken from Table I-9.2 for the total specified number of temperature difference fluctuations, E is the modulus of elasticity, and α is the mean coefficient of thermal expansion, all evaluated at temperature. The total number of temperature fluctuations will not exceed the number of uses of the package, which is 1,250 as calculated above. It will be conservative to use the value of S_a from Table I-9.2 of the ASME Code for 2,500 cycles, which is 80,140 psi. From Section 2.2.1, *Material Properties and Specifications* at a bounding temperature of 200 °F, the value of the mean thermal expansion coefficient is $\alpha = 8.9(10^{-6})$/ °F and the modulus of elasticity, $E = 27.5(10^6)$ psi. Therefore, the value of $1/2(S_a/E\alpha) = 1/2(80{,}140/[27.5(10^6)8.9(10^{-6})]) = 164$ °F. Since the package design temperature is 200 °F under ambient conditions of 100 °F, the temperature difference between any two adjacent points cannot approach the 164 °F value. Thus, the third criterion is satisfied.

__(4) Temperature Difference — Normal Service:__ The temperature difference between any two adjacent points does not change during normal service by more than the quantity $1/2(S_a/E\alpha)$, where S_a, E, and α are as defined above. However, normal operating temperatures of the containment boundary are largely determined by the steady heat load, and any changes in temperature due to changes in ambient conditions, warm-up, or cool-down will be relatively slow and even due to the large thermal mass of the package. Therefore, the fourth criterion is satisfied.

__(5) Temperature Difference — Dissimilar Materials:__ The fifth criterion is concerned with dissimilar materials. The containment boundary is constructed of Type 304 stainless steel, and includes a brass vent port plug. The ASTM B16 free-cutting brass used in the vent port plug has a coefficient of thermal expansion which is very similar to that of the stainless steel and the temperature of the plug and the surrounding steel is essentially identical. The plug is inspected at each use of the package, and is easily replaced if necessary. Alloy steel closure bolts are used to connect the two parts of the containment vessel. Consideration of the effect of temperature variation on the alloy steel closure bolts and stainless steel flanges is included in the closure bolt stress evaluation under criterion six below. Thus, dissimilar materials are not of concern and the fifth criterion is satisfied.

(6) Mechanical Loads: The specified full range of mechanical loads does not result in stresses whose range exceeds the S_a design fatigue curve for the total specified number of load fluctuations. The only repeating mechanical loads will be those associated with tightening of the closure bolts.

The maximum stress intensity developed in the closure bolts during normal operations, given in Section 2.6.1.5, *Closure Bolts*, is bounded by a value of S_{max} = 38,000 psi. This stress includes preload stress, thermal stress, and a conservative inclusion of 50% of the applied preload torque as a residual torsion stress. From Table 2.2-3, the ASME allowable stress for the bolting material, S_m, at 200 °F is 33,000 psi. As defined by Table I-9.0 of the ASME B&PV Code, the Maximum Nominal Stress (MNS) of 38,000 psi is less than $2.7S_m$ (i.e., 2.7(33,000) = 89,100 psi). Per NB-3232.3(c), a stress concentration factor of four shall be applied to one-half the value of S_{max}, i.e., $4(0.5S_{max}) = 4 \times 0.5 \times 38,000 = 76,000$ psi. Per NB-3232.3(d), the alternating stress must be adjusted for the elastic modulus used in the fatigue curves. The modulus at a temperature of 200 °F is $27.1(10^6)$ psi and the modulus used for the fatigue curve in Figure I-9.4 is $30(10^6)$ psi. The adjusted alternating stress is:

$$S_{ALT} = \frac{30}{27.1} 76 = 84.1 \text{ ksi}$$

From Table I-9.0 for figure I-9.4, the conservative lower-bound service cycles allowed for a stress of 84.1 ksi is 1,400. Since closure bolts are tightened twice per package service cycle, the allowable number of package service cycles is half of this value. Therefore the closure bolts should be replaced every 1,400/2 = 700 service cycles for the package, and the sixth criterion is satisfied.

Summary: The previous discussion verifies that fatigue failure of the packaging containment boundary due to normal operating cycles is not a concern, per Section III, Subsection NB, Article NB-3222.4(d) of the ASME Code. Therefore the resistance of the 435-B package to fatigue is adequate to ensure a minimum 25 year service life of up to 50 shipments per year.

2.1.2.3.2.2 Normal Vibration Over the Road

Fatigue associated with normal vibration over the road is addressed in Section 2.6.5, *Vibration*.

2.1.2.3.3 Buckling Assessment

Buckling, per Regulatory Guide 7.6, is an unacceptable failure mode for the containment vessel. The intent of this provision is to preclude large deformations that would compromise the validity of linear analysis assumptions and quasi-linear stress allowable limits, as given in Paragraph C.6 of Regulatory Guide 7.6.

Buckling investigations contained herein consider the cylindrical shell and torispherical heads of the 435-B package. The cylindrical shell buckling analysis is performed using the methodology of ASME B&PV Code Case N-284-2 [13]. Consistent with Regulatory Guide 7.6 philosophy, factors of safety corresponding to ASME B&PV Code, Level A and Level D service conditions are employed. For NCT (Service Level A), the factor of safety is 2.0, and for HAC (Service Level D), the factor of safety is 1.34. The torispherical head buckling analysis is performed using ASME B&PV Code, Section III, Subsection NE, Paragraph NE-3133.4(e). Buckling analysis details are provided in Section 2.6.4, *Increased External Pressure*, and Section 2.7.6, *Immersion – All Packages*. Buckling resistance to free drop impact loads is demonstrated by full scale certification test.

2.1.3 Weights and Centers of Gravity

The maximum gross weight of the 435-B package is 10,100 lb. The packaging component weights are summarized in Table 2.1-2. When transporting a LTSS, the center of gravity (CG) of the package is located 34.5 inches from the bottom outside surface of the external impact limiter. When transporting a shielded device, this dimension is 38.0 inches, assuming the shielded device is centered vertically inside the inner container. The mass moment of inertia of the cask about a transverse axis through the center of gravity is 7,370 in-lb-s^2 for LTSS transport, and 8,550 in-lb-s^2 for shielded device transport.

2.1.4 Identification of Codes and Standards for Package Design

The 435-B package is designated a Category I package. Per the guidance of NUREG/CR-3854, the appropriate design criteria for the containment is Section III, Subsection NB of the ASME B&PV Code. Consequently, the design of the containment boundary is based on the methodology of Regulatory Guide 7.6, and load cases are applied and combined according to Regulatory Guide 7.8. The closure bolts are designed using the guidance of NUREG/CR-6007.

The lodgment and the inner container are designated as "other safety" from Table 1.1 of [7], and the criteria is taken from Section III, Subsection ND of the ASME B&PV Code. For other structures such as the thermal shield, impact limiter shells, internal impact limiter components, the criteria is taken from Section III, Subsection NF of the ASME B&PV Code.

Table 2.1-1 – Containment Structure Allowable Stress Limits

Stress Category	NCT	HAC
General Primary Membrane Stress Intensity	S_m	Lesser of: $2.4S_m$, $0.7S_u$
Local Primary Membrane Stress Intensity	$1.5S_m$	Lesser of: $3.6S_m$, S_u
Primary Membrane + Bending Stress Intensity	$1.5S_m$	Lesser of: $3.6S_m$, S_u
Range of Primary + Secondary Stress Intensity	$3.0S_m$	Not Applicable
Pure Shear Stress	$0.6S_m$	$0.42S_u$
Peak	Per Section 2.1.2.3.2, *Fatigue Assessment*	
Buckling	Per Section 2.1.2.3.3, *Buckling Assessment*	
Containment Fasteners:[1]		
Average Tensile Stress Intensity	S_m [2]	Lesser of: S_y, $0.7S_u$
Average Tensile + Average Shear + Bending + Residual Torsion Stress Intensity	$1.35S_m$ for $S_u > 100$ ksi	Not Applicable

Notes:
1. Containment fastener stress limits are in accordance with NUREG/CR-6007.
2. S_m is defined as $(2/3)S_y$ as recommended by NUREG/CR-6007.

Table 2.1-2 – 435-B Package Component Weights, pounds

Item	LTSS	Shielded Device
Lower body assembly (base)	2,270	2,270
Upper body assembly (bell)	2,670	2,670
Total empty package	4,940	4,940
Lodgment	500	---
LTSS	4,660	---
Inner Container + blocking	---	1,660
Shielded Device (maximum)	---	3,500
Total package (maximum)	**10,100**	**10,100**

2.2 Materials

The 435-B package structural components, including the external impact limiter shell and the deformable tubes of the internal impact limiters, are fabricated from Type 304 stainless steel in various product forms. The lodgment and the internal impact limiter load-bearing plates are fabricated from 6061-T651 aluminum. The inner container is fabricated from Type 304 stainless steel. Polyurethane foam is used for impact energy absorption. Other materials performing a structural function are ASTM B16 UNS C36000 brass alloy (for the test and vent port plugs), and ASTM A320, L43, alloy steel for the closure bolts. Alloy steel, stainless steel, or Nitronic 60 is used for the optional thread inserts used throughout the packaging components. The containment O-ring seal is made from butyl rubber. Plastic is used for the fire-consumable vent plugs in the foam cavities. The drawings presented in Appendix 1.3.3, *Packaging General Arrangement Drawings*, delineate the specific materials used for each 435-B package component.

2.2.1 Material Properties and Specifications

Table 2.2-1 through Table 2.2-6 present the mechanical properties for the structural materials used in the 435-B package. The density of stainless steel is 0.29 lb/in^3, and Poisson's ratio is 0.31. Poisson's ratio for the alloy steel closure bolts is 0.30. The density of aluminum is 0.098 lb/in^3, and Poisson's ratio is 0.33. Data is interpolated or extrapolated from the available data, as necessary, as noted in the tables.

Per drawing 1916-01-01-SAR, Flag Note 12, the cylindrical side shell and the torispherical head of the upper body assembly are made from ASTM A240 Type 304 plate, having a minimum yield of 40 ksi and a minimum ultimate strength of 80 ksi, which are higher than the strengths shown in Table 2.2-1. The increased properties are used to develop the material model for the computer model described in Appendix 2.12.4, *Finite Element Analysis*.

The performance of the 435-B package in free drop and puncture events is partially dependent on the energy-absorbing performance of polyurethane foam. The foam is poured in place within the impact limiter steel shell. Nominally 15 lb/ft^3 polyurethane foam is used. Section 8.1.5.1, *Polyurethane Foam* presents the details of acceptance tests for this material. The nominal, room-temperature crush properties of the polyurethane foam component are given in Table 2.2-6. Properties for both "parallel to rise" and "perpendicular to rise" are given. The "rise" direction is parallel to the force of gravity during solidification, and is oriented to be parallel to the cylindrical axis of the impact limiters.

2.2.2 Chemical, Galvanic, or Other Reactions

The materials of construction of the 435-B package will not have significant chemical, galvanic or other reactions in air or water environments. These materials have been previously used, without incident, in radioactive material packages for transport of similar payload materials such as the RH-TRU 72-B (NRC Docket 9212) and the BEA Research Reactor Cask (NRC Docket 9341). The polyurethane foam is fully enveloped by sheets of stainless steel and welded closed. The foam is a rigid, closed-cell (non-water absorbent) material that is free of halogens and chlorides, as discussed in Section 8.1.5.1, *Polyurethane Foam*. The lead gamma shielding in the LTSS or in the shielded devices is fully encased in a steel or stainless steel weldment and cannot be affected by water or atmospheric moisture.

The brass alloy vent port plug is very corrosion resistant. Any damage that could occur to the material is easily detectable since the fitting is handled each time the 435-B package is loaded and unloaded. Similarly, the alloy steel closure bolts, which are plated with corrosion-resistant nickel plating, can be readily inspected at each use for the presence of corrosion. The optional alloy steel thread inserts are plated for protection against corrosion.

The butyl elastomer that is used for the containment O-ring seals contains no corrosives that would react with or adversely affect the 435-B package. This material is organic in nature and noncorrosive to the stainless steel containment boundary of the 435-B package.

A successful RAM packaging history combined with successful use of these fabrication materials in similar industrial environments ensures that the integrity of the 435-B package will not be compromised by any chemical, galvanic or other reactions.

2.2.3 Effects of Radiation on Materials

The radiation associated with the source payload will have no effect on the containment or other safety components comprising the 435-B package. Since the payload of the 435-B package is heavily shielded, the radiation exposure of the package materials (including the butyl rubber containment seal) is negligible. For these reasons, there will be no deleterious radiation effects on the packaging, and the requirements of 10 CFR §71.43(d) are met.

Table 2.2-1 – Mechanical Properties of Wrought Type 304 Stainless Steel

Material Specification	Temperature (°F)	① Yield Strength, S_y (psi)	② Ultimate Strength, S_u (psi)	③ Allowable Strength, S_m (psi)	④ Elastic Modulus, E (×10^6 psi)	⑤ Thermal Expansion Coefficient, α (×10^{-6} /°F)
ASTM A240 ASTM A249 ASTM A269 ASTM A276 ASTM A479 Type 304	-40	**30,000**	**75,000**	**20,000**	**28.9**	**8.2**
	-20	30,000	75,000	20,000	**28.8**	**8.2**
	70	30,000	75,000	20,000	28.3	8.5
	100	30,000	75,000	20,000	**28.1**	8.6
	200	25,000	71,000	20,000	27.5	8.9
	300	22,400	66,200	20,000	27.0	9.2
	400	20,700	64,000	18,600	26.4	9.5
	500	19,400	63,400	17,500	25.9	9.7
	600	18,400	63,400	16,600	25.3	9.9
	700	17,600	63,400	15,800	24.8	10.0
	800	16,900	62,800	15,200	24.1	10.1

Notes: ① ASME Code, Section II, Part D, Table Y-1. Value at -40 °F extrapolated using the values at -20 °F and 70 °F.

② ASME Code, Section II, Part D, Table U. Value at -40 °F extrapolated using the values at -20 °F and 70 °F.

③ ASME Code, Section II, Part D, Table 2A. Value at -40 °F extrapolated using the values at -20 °F and 70 °F.

④ ASME Code, Section II, Part D, Table TM-1, Material Group G. Values for -40 °F and -20 °F interpolated from 70 °F and -100 °F. Value at 100 °F interpolated using the values at 70 °F and 200 °F.

⑤ ASME Code, Section II, Part D, Table TE-1, Material Group 3, Mean Coefficient. Values for -40 °F and -20 °F extrapolated from 70 °F and 100 °F.

Table 2.2-2 – Mechanical Properties of Forged Type 304 Stainless Steel

Material Specification	Temperature (°F)	① Yield Strength, S_y (psi)	② Ultimate Strength, S_u (psi)	③ Allowable Strength, S_m (psi)	④ Elastic Modulus, E ($\times 10^6$ psi)	⑤ Thermal Expansion Coefficient, α ($\times 10^{-6}$ /°F)
ASTM A182 Type F304	-40	**30,000**	**70,000**	**20,000**	**28.9**	**8.2**
	-20	30,000	70,000	20,000	**28.8**	**8.2**
	70	30,000	70,000	20,000	28.3	8.5
	100	30,000	70,000	20,000	**28.1**	8.6
	200	25,000	66,300	20,000	27.5	8.9
	300	22,400	61,800	20,000	27.0	9.2
	400	20,700	59,700	18,600	26.4	9.5
	500	19,400	59,200	17,500	25.9	9.7
	600	18,400	59,200	16,600	25.3	9.9
	700	17,600	59,200	15,800	24.8	10.0
	800	16,900	58,600	15,200	24.1	10.1

Notes: ① ASME Code, Section II, Part D, Table Y-1. Value at -40 °F extrapolated using the values at -20 °F and 70 °F.

② ASME Code, Section II, Part D, Table U. Value at -40 °F extrapolated using the values at -20 °F and 70 °F.

③ ASME Code, Section II, Part D, Table 2A. Value at -40 °F extrapolated using the values at -20 °F and 70 °F.

④ ASME Code, Section II, Part D, Table TM-1, Material Group G. Values for -40 °F and -20 °F interpolated from 70 °F and -100 °F. Value at 100 °F interpolated using the values at 70 °F and 200 °F.

⑤ ASME Code, Section II, Part D, Table TE-1, Material Group 3, Mean Coefficient. Values for -40 °F and -20 °F extrapolated from 70 °F and 100 °F.

Table 2.2-3 – Mechanical Properties of ASTM A320, Grade L43 Alloy Bolting Material

Material Specification	Temperature (°F)	① Yield Strength, S_y (psi)	② Ultimate Strength, S_u (psi)	③ Allowable Strength, S_m (psi)	④ Elastic Modulus, E ($\times 10^6$ psi)	⑤ Thermal Expansion Coefficient, α ($\times 10^{-6}$ /°F)
ASTM A320 Grade L43	-40	**105,000**	**125,000**	**35,000**	**28.3**	**6.2**
	-20	105,000	**125,000**	35,000	**28.2**	**6.3**
	70	105,000	**125,000**	35,000	27.8	6.4
	100	105,000	125,000	35,000	**27.6**	6.5
	200	99,000	125,000	33,000	27.1	6.7
	300	95,700	125,000	31,900	26.7	6.9
	400	91,800	125,000	30,600	26.2	7.1
	500	88,500	125,000	29,500	25.7	7.3
	600	84,300	125,000	28,100	25.1	7.4
	700	79,200	125,000	26,400	24.6	7.6

Notes: ① ASME Code, Section II, Part D, Table Y-1. Value at -40 °F extrapolated using the values at -20 °F and 70 °F.

② ASME Code, Section III, Code Case N-249-14, Table 5, for AISI 4340 bar stock having a minimum yield strength of 105 ksi. Values at -40 °F through 70 °F extrapolated using the values at 100 °F and 200 °F.

③ ASME Code, Section II, Part D, Table 4. Value at -40 °F extrapolated using the values at -20 °F and 70 °F.

④ ASME Code, Section II, Part D, Table TM-1, Material Group B. Values for -40 °F and -20 °F interpolated from 70 °F and -100 °F. Value at 100 °F interpolated using the values at 70 °F and 200 °F.

⑤ ASME Code, Section II, Part D, Table TE-1, Material Group 1, Mean Coefficient. Values for -40 °F and -20 °F extrapolated from 70 °F and 100 °F.

Table 2.2-4 – Mechanical Properties of 6061-T651 Aluminum Alloy

Material Specification	Temperature (°F)	① Tensile Yield Strength, S_y (psi)	② Tensile Ultimate Strength, S_u (psi)	③ Elastic Modulus, E ($\times 10^6$ psi)	④ Thermal Expansion Coefficient, α ($\times 10^{-6}$ /°F)
ASTM B209 6061-T651	-40	**35,000**	42,000	**10.3**	**11.0**
	-20	35,000	42,000	**10.3**	**11.2**
	70	35,000	42,000	10.0	12.1
	100	35,000	41,400	**9.9**	12.4
	200	33,700	39,400	9.6	13.0
	300	27,400	31,700	9.2	13.3
	400	13,300	17,700	8.7	13.6
	450	---	---	---	13.8

Notes: ① ASME Code, Section II, Part D, Table Y-1. Value at -40 °F extrapolated using the values at -20 °F and 70 °F.

② Based on *Engineering Data for Aluminum Structures*, Section 3 of the *Aluminum Construction Manual*, The Aluminum Association, Washington, D.C., 5th Edition, 1986. Typical data for ultimate strength at temperature ($S_{u\text{-}typ}$) taken from Table 8 and reduced to expected minimum values by the ratio $S_{u\text{-}min}/S_{u\text{-}typ}$ = (42/45.1), where $S_{u\text{-}min}$ = 42 ksi from Table 3 of ASME Code, Section II, Part B, SB-209, and $S_{u\text{-}typ}$ = 45.1 ksi at 70 °F by interpolation from Table 8 of *Engineering Data for Aluminum Structures*. For example, since $S_{u\text{-}typ}$ = 42.263 ksi at 200 °F, then $S_{u\text{-}min}$ = 42.263 × (42/45.1) = 39.358 ksi ~ 39,400 psi.

③ ASME Code, Section II, Part D, Table TM-2. Values for -40 °F and -20 °F interpolated from 70 °F and -100 °F. Value at 100 °F interpolated using the values at 70 °F and 200 °F.

④ ASME Code, Section II, Part D, Table TE-2, Mean Coefficient. Values for -40 °F and -20 °F extrapolated from 70 °F and 100 °F.

Table 2.2-5 – Mechanical Properties of Brass Material

Material	Minimum Mechanical Properties
ASTM B16, UNS C36000, Temper H02	Yield Strength, σ_y = 25,000 psi Ultimate Strength, σ_u = 55,000 psi

Table 2.2-6 – Nominal Material Properties of 15 lb/ft^3 Polyurethane Foam

Property	Direction	Room Temperature Value
Compressive Strength, S	Axial (Parallel-to-Rise)	629 psi @ 10% Strain 754 psi @ 40% Strain 2,645 psi @ 70% Strain
	Radial (Perpendicular-to-Rise)	603 psi @ 10% Strain 769 psi @ 40% Strain 2,691 psi @ 70% Strain

2.3 Fabrication and Examination

2.3.1 Fabrication

The 435-B package is fabricated using conventional metal forming and joining techniques. All welding procedures and welding personnel must be qualified in accordance with Section IX of the ASME Boiler and Pressure Vessel Code [14]. Containment boundary welds are full penetration joints. All non-containment joints are fabricated in accordance with the requirements delineated on the drawings in Appendix 1.3.3, *Packaging General Arrangement Drawings*. The containment shell fabrication complies with the tolerance requirements of the ASME Code, Subsection NE, Article NE-4220 [15]. Article NE-4220 is selected because the package cylindrical shells are verified for HAC buckling performance using the ASME Code Case N-284-2. This Code Case is for Section III, Division 1, Class MC construction, and is based on the fabrication requirements of NE-4222, as stated in Section 1120 of the Code Case. Therefore, it is appropriate to fabricate the 435-B package using shell tolerances from NE-4220, rather than NB-4220.

The polyurethane foam and butyl rubber O-rings are procured using written procedures. See Section 8.1.5, *Component and Material Tests*, for details of the fabrication and performance requirements of these components.

2.3.2 Examination

Each of the materials performing a significant safety function must meet the ASTM specifications delineated on the drawings in Appendix 1.3.3, *Packaging General Arrangement Drawings*. Safety-significant materials not having an ASTM designation are controlled by means of written procedures whose requirements are summarized in Section 8.1.5, *Component and Material Tests*.

Forgings are subject to ultrasonic and liquid penetrant inspection per the ASME Code, Subsection NB, Article NB-2540 [16]. All welds are subject to visual examination per AWS D1.6 [17]. The full penetration welds utilized in the containment boundary are subject to radiographic inspection in accordance with the ASME Code, Subsection NB, Article NB-5000, and Section V, Article 2 [18] and liquid penetrant inspection on the final pass in accordance with the ASME Code, Subsection NB, Article NB-5000, and Section V, Article 6 [19]. All other welds on the packaging except seal welds are liquid penetrant inspected on the final pass in accordance with the ASME Code, Subsection NF, Article NF-5000, and Section V, Article 6 [20]. Welds on the lodgment are subject to visual examination per AWS D1.2 [26]. Welds on the inner container are subject to visual examination per [17] and, when specified, to liquid penetrant inspection in accordance with [20].

Each 435-B package will also be subjected to the following tests:

- An internal pressure test, in which the containment boundary is pressurized to 125% of the design pressure per the ASME Code [21], or 150% of the MNOP, per 10 CFR §71.85(b), whichever is greater. The pressure test requirements are described in Section 8.1.3.2, *Containment Boundary Pressure Testing*.
- Containment boundary leakage rate test, which includes helium leakage rate tests of the containment boundary, the main containment O-ring seal, and the vent port containment O-ring seal. The leakage rate test requirements are described in Section 8.1.4, *Fabrication Leakage Rate Tests*.

2.4 General Standards for All Packages

This section defines the general standards for all packages. The 435-B package meets all requirements delineated for this section.

2.4.1 Minimum Package Size

The minimum dimension of the 435-B package is approximately 45 inches (the upper torispherical head thermal shield outer diameter). Thus, the 4-in. minimum requirement of 10 CFR §71.43(a) is satisfied.

2.4.2 Tamper-Indicating Feature

A tamper-indicating seal is made by passing a lock wire through a hole in two adjacent rain shield retention bolts. The wire must be destroyed in order to remove the rain shield segment, which would be necessary to access the closure bolts beneath the rain shield. Destruction of the wire provides evidence of possible tampering. Thus, the requirement of 10 CFR §71.43(b) is satisfied.

2.4.3 Positive Closure

The 435-B package cannot be opened unintentionally. The two rain shield segments, which are each attached using ½-inch diameter bolts, blocks access to the closure bolts and to the vent and seal test ports. Thus, the requirements of 10 CFR §71.43(c) are satisfied.

2.4.4 Valves

The containment boundary of the 435-B package does not contain any valves. The upper flange contains one vent port which penetrates the containment boundary and which is closed with a brass port plug. The vent port is closed and tested during pre-shipment leak testing of the 435-B package. The port is protected from inadvertent use or from tampering by the rain shield as described above. Thus, the requirements of 10 CFR §71.43(e) are satisfied.

2.4.5 Package Design

As shown in Chapter 2.0, *Structural Evaluation*, Chapter 3.0, *Thermal Evaluation*, and Chapter 5.0, *Shielding Evaluation*, the structural, thermal, and shielding requirements, respectively, of 10 CFR §71.43(f) are satisfied for the 435-B package.

2.4.6 External Temperatures

As shown in Table 3.3-1 from Section 3.3, *Thermal Evaluation for Normal Conditions of Transport*, the maximum accessible surface temperature with maximum internal decay heat load and no insolation is bounded by 122 °F. This satisfies the limit of 10 CFR §71.43(g) for non-exclusive use shipments.

2.4.7 Venting

The 435-B package does not include any features intended to allow continuous venting of the containment boundary during transport. Thus, the requirements of 10 CFR §71.43(h) are satisfied.

2.5 Lifting and Tie–down Standards for All Packages

2.5.1 Lifting Devices

The 435-B package is only lifted by means of a pallet using a fork truck. The threaded hole in the center of the upper torispherical head is not used for lifting the package, and is labeled "Bell Lift Only" (i.e., upper body assembly lift only). Since there are no lifting attachments used to lift the package that are structural parts of the package, 10 CFR §71.45(a) does not apply to the 435-B.

2.5.2 Tie–down Devices

During transport, the 435-B package rests on a pallet, and is held down to the pallet by means of flexible straps which go over the top of the impact limiter and which fasten to the conveyance or the pallet. An optional tiedown method is by means of a metal frame or brackets, which bear against the top of the impact limiter and which is fastened to the conveyance or the pallet. In either case, the tiedown loads are applied to the package through the top slanted surface of the impact limiter as shown in Figure 2.5-1. Chocks are attached to the conveyance to react lateral loads through the pallet. In this configuration, the 435-B contacts only the pallet on the bottom and the flexible straps or metal frame/brackets on the top of the impact limiter, and therefore has no integral tie-down devices which are a structural part of the package. Therefore, per 10 CFR §71.45(b)(1), no evaluation of tie-down devices is required.

The threaded hole in the top of the package used for lifting the upper body assembly is covered by mechanical means, such as a bolt, during transport. Thus, 10 CFR §71.45(b)(2) is satisfied.

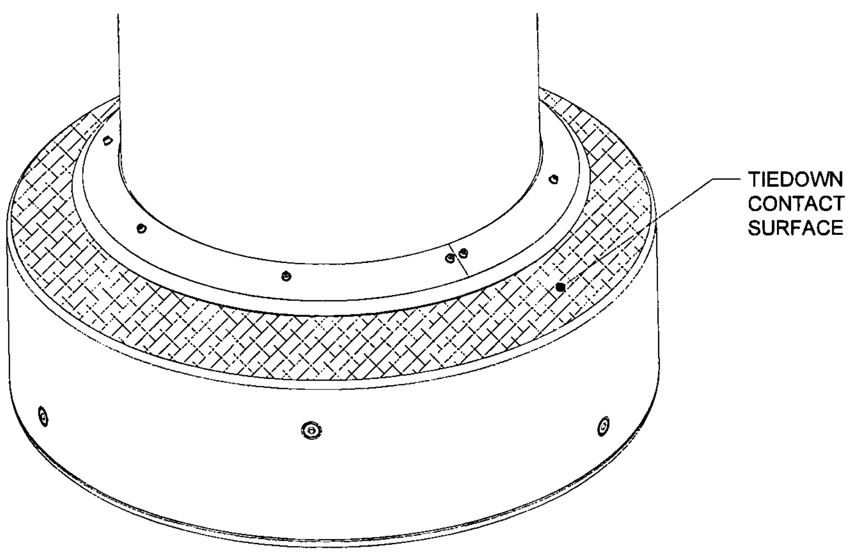


Figure 2.5-1 – 435-B Tiedown Contact Surface

2.6 Normal Conditions of Transport

When subjected to normal conditions of transport (NCT) as specified in 10 CFR §71.71, the 435-B package meets the performance requirements specified in Subpart E of 10 CFR 71. This is demonstrated in the following subsections where each NCT condition is addressed and shown to meet the applicable design criteria. Load combinations used in this section are consistent with Regulatory Guide 7.8.

2.6.1 Heat

The normal heat condition, as defined in 10 CFR §71.71(c)(1), is evaluated in Section 3.0, *Thermal Evaluation*. The bounding temperatures and pressures for use in structural analyses are summarized in the following section. Material properties and stress limits, consistent with the design criteria shown in Table 2.1-1, are summarized for the relevant bounding temperatures in Table 2.6-1.

2.6.1.1 Summary of Pressures and Temperatures

The bounding maximum temperatures for the 100 °F ambient NCT condition of the 435-B package are presented in Table 3.1-1 of Chapter 3, *Thermal Evaluation*. All components of the package, including the containment boundary, flanges, closure bolts, and elastomer seals, are bounded by a temperature of 200 °F. The lodgment, LTSS, inner container, and shielded device temperatures are also bounded by a value of 200 °F. The bulk average polyurethane foam in the impact limiter is bounded by a temperature of 150 °F.

The initial pressure in the package at assembly is ambient, i.e., 14.7 psia. As determined in Section 3.3.2, *Maximum Normal Operating Pressure*, the maximum normal operating pressure (MNOP) can be conservatively defined to be 5 psig. The design pressure of the 435-B package is 25 psig, which is significantly higher than the MNOP.

2.6.1.2 Differential Thermal Expansion

The following calculations demonstrate a positive clearance between the 435-B payload cavity and the lodgment, conservatively neglecting the expansion of the payload cavity itself. Since the coefficient of thermal expansion of aluminum (used for the lodgment) is significantly greater than that of stainless steel (used for the inner container), and since the lodgment and inner container have the same bounding dimensions and tolerances, the clearances applicable to the lodgment bound those that would occur when using the inner container.

The payload cavity has a nominal length of 60.30 inches with a tolerance of ± 0.25 inches, giving a minimum length of 60.05 inches. The lodgment has a nominal length of 59.50 inches with a tolerance of ± 0.25 inches, giving a maximum length of 59.75 inches, for a minimum room temperature axial clearance of 0.3 inches. The length of the lodgment at the NCT warm case temperature of 200 °F is:

$$L = 59.75[1 + \alpha(200 - 70)] = 59.85 \text{ inches}$$

where the coefficient of thermal expansion for the aluminum lodgment, $\alpha = 13.0(10^{-6})$ in/in/°F from Table 2.2-4, and the reference temperature is 70 °F. The increase in length of the lodgment is therefore 59.85 – 59.75 = 0.1 inches. The minimum axial clearance, conservatively neglecting any expansion of the payload cavity length, is:

$$CLR_{axial} = 0.3 - 0.1 = 0.2 \text{ inches}$$

The payload cavity has a nominal inner diameter of 43.5 inches with a tolerance of ± 0.3 inches, giving a minimum diameter of 43.2 inches. The lodgment has a nominal diameter of 42.75 inches with a tolerance of ± 0.12 inches, giving a maximum diameter of 42.87 inches, for a minimum room temperature diametral clearance of 0.33 inches. The diameter of the lodgment at the NCT warm case temperature of 200 °F is:

$$L = 42.87[1 + \alpha(200 - 70)] = 42.94 \text{ inches}$$

where α is defined above. The increase in diameter of the lodgment is therefore 42.94 – 42.87 = 0.07 inches. The minimum diametral clearance, conservatively neglecting any expansion of the payload cavity diameter (which would be of a similar magnitude to that of the lodgment), is:

$$CLR_{diametral} = 0.33 - 0.07 = 0.26 \text{ inches}$$

Thus, clearance is maintained at the maximum NCT warm temperature.

2.6.1.3 Stress Calculations

2.6.1.3.1 Stresses Due to Pressure Loading

The stress in the torispherical heads due to the design pressure is found from the ASME Code, Section VIII, Subsection UG-32(e) [33]. This paragraph is applicable since $t/L = 0.011 > 0.002$, where the thickness of the head, $t = 0.5$ inches, and the inside crown radius, $L = 43.5$ inches. Further, the inside knuckle radius, $r = 3.5$ inches, is over 6% of the inside crown radius ($r/L \times 100 = 8.0\%$).

The formula given in the code is:

$$t = \frac{0.885PL}{SE - 0.1P}$$

where P is the internal design pressure, equal to 25 psi, E is the joint efficiency, which for a full penetration, radiographed joint as used in the containment of the 435-B is equal to unity as specified in Subsection UW-12, and S is the maximum allowable stress. Solving this relation for the stress:

$$S = \frac{P(0.885L + 0.1t)}{Et} = 1{,}927 \text{ psi}$$

For the cylindrical sidewall of the containment, the stress is:

$$S_c = \frac{Pr_{avg}}{t_c} = 1{,}100 \text{ psi}$$

where $r_{avg} = 22.0$ inches is the meridional radius of the shell, and $t_c = 0.5$ inches. The bounding stress in the containment is therefore 1,927 psi in the upper or lower torispherical head.

2.6.1.3.2 Stresses Due to Thermal Loading

Since the 435-B package has a simple pressure vessel design, having relatively modest temperature gradients (see Figure 3.3-1 and Figure 3.3-3) and no significant restraints against thermal expansion, the thermal stresses due to NCT temperatures will not be significant, and are not specifically evaluated.

2.6.1.4 Comparison with Allowable Stresses

The bounding stress in the torispherical head determined above will be conservatively compared to the minimum, i.e., the membrane allowable stress. From Table 2.1-1, the limit on primary membrane stress is S_m. At the bounding temperature of 200 °F given in Section 2.6.1.1, *Summary of Pressures and Temperatures*, the value of S_m for Type 304 is 20,000 psi from Table 2.6-1. Applying this limit to the bounding stress intensity of 1,927 psi calculated for the torispherical head, the margin of safety is:

$$MS = \frac{20{,}000}{1{,}927} - 1 = +9.4$$

Thus, the margin of safety for the NCT warm condition is large.

2.6.1.5 Closure Bolts

Twenty-four closure bolts attach the upper body assembly to the lower body assembly. The closure joint is sized such that support against lateral loads (i.e., loads in the plane of the joint) is obtained from the radial bearing between the flanges, thus preventing any shear loading of the closure bolts.

The closure bolts are tightened to 300 ± 30 ft-lb of torque, or a maximum of 330 ft-lb. From Section 4.2 of [10], the maximum non-prying tensile force per bolt due to the preload, Fa_max, is found from:

$$Fa\_max = \frac{Q\max}{(K)(Db)} = 21{,}120 \text{ lb}$$

where Qmax = 330 × 12 = 3,960 in-lb is the maximum bolt torque, K = 0.15 is the nut factor for a lubricated bolt (approximately equal to the average of the values for lubricated surfaces in Table 4.1 of [10]), and Db = 1.25 inches is the nominal diameter of the closure bolt. The maximum residual torsion is 50% of the applied torsion, or:

$$Mtr = 0.5(Q\max) = 1{,}980 \text{ in} - \text{lb}$$

From Section 4.4 of [10], the maximum non-prying tensile force per bolt, Fa_max, due to pressure loads are:

$$Fa\_max = \frac{\pi Dlg^2(Pli - Plo)}{4Nb} = 2{,}787 \text{ lb}$$

where Dlg = 48.5 inches is the diameter of the pressure boundary, which for convenience is conservatively taken as equal to the bolt circle, Pli = 25 psig + 14.7 psia = 39.7 psia is the internal pressure, Plo = 3.5 psia is the NCT cold external reduced pressure from Section 2.6.3, *Reduced External Pressure*, and Nb = 24 is the quantity of closure bolts. From this it is clear that the preload force is governing over the pressure force.

Even though the temperatures of the closure joint and the bolts are the same, a thermally induced loading is applied to the closure bolts due to the difference in thermal expansion coefficient between the ASTM A320 L43 alloy steel closure bolts and the Type 304 stainless steel closure flange. From Section 4.5 of [10], the maximum non-prying tensile force due to thermal expansion effects is:

$$Fa = \frac{\pi}{4} Db^2 (Eb)[al(Tl) - ab(Tb)] = 9{,}511 \text{ lb}$$

where the modulus of elasticity of the bolt, $Eb = 27.1(10^6)$ psi, the thermal expansion coefficient of the closure joint, $al = 8.9(10^{-6})$ in/in/°F, and the thermal expansion coefficient of the bolt, $ab = 6.7(10^{-6})$ in/in/°F, all from Table 2.6-1. The change in temperature of both components, Tl = Tb = (200 – 70) = 130 °F, where the bounding temperature of the components is 200 °F, and the ambient temperature is 70 °F.

The maximum stress in the bolt occurs in the shank, which is necked down to a value of 1.09 inches (slightly below the thread root diameter). The area of the shank is:

$$A_{sh} = \frac{\pi}{4}\left(1.09^2\right) = 0.933 \text{ in}^2$$

The average axial bolt stress corresponding to these loadings is:

$$Sba = \frac{(21{,}120 + 9{,}511)}{A_{sh}} = 32{,}831 \text{ psi}$$

where the load term in the numerator is the sum of the preload and thermal loads. The residual torsional stress is:

$$Sbt = \frac{(Mtr)c}{J} = 7{,}763 \text{ psi}$$

where J is the torsional moment of inertia and c is the shank radius, equal to:

$$J = \frac{\pi\left(1.09^4\right)}{32} = 0.139 \text{ in}^4 \qquad c = 1.09/2 = 0.545 \text{ in}$$

From Table 2.1-1, for NCT the allowable average tensile stress is $S_m = (2/3)S_y$, which from Table 2.6-1 is equal to 66,000 psi at the NCT hot temperature of 200 °F. The margin of safety is:

$$MS_{Sba} = \frac{66{,}000}{Sba} - 1 = +1.01$$

Combining the axial and residual torsional shear stresses, the maximum closure bolt stress intensity is:

$$Sbi = \sqrt{Sba^2 + 4Sbt^2} = 36{,}317 \text{ psi}$$

From Table 2.1-1, the allowable stress intensity is $1.35S_m$ for cases where S_y is greater than 100 ksi. The margin of safety is:

$$MS_{Sbi} = \frac{1.35(66{,}000)}{Sbi} - 1 = +1.45$$

Thus the closure bolts are not of concern for the NCT warm condition, including the reduced external pressure load case.

2.6.2 Cold

For the cold condition, a -40 °F steady state ambient temperature is utilized per Regulatory Guide 7.8 [3], with zero insolation and zero decay heat. This results in a uniform temperature of -40 °F throughout the cask. The materials of construction for the 435-B package are not adversely affected by the -40 °F condition, including brittle fracture, which is evaluated in Section 2.1.2.3.1, *Brittle Fracture*.

Since the coefficient of thermal expansion of the flange material is slightly larger than that of the bolting material, a reduction in closure bolt preload will occur at the NCT cold condition. Using the terminology of [10], the reduction in preload is:

$$Fa = \frac{\pi}{4} Db^2 (Eb)[al(Tl) - ab(Tb)] = -7{,}640 \text{ lb}$$

where the bolt nominal diameter, Db = 1.25 inches, the bolt modulus of elasticity, Eb = $28.3(10^6)$ psi, the coefficient of thermal expansion of the flange material, al = $8.2(10^{-6})$ in/in/°F for Type 304 stainless steel, the coefficient of thermal expansion of the bolt material, ab = $6.2(10^{-6})$ in/in/°F for A320 L43 alloy steel, and Tl = Tb = –40 – 70 = –110 °F. The material properties are taken from Table 2.6-1. The minimum bolt preload torque is 300 ft-lb minus 30 ft-lb, or Qmin = 3,240 in-lb. The minimum bolt preload force is:

$$Fa\_min = \frac{Qmin}{K(Db)} = 17{,}280 \text{ lb}$$

where Db is defined above and K = 0.15, consistent with the definition in Section 2.6.1.5, *Closure Bolts*. Accounting for differential thermal expansion, the remaining preload is 17,280 – 7,640 = 9,640 lb. Thus a large positive preload force remains at the NCT minimum temperature of -40 °F.

2.6.3 Reduced External Pressure

The effect of reduced external pressure of 3.5 psia, per 10 CFR §71.71(c)(3), is considered negligible for the 435-B package compared to other design loadings. This conclusion is based on the NCT structural analyses presented in Section 2.6.1, *Heat*, demonstrating the structural integrity for a 25 psig internal design pressure. Based on the Maximum Normal Operating Pressure (MNOP) of 5 psig, the reduced external pressure conditions would cause a pressure of 16.2 psig. Therefore, the 25 psig internal design pressure analysis is conservatively bounding for the reduced external pressure case.

2.6.4 Increased External Pressure

The effect of an increased external pressure of 20 psia, per 10 CFR §71.71(c)(4), is acceptable for the 435-B package. Consistent with Regulatory Guide 7.8, this loading corresponds to an ambient temperature of -20 °F, no insolation, no decay heat, and minimum internal pressure.

As stated in Chapter 7, *Package Operations*, at the time of shipment, the package cavity is backfilled to a pressure of approximately one atmosphere, or 14.7 psia. Since the cask is closed under ambient conditions, the internal pressure in the cask at a temperature of -20 °F is

$$p_i = p_{amb}\frac{(-20 + 460)}{(70 + 460)} = 12.2 \text{ psia}$$

where p_{amb} is 14.7 psia. Therefore the net external differential gas pressure $p_o = 20 - 12.2 = 7.8$ psi. The compressive hoop stress is:

$$\sigma_\theta = p_o\frac{r_{avg}}{t} = 343 \text{ psi}$$

where the meridional radius, $r_{avg} = 22.0$ inches and the wall thickness, $t = 0.5$ inches. It is evident from this small resultant that a significant state of stress will not occur from the increased external pressure case. In addition, the package is subjected to an external pressure differential of a full atmosphere (14.7 psi) during the fabrication verification leakage rate testing (see Section 8.1.4, *Fabrication Leakage Rate Tests*) and at maintenance intervals (see Section 8.2.2, *Maintenance/Periodic Leakage Rate Tests*), without evidence of buckling or distortion. The factor of safety on buckling is therefore at least equal to 14.7/7.8 = 1.9. The actual factor of safety is much higher than 2.0 since the package is routinely subjected to a full vacuum without imminent risk of buckling. This is consistent with the factor of safety recommended in [13] for NCT. Thus, the increased external pressure load case is not of concern for the 435-B package.

2.6.5 Vibration

The effects of vibration normally incident to transport are shown to be insignificant. Draft ANSI Standard N14.23 [23] identifies peak truck trailer vibration inputs. Table 2 of [23] shows peak vibration accelerations of a trailer bed as a function of package and tiedown system natural frequency. For the frequency range 0 to 5 Hz, and conservatively assuming a light package, Table 2 gives peak accelerations (99% level) of 2*g* in the vertical direction, and 0.1*g* in both the lateral and longitudinal directions. All other frequency ranges give significantly lower acceleration levels. Due to cask symmetry, the vertical load of ±2*g* governs the ±0.1*g* in the lateral and longitudinal directions.

Design fatigue curves are taken from Figure I-9.2 and Table I-9.2 of [12] for the Type 304 stainless steel cask material, from which the allowable amplitude, S_a, of the alternating stress component (1/2 of the alternating stress range) as a function of number of loading cycles may be obtained. The allowable amplitude, S_a at the fatigue limit, which is used in the fatigue assessment of transportation vibration, is 13,600 psi from Table I-9.2 for Type 304 stainless steel cask material at 10^{11} cycles. This value is adjusted based on the ratio of room temperature elastic modulus of $28.3(10)^6$ psi, which is the basis for Table I-9.2, and the elastic modulus at NCT maximum temperature, as follows:

$$S_a = 13{,}600\left[\frac{27.5(10^6)}{28.3(10^6)}\right] = 13{,}216 \text{ psi}$$

where $27.5(10^6)$ psi is the elastic modulus at the bounding temperature of 200 °F from Table 2.6-1.

The 435-B package is transported vertically. In this orientation, the upper torispherical head experiences the ±2g loading as a transverse load (i.e., along the package axis). Conservatively, the head will be evaluated as a simply supported flat plate having the same mass. This representation has much less transverse stiffness and results in larger vibrational stress than would occur in the actual head. The weight of the head, including the crown, knuckle, and lifting boss, is bounded by W = 310 lb. The diameter of the plate is equal to the outside diameter of the head skirt of 44.5 inches, or a = 44.5/2 = 22.25 inches. The projected area of the plate is thus

$$A = \pi a^2 = 1{,}555.3 \text{ in}^2$$

Under a load of 2g, the maximum bending moment in the plate (at the center) is found from Table 24, Case 10a of [24], and is:

$$M = 2K_M q a^2 = 40.8 \text{ in} - \text{lb/in}$$

where the factor 2 is the vibrational load, $K_M = 0.20625$ for $r_o = 0$ from [24], the plate radius, a, is defined above, and q is the 1-g plate loading, equivalent to a pressure, found from:

$$q = \frac{W}{A} = 0.2 \text{ psi}$$

where W and A are defined above. The stress in the flat head is:

$$\sigma = \frac{6M}{t^2} = 979.2 \text{ psi}$$

where the thickness of the head, t = 0.5 inches. For the allowable amplitude, S_a, found above, equal to 13,216 psi, the margin of safety against fatigue of the torispherical head due to vibration is:

$$MS = \frac{13{,}216}{979.2} - 1 = +12.5$$

Therefore, fatigue of the 435-B package due to transportation vibration is not of concern.

2.6.6 Water Spray

The materials of construction used in the 435-B package are not affected by the water spray test identified in 10 CFR §71.71(c)(6).

2.6.7 Free Drop

Section 10 CFR §71.71(c)(7) specifies a free drop from a height of 4 ft for a package weight less than 11,000 lb. As discussed in Appendix 2.12.2, *Certification Test Plan*, each HAC, 30-ft free drop was preceded by a NCT, 4-ft free drop in the same orientation and impact location, and performed at the same worst-case temperatures as the HAC free drop. Because the NCT and HAC free drops were identical (except for the drop height), the damage resulting from any NCT free drop was similar to the corresponding HAC damage, except having a significantly lesser magnitude. The damage resulting from the bounding HAC free drops is described and illustrated by photographs in Appendix 2.12.3, *Certification Test Results*. The impact magnitudes of the NCT and HAC free drops, as recorded by active accelerometers, is given in Appendix 2.12.3. Since the packaging containment was leaktight per the requirements of [3] after each full sequence of NCT free drop, HAC free drop, and HAC puncture drop, then the packaging was leaktight following all NCT free drops. Thus, the effects of the damage resulting from the NCT free drop is demonstrated not to affect the ability of the 435-B package to meet the HAC requirements of 10 CFR §71.73.

2.6.8 Corner Drop

The 435-B package is not required to be evaluated for the corner drop condition, since 10 CFR §71.71(c)(8) applies only to rectangular fiberboard or wood packages weighing less than 110 lb or to cylindrical fiberboard or wood packages weighing less than 220 lb. The weight of the 435-B package exceeds these limits and therefore does not need to be evaluated for the NCT corner drop.

2.6.9 Compression

Section 10 CFR §71.71(c)(9) specifies, for packages weighing up to 11,000 lb, a compression loading equal to the greater of the equivalent of five times the package weight or 2 lb/in^2 over the package projected area. Since the 435-B weighs 10,100 lb, five times the package weight is W = 50,500 lb. The projected area of the head thermal shield, having an outer diameter of 44.9 inches, is A = 1,583 in^2. The resulting pressure, W/A = 31.9 psi. This is greater than 2 psi and is thus required to be used for this evaluation.

As shown in Section 2.7.6, *Immersion – All Packages*, the maximum pressure loading which may be applied to the head per ASME B&PV Code, Section III, Subsection NE-3133.4(e) (before application of the factor of 1.5 for HAC) is 92.0 psi. Since this pressure is nearly three times the bounding compression loading determined above, the compression load on the 435-B package is not of concern.

2.6.10 Penetration

The impact of a 1.25–inch diameter, hemispherically ended, 13–lb steel bar, per 10 CFR §71.71(c)(10), dropped vertically from a height of 40 inches, has no significant effect on the 435-B package. Slight denting of the thermal shield on the outside of the cask can occur, but the bar cannot penetrate or rip into the shield, and cannot harm the impact limiter nor damage the ½-13 UNC rain shield attachment bolts. Therefore, this test has no significant effect on the package.

Table 2.6-1 – Summary of NCT Design Parameters

Parameter	Containment (Type 304)	Closure Bolts (A320, Grade L43)
NCT Hot Bounding Temperature, °F	200	200
Coefficient of Thermal Expansion, α,(in/in/°F)	8.9×10^{-6}	6.7×10^{-6}
Elastic Modulus, psi	27.5×10^{6}	27.1×10^{6}
Design Stress, S_m, psi	20,000	66,000
Yield Stress, S_y, psi	25,000	99,000
Primary Membrane Stress Intensity (P_m), psi	$S_m = 20,000$	n/a*
Primary Membrane + Bending Stress Intensity ($P_m + P_b$), psi	$1.5S_m = 30,000$	n/a*
Primary Membrane + Bending + Secondary Stress Intensity ($P_m + P_b + Q$), psi	$3.0S_m = 60,000$	n/a*
NCT Cold Bounding Temperature, °F	-40	-40
Coefficient of Thermal Expansion, α,(in/in/°F)	8.2×10^{-6}	6.2×10^{-6}
Elastic Modulus, psi	28.9×10^{6}	28.3×10^{6}

* Bolting allowable stresses are discussed in the sections where they are used.

2.7 Hypothetical Accident Conditions

When subjected to the hypothetical accident conditions (HAC) as specified in 10 CFR §71.73 [1], the 435-B package meets the performance requirements specified in Subpart E of 10 CFR 71. The method of demonstration is primarily by full-scale test. Analysis is used for all NCT except the NCT free drop, for the HAC immersion case, and to evaluate free drop orientations not tested. Three certification test units (CTUs) were used to perform a total of six, NCT 4-ft free drops, six, HAC 30-ft free drops, and seven, HAC puncture drops. The test program confirms that the 435-B containment boundary remains leaktight following a worst case HAC sequence. Deformations that could affect thermal performance are included in Chapter 3, *Thermal Analysis*. Detailed information is provided in Appendix 2.12.3, *Certification Test Results* and summarized in Section 2.7.8, *Summary of Damage*. A detailed discussion of the basis of the structural certification testing performed is provided in Appendix 2.12.2, *Certification Test Plan.*

2.7.1 Free Drop

Subpart F of 10 CFR 71 requires that a 30 ft free drop be considered. The free drop is to occur onto a flat, essentially unyielding, horizontal surface, and the cask is to strike the surface in an orientation for which maximum damage is expected. Several impact orientations and bounding ambient environments are considered. Because the NCT free drop height of 4 ft is over 13% of the HAC free drop height of 30 ft, the damage caused by the NCT free drop is explicitly considered. To maximize the accumulation of damage between the NCT and HAC free drops, each HAC free drop was preceded by a NCT free drop using the same orientation and impact location.

2.7.1.1 Technical Basis for the Free Drops

In order to determine the worst case free drop orientation, a consideration of the features of the package that could be vulnerable to damage in a free drop event was made. Components of the packaging could experience potentially significant damage as follows:

1. Closure joint, including structural deformation making the O-ring ineffective as well as impact limiter damage leading to excessive O-ring temperature in the fire.

   Free drop impact could impart significant structural loading to the closure joint bolts. Local puncture deformation could cause leakage of the joint. Inside-out deformation from a failure of the lodgment to control the LTSS (or a failure of the inner container to control the shielded device) could cause deformation in the joint. Puncture bar damage near the joint could lead to excessive O-ring temperatures in the fire event.

2. Containment boundary, either from excessive strains in the free drop impact or from the subsequent puncture.
3. Lodgment, whether from a failure to keep the LTSS from gross movement or from causing internal damage to the containment.
4. LTSS (or shielded device), by suffering damage from interaction with the lodgment (or inner container) that could reduce its shielding function.

5. Inner container, from a failure to keep the dummy device from causing internal damage to the containment.

Computer modeling is used to guide the selection of worst-case orientations. As shown in Appendix 2.12.4, *Finite Element Analysis*, and in Figure 2.12.4-43 for impact results, Figure 2.12.4-45 for foam crush results, and Figure 2.12.4-46 for containment boundary strain results, the worst case free drop orientations are as follows:

- The highest overall impact load is for the bottom-down orientation. This impact orientation applies bounding loads in the axial direction to the closure flange, to the attachment between the impact limiter and the lower flange, and to the LTSS and lodgment or to the shielded device and inner container.
- The highest lateral impact load is for the side orientation (simultaneous at each end). This impact orientation applies bounding loads in the lateral direction to the closure and to the LTSS and lodgment or to the shielded device and inner container.
- The minimum remaining polyurethane foam after crush deformation is for the side orientation. When combined with a puncture drop, this represents a possible governing case for the HAC fire event.
- The largest value of strain in the containment boundary material is essentially for the CG over knuckle orientation (head down, 63° from horizontal). It is noted from Figure 2.12.4-46 that the 70° from horizontal case exhibits slightly more strain than the CG over knuckle (32.3% vs. 31.0%). However, this difference (Δ1.3% strain) is very small, and the CG over knuckle orientation will apply the full drop energy into the package as a whole. Furthermore, the strain will be maximized by applying a puncture drop in the same location.

A more detailed discussion of the free drop orientations which were considered, including orientations that are not governing, is given in Section 2.12.2.3.1, *Free Drops*. The free drops actually performed were distributed across the three CTUs to avoid overtesting a single test unit. The tests performed and the justification for choosing them is detailed in Section 2.12.2.4, *Summary of Certification Tests*, summarized in Table 2.12.2-1, and depicted in Figure 2.12.2-1.

2.7.1.2 Certification Test Units and Test Conditions

Each of the CTUs was an essentially prototypic representation, in full scale, of the 435-B packaging. Any differences between them and the drawings in Appendix 1.3.3, *Packaging General Arrangement Drawings*, were not material, and are discussed and justified in Section 2.12.3.3, *Certification Test Unit Configuration.* CTU #1 and #2 contained a prototypic representation of the LTSS and lodgment, and CTU #3 contained an inner container and blocking, and a simulated, representative shielded device called the dummy payload. CTU #1 was tested with the polyurethane foam energy-absorbing material at cold temperature, in order to evaluate the effects of the maximum impact magnitude on the packaging and on the LTSS and lodgment. CTU #3 was also tested at cold temperature to evaluate the effects of the maximum impact magnitude on the ability of the inner container to control and protect the shielded device. One test sequence on CTU #2 was tested with the polyurethane foam at warm temperature, in order to evaluate the maximum crush deformation and the related thermal consequences, and the other test sequence on CTU #2 was performed at ambient temperature, since foam was not relevant to that test. The cold test foam, at a temperature of 0 °F or below, accurately simulated the stress-strain behavior of the prototypic foam at a temperature of -40 °F, as described in Section 2.12.3.3, *Certification Test Unit Configuration.* The low temperature of -40 °F was chosen instead of the less conservative temperature of -20 °F in order to establish the compliance of the tests with the cold environment temperature required by [27]. The warm test foam, at a temperature of 110 °F or above, approached the stress-strain behavior of the prototypic foam at a the bulk average NCT hot temperature of 150 °F. Since the test foam at the test temperature was slightly stronger than the minimum-strength prototypic foam, a small adjustment to the maximum test crush deformation is made in Section 2.7.1.5, *Results of Free Drops Evaluated by Finite Element Analysis*. Each free drop test was instrumented with active accelerometers. Refer to Section 2.12.3.2, *Test Facilities and Instrumentation*, for further detail.

2.7.1.3 Acceptance Criteria

The acceptance criteria for the free drop tests (including the subsequent puncture drop tests) is given in Section 2.12.2.5, *Acceptance Criteria*. Discussion of the test results relative to the acceptance criteria is given in Section 2.7.8, *Summary of Damage*.

2.7.1.4 Summary of the Results of the Free Drop Tests

The damage resulting from the free drop tests is summarized below, with further details and photographs given in Appendix 2.12.3, *Certification Test Results*. The principal test criterion is that, after the worst-case sequence of NCT free drop, HAC free drop, and puncture drop, the containment boundary is leaktight per the requirements of [4]. After each test sequence (or pair of test sequences), a helium leakage rate test was performed on the containment boundary penetrations, i.e., on the containment O-ring seal and on the vent port sealing washer. In each case, the seals were leak tight. At the conclusion of all testing, each containment boundary was helium leakage rate tested, and the results were leak tight.

The lodgment holding the LTSS suffered negligible damage from any of the free drops, and the position of the LTSS inside the package was essentially unchanged. The LTSS did not experience any lead slump or damage to the closure doors, thus ensuring that the radioactive sources will stay in position relative to the lead shielding.

A discussion of the shielded device payload and the inner container is given in Section 2.7.1.6, *Structural Evaluation of the Shielded Devices.*

2.7.1.4.1 Test Series D1 (Free Drops D1N and D1H)

Test Series D1 was performed on CTU #1 and consisted of a free drop in the bottom-down orientation, with the axis vertical, followed by an oblique puncture drop test (P1) on the flat bottom of the impact limiter. The polyurethane foam was chilled to a temperature of approximately -10 °F. The averaged impact acceleration is given in Table 2.7-1. Deformation of the external packaging structures from either of these tests was negligible. Internally, the lower internal impact limiter crushed approximately 1.43 inches (total from both drops). The weld connecting the impact limiter to the lower flange showed no cracking or failure. Other than some damage to the toggle clamps that secure the LTSS in position, there was no material damage to the lodgment. There was no apparent damage to the LTSS. More detail is given in Section 2.12.3.4.1, *Test Series D1*.

2.7.1.4.2 Test Series D2 (Free Drops D2N and D2H)

Test Series D2 was performed on CTU #1 and consisted of a free drop on the side of the package, with the upper torispherical knuckle and the top edge of the impact limiter contacting the ground simultaneously, followed by a puncture near to the upper knuckle free drop damage (P2). The test reused all of the same components from Test Series D1. The polyurethane foam was chilled to a temperature of approximately -9 °F. The averaged impact acceleration is given in Table 2.7-1. The deformation consisted of flat spots on the knuckle and on the impact limiter. The foam impact limiter crush equaled 4.27 inches perpendicular to the ground. The internal impact limiters did not crush significantly. The upper internal limiter aluminum plate was somewhat buckled due to the deformation that occurred in the knuckle region. There was further damage to the toggle clamps, but the lodgment damage was negligible, and the LTSS was still in its original location. The only change to the LTSS configuration was faintly visible deformations on the impact side, approximately 1/8 inches deep, that corresponded to the circular rings of the lodgment. (Since the shielding analysis conservatively considers a 0.3-inch gap between the LTSS steel shell and the lead, this dent has no effect on the calculated dose rate). The containment wall was also deformed locally approximately 1/8 inches toward the ground due to the weight of the payload in the impact. More detail is given in Section 2.12.3.4.3, *Test Series D2.*

2.7.1.4.3 Test Series D3 (Free Drops D3N and D3H)

Test Series D3 was performed on CTU #2 and consisted of a free drop in the CG-over-top knuckle orientation, followed by a puncture on the damage, in the same orientation (P3). The test used a new lodgment, but the same LTSS. The polyurethane foam did not participate in the impact and was therefore left at ambient temperature. The averaged impact acceleration is given in Table 2.7-1. The deformation consisted of a flat on the top end, biased toward one side. The package was not opened until following Test Series D4. Discussion of the internal configuration will be deferred to the following section. More detail is given in Section 2.12.3.4.4, *Test Series D3.*

2.7.1.4.4 Test Series D4 (Free Drops D4N and D4H)

Test Series D4 was performed on CTU #2 and consisted of a simultaneous side drop (the same as Test Series D2), followed by a puncture drop on the foam impact limiter deformed surface (P4). For D4, the vent port was located nearest the ground. The polyurethane foam was warmed to a core temperature of approximately 117 °F. The averaged impact acceleration is given in Table 2.7-1. The deformation consisted of flat spots on the knuckle and on the impact limiter. The foam impact limiter crush equaled 4.68 inches perpendicular to the ground. The upper internal impact limiter was crushed in the region of the D3 free drops, but the lodgment did not move significantly in an axial direction. The lodgment plates that were nearest to the D3 impact showed some very local buckling, but global damage to the lodgment was negligible, and the LTSS remained in its original position. Further damage to the LTSS was negligible. Note that the LTSS experienced four complete test series without material damage. More detail is given in Section 2.12.3.4.6, *Test Series D4.*

2.7.1.4.5 Test Series D5 (Free Drops D5N and D5H)

Test Series D5 was performed on CTU #3 and consisted of a free drop in the bottom-down orientation, with the axis vertical (identical to Test Series D1), followed by an oblique puncture drop test (P6) on the flat bottom of the impact limiter. The polyurethane foam was chilled to a temperature of approximately -5 °F. The averaged impact acceleration is given in Table 2.7-1. Deformation of the external packaging structures from either of these tests, as for the case of Test Series D1, was negligible. Crush of the lower internal impact limiter was limited. The bottom structure of the inner container deformed downward 0.9 inches. The wood dunnage inside the inner container crushed by the dummy payload. More detail is given in Section 2.12.3.4.2, *Test Series D5.*

2.7.1.4.6 Test Series D6 (Free Drops D6N and D6H)

Test Series D6 was performed on CTU #3 and consisted of a simultaneous side drop (the same as Test Series D2), followed by a puncture drop on the prototypic side thermal shield (P7) and a second puncture drop on the rain shield/tube sheet region (P5). The polyurethane foam was chilled to a temperature of approximately -3 °F. The averaged impact acceleration is given in Table 2.7-1. The deformation consisted of flat spots on the knuckle and on the impact limiter. The foam impact limiter crush equaled 3.04 inches perpendicular to the ground. The damage to the package was very similar to that sustained by CTU #1 from Test Series D2. More detail is given in Section 2.12.3.4.5, *Test Series D6.*

2.7.1.5 Results of Free Drops Evaluated by Finite Element Analysis

As discussed in Appendix 2.12.4, *Finite Element Analysis,* The results of the certification tests were used to benchmark the LS-Dyna finite element model that had been developed during the test planning stage. The benchmarking criteria were primarily measured impact acceleration and deformation. Subsequently, the model was used to perform structural evaluations that were not part of the certification testing.

2.7.1.5.1 Maximum Closure Bolt Stress

As shown in Section 2.12.4.5.2, *Slapdown Free Drop Results,* the maximum load in any closure bolt occurs for the near-vertical, bottom-down drop orientation with the cask axis at an angle of 75° from the horizontal. This orientation was not tested and is consequently evaluated using the benchmarked finite element analysis model. The resulting bolt load depends on the location of the CG of the payload. Of the two payload types (LTSS/lodgment or inner container/shielded device), the CG is highest for the inner container, since the CG of the LTSS is located below the mid-height of the lodgment, whereas the device CG may be located at the mid-height of the inner container. When loaded with a device weighing 3,500 lb located at the mid-height of the cavity and using dunnage weighing 500 lb, the center of gravity of the loaded inner container is located 30.1 inches above the outside bottom of the inner container. When inserted into the finite element model upside-down, the lodgment/LTSS CG is located 33.5 inches from the lower end (the normal top surface) of the lodgment. Therefore, using the lodgment upside-down in the analysis model will result in a conservatively bounding maximum bolt load in the worst-case free drop impact. To further maximize the bolt load, the lodgment was placed at the top of the 435-B cavity in the model, leaving a gap of 0.67 inches at the bottom at the moment of impact. The resulting maximum bolt load is 35,774 lb. (Since the maximum bolt load with the gap omitted was 33,373 lb, it can be seen that the effect of the gap is relatively small.)

From [10], the load per bolt due to the design pressure is found from:

$$Fa\_max = \frac{\pi Dlg^2(Pli - Plo)}{4Nb} = 1{,}924 \text{ lb}$$

where the pressure diameter, Dlg is taken for convenience as equal to the bolt circle of 48.5 inches, the number of bolts, Nb = 24, the internal design gage pressure, Pli = 25 psi, and the external gage pressure, Plo = 0 psi. The maximum load on a closure bolt under HAC is therefore 35,774 + 1,924 = 37,698 lb, which exceeds the preload and is conservatively bounded by a value of Fa_max = 40,000 lb. The average tensile stress is:

$$Sba = \frac{Fa\_max}{A_{sh}} = 42{,}872 \text{ psi}$$

where A_{sh} was calculated to be equal to 0.933 in^2 in Section 2.6.1.5, *Closure Bolts*. From Table 2.1-1, the allowable average stress intensity for HAC is equal to the lesser of $0.7S_u$ or S_y, which for the ASTM A320 L43 bolting material is $0.7S_u$ = 87,500 psi at 200 °F. The margin of safety is:

$$MS = \frac{87{,}500}{42{,}872} - 1 = +1.04$$

Thus, the closure bolt stress in the worst-case HAC free drop impact is not of concern.

2.7.1.5.2 Maximum Impact Limiter Crush Deformation

As shown in Figure 2.12.4-1, the strength of the polyurethane foam in the external impact limiter in the warm test (D4) was slightly stronger than the minimum strength of the prototypic, 15 lb/ft^3 foam at the bounding NCT warm environment temperature. Therefore, the maximum crush in the worst case (side-simultaneous orientation) will be slightly more than the amount measured in free drop test D4. Section 2.12.4.5.3, *Warm Free Drop Results*, describes a pair of finite element runs made to compare the foam crush from the two cases (test case, 14 lb/ft^3 density at 117 °F vs prototype case, 15 lb/ft^3 density at 150 °F). Note that the finite element runs are not intended to exactly duplicate the warm case results, but rather to determine a delta-crush amount that will be applied to the maximum certification test measurement. In the following, note that the nominal radial thickness of foam, based on the limiter OD of 70 inches, the shell thickness of ¼ inches, and the lower flange OD of 52 inches, is 8.75 inches.

For the finite element model using test conditions, the amount of foam remaining at the location of the lower flange after the impact is 2.5 inches. Since the original foam was 8.75 inches thick, the crush was 8.75 – 2.5 = 6.25 inches. Similarly, for the prototype case, the amount of foam remaining in the model is 2.0 inches, and the crush was therefore 6.75 inches. As shown in Section 2.12.3.4.6, *Test Series D4*, and in Figure 2.12.3-48, the minimum measured amount of foam remaining after the warm test was 5.13 inches, giving a crush distance of 3.62 inches. The analytical test case crush result can then be benchmarked using the factor:

$$\frac{\text{Measured test result}}{\text{Calculated test result}} = \frac{3.62}{6.25} = 0.579$$

Consequently, the expected maximum crush using prototypic, 15 lb/ft^3 foam under warm conditions is equal to 0.579 × 6.75 = 3.91 inches. The increase in crush due to the lower foam strength is 3.91 – 3.62 = 0.29 inches. This value will be conservatively rounded up to 0.5 inches. Thus, the thickness of foam remaining in the worst case, based on certification test measurements and applicable to the thermal analysis, is 5.13 – 0.5 = 4.63 inches.

2.7.1.6 Structural Evaluation of the Shielded Devices

The inner container will contain shielded devices from Group 1 and Group 3 as noted in Table 1.2-2. The devices contain the radioactive sources and provide shielding. The Sealed Source Device Registry (SSDR) number for each device is given in the table. Shielded devices are designed to be used in a normally occupied environment, and the external dose rates are small. The main structural members of the devices are made of carbon steel, stainless steel, or cast iron, and contain the lead shielding. If the radioactive source is movable, it is placed into the shielded transport position and secured. To ensure safe transport of the source, it must remain in a shielded position within the device under all NCT and HAC.

As shown in Appendix 2.12.3, *Certification Test Results*, the dummy shielded device was contained within the inner container and located using wood dunnage. In the free drop events, some of the energy of the dummy device was absorbed either by the crush of the wood dunnage (see Figure 2.12.3-15) or by deformation of the inner container (see Figure 2.12.3-37). Conversely, the lodgment and LTSS responded in a more rigid manner, having only negligible damage as shown in Figure 2.12.3-20 and Figure 2.12.3-21. For this reason, the calculated acceleration of the LTSS will bound the acceleration of the shielded device. As shown in Section 2.12.4.5.2, *Slapdown Free Drop Results*, the maximum acceleration of the LTSS is 206g in the bottom down orientation, and 228g in the side orientation. In the analyses which follow, a conservative bounding value of 300g is used. This value is valid for other kinds of dunnage such as rigid polymer foams or aluminum structures.

2.7.1.6.1 Group 1 Shielded Devices

Group 1 shielded devices have fixed, pencil-shaped sources that are held in position inside the shield by a shield plug which is welded to the outer shell. The devices are shipped with their axis vertical. Figure 2.7-1, which shows the GC-3000, illustrates the plug attachment. The plug is located in the upper right of the figure. A circular butt weld between the top plate of the plug and the outer shell of the device retains the plug in position. The plug is stepped, having a larger diameter equal to 5.75 inches and a smaller diameter equal to 4.5 inches. The overall depth of the plug is 3.5 inches. To calculate a bounding weight, it will be assumed to be of a single diameter equal to 6 inches and a depth of 4 inches, and the entire volume will be assumed to be lead (no steel). The weight of this cylinder, using a density of 0.41 lb/in^3 for lead, is 46.4 lb. The source and holder can be bounded by a block of steel 13.25 inches long, 2.5 inches wide, and 0.9 inches thick, having a weight of 8.6 lb. With an impact of 300g, the force on the weld is (46.4 + 8.6) × 300 = 16,500 lb. The circular weld has a 5.75-inch diameter on the GC-3000, but will be conservatively represented by a 5.0-inch diameter weld. A conservatively low material yield strength of 25,000 psi is assumed. The shear yield strength is therefore 0.6 × 25,000 =

15,000 psi. If the depth of penetration of the weld is *h* and the weld stress is τ, then the shear stress in the weld can be written:

$$\tau = \frac{16{,}500}{5\pi h} = 15{,}000 \text{ psi}$$

This can be solved for *h*, which is the required minimum weld penetration of 0.07 inches. Since the material thickness of the shell and the top plate of the shield plug is 3/8 inches thick, a weld penetration of 0.07 inches will be assured. (Note: full depth penetration has been confirmed during numerous device disassembly operations by a DOE contractor.) Note also that weld yield shear strength has been conservatively used instead of the ultimate shear strength. Use of ultimate strength would be justified, since the source cannot be released until the weld completely fails. In a side drop, the plug is supported by the structure of the device and no load is applied to the weld. Thus, a conservative analysis shows that the source will be retained inside the Group 1 devices in the worst-case HAC impact event.

2.7.1.6.2 Group 3 Shielded Devices

Group 3 shielded devices have a sliding source drawer. For shipping, the drawer containing the source is moved all the way to the left in Figure 2.7-2, and a shipping spacer is placed in the remaining cavity. The drawer and spacer are retained in this position by shipping retainers on each end. The retainers are made of steel, nominally 1.5 inches thick, and are retained by four, 3/8-16 UNC socket head cap screws (SHCS). The shipping retainers interlock with the body of the device on each end by means of an approximately 0.1" deep step, which prevents shear loads from being applied to the bolts. In addition, the outer edge of the retainers have a virtually full-depth taper of approximately 45°, as shown in Figure 2.7-2. This feature prevents significant side loads from being applied to the shipping retainers.

An upper bound weight which would be applied to the shipping retainer SHCS on one side in the worst case HAC drop impact can be found by assuming that the drawer is made of solid lead, 2.5 inches in diameter and 16 inches long. The drawer weight is therefore bounded by 32.2 lb. The shipping spacer is a cylinder, 11.4 inches long, 2.5 inches O.D., and ¼ inches thick, made of stainless steel. It weighs 5.8 lb. The shipping retainer can be modeled as a disk, 9 inches in diameter and 1.5 inches thick which has a bounding weight of 27.7 lb. With an impact of 300g, the load on one SHCS is:

$$F_b = 300(32.2 + 5.8 + 27.7)/4 = 4{,}928 \text{ lb}$$

The SHCS may be made of stainless steel or alloy steel. For stainless steel, ASTM standard F837 [28], Table 4, gives a minimum tensile strength for a 0.375-16 fastener made of stainless steel as 6,199 lb. For alloy steel, ASTM standard A574 [29], Table 4, gives a minimum tensile strength for the 0.375-16 fastener of 13,900 lb. The minimum margin of safety on the SHCS is for the stainless steel screw and is:

$$MS = \frac{6{,}199}{4{,}928} - 1 = +0.26$$

Thus, a conservative analysis shows that the source will be retained inside the Group 3 devices in the worst-case HAC impact event.

2.7.2 Crush

Since the weight of the 435-B package exceeds 1,100 lb, the crush test specified in 10 CFR §71.73(c)(2) does not apply.

2.7.3 Puncture

The 435-B package is evaluated for puncture resistance under HAC as defined in 10 CFR §71.73(c)(3). The puncture event is defined as a free drop from a height of 40 inches onto a vertical, cylindrical mild steel bar, 6 inches in diameter, in an orientation and in a location for which maximum damage is expected. The puncture event must occur subsequent to the free drop event. Seven different puncture tests were performed on the three 435-B CTUs.

2.7.3.1 Technical Basis for the Puncture Drops

Section 2.7.1.1, *Technical Basis for the Free Drops*, includes a list of the packaging components that are subject to possible damage in the HAC puncture drop event. The susceptibility of the 435-B package to puncture damage was considered and assumed to occur on undamaged areas as well as on prior free drop damage. As discussed in Section 2.12.2.3.2, *Puncture Drops*, the worst-case puncture drops are as follows (all punctures are through the CG, unless stated otherwise):

- A puncture directly on the prior CG-over-knuckle free drop damage would maximize the containment boundary strain, since it would add to the strain generated in the free drop.
- An oblique puncture on the bottom-down free drop damage could tear into the impact limiter shell and damage the lower torispherical head, or expose excessive amounts of polyurethane foam, with consequences for the containment seals in the HAC fire event.
- A puncture on the impact limiter side drop damage, generated in the warm side drop, would create the minimum remaining foam thickness (locally) and, if the shell tore, could expose excessive amounts of foam, with consequences for the containment seals in the HAC fire event.
- A puncture from the side on the rain shield/tube sheet region could impart enough deformation to compromise the vent port containment sealing washer, or make the rain shield unable to retain the port insulation cylinder. In order to place the puncture bar impact in the most damaging location and orientation, it may not be possible to aim the bar through the CG, however, the effect will be small.
- A puncture on the side drop damage to the knuckle would be similar to the puncture on the CG-over-corner damage to the knuckle, but in a different orientation. A puncture impact directly on the side drop knuckle damage would cause little damage, due to the geometric relationship of the CG to the damage. Therefore, an impact on the head, in the thinner knuckle region, adjacent to the side drop damage, would apply further strain deformation to the prior deformation of the containment boundary.
- A puncture on the side thermal shield could cause the relatively thinner thermal shield sheet(s) to rip and expose the inner shield sheet or even the containment boundary wall to the HAC fire heat.

A more detailed discussion of the puncture drop orientations which were considered, including orientations that are not governing, is given in Section 2.12.2.3.2, *Puncture Drops*. The seven puncture drops actually performed were distributed across the three CTUs to avoid overtesting a single test unit, and in most cases were applied on, or in relation to, prior free drop damage. The tests performed and the justification for choosing them is detailed in Section 2.12.2.4, *Summary of Certification Tests*, summarized in Table 2.12.2-1, and depicted in Figure 2.12.2-2.

2.7.3.2 Summary of the Results of the Puncture Drop Tests

The damage resulting from the puncture tests is summarized below, with further details and photographs given in Appendix 2.12.3, *Certification Test Results*. None of the puncture tests compromised the leak tight condition of the containment, nor caused exposure of excessive polyurethane foam (only one puncture test exposed any foam). There was no significant damage to either the rain shield or to the external thermal shield.

2.7.3.2.1 Puncture Drop Tests P1 and P6

Puncture tests P1 and P6 were identical tests performed on CTU #1 (subsequent to free drop test D1H) and CTU #3 (subsequent to free drop test D5H), respectively. For both tests, the package orientation, impact location, and prior free drop test were identical. CTU #1 was used to test the packaging and the lodgment/LTSS payload; CTU #3 was used to test the response of the packaging to the inner container/shielded device payload. The purpose of repeating the puncture test was to maintain consistency between the two test units. Puncture test P1 made a dent 3-1/8 inches deep, and partially cut through the impact limiter shell over a portion of the bar circumference, and exposed a segment of foam approximately 1.5 inches wide. As shown in Section 3.5.4, *'Last-A-Foam' Response under HAC Conditions*, the polyurethane foam used in the impact limiter forms a char in the hypothetical fire which will tend to block this opening from direct exposure to the flame, preventing significant local temperature peaks. Of note, no other puncture drop test exposed any foam. Puncture test P6 made a dent 1-9/16 inches deep, without cutting the shell. In neither case was any damage imparted to the lower torispherical head or lower flange. More detail is given in Section 2.12.3.4.1, *Test Series D1*, and Section 2.12.3.4.2, *Test Series D5*.

2.7.3.2.2 Puncture Drop Test P2

Puncture drop test P2 was performed on CTU #1 subsequent to free drop D2H. The bar struck the upper torispherical head adjacent to the side free drop damage to the knuckle, and left a dent approximately ¾ inches deep. There was no evidence of cracking of the containment boundary. Of note, this test was conservative because the 0.105-inch thick upper thermal shield was not present on CTU #1, which would have added to the resistance to this puncture. More detail is given in Section 2.12.3.4.3, *Test Series D2*.

2.7.3.2.3 Puncture Drop Test P3

Puncture drop test P3 was performed on CTU #2 subsequent to free drop D3H. The package orientation for the puncture drop was identical to that for the free drop. The bar struck the package at a location three inches radially inboard from the outside edge of the damaged knuckle region. The bar struck in a location such that it did not receive support from the lodgment ribs inside. The resulting dent was approximately 1-3/8 inches deep relative to the flat damaged area. More detail is given in Section 2.12.3.4.4, *Test Series D3*.

2.7.3.2.4 Puncture Drop Test P4

Puncture drop test P4 was performed on CTU #2 subsequent to free drop D4H. The bar struck the damaged impact limiter surface, through the CG, and left a dent approximately 1-1/2 inches deep. The bar did not cut the impact limiter shell. More detail is given in Section 2.12.3.4.6, *Test Series D4*.

2.7.3.2.5 Puncture Drop Test P5

Puncture drop test P5 was performed on CTU #3 subsequent to free drop D6H. The bar struck the tube sheet and deformed the edge of the sheet by approximately ½ inches. Very slight deformation of the rain shield also occurred, but none of the rain shield attachment bolts were loosened, and the rain shield still covered the bolt tubes and the vent port and seal test port tubes. More detail is given in Section 2.12.3.4.5, *Test Series D6*.

2.7.3.2.6 Puncture Drop Test P7

Puncture drop test P7 was performed on CTU #3 subsequent to free drop D6H. The bar struck the side of the package on the dual thermal shield, aiming through the CG. The resulting dent was 1-7/8 inches deep. The outer, 0.105-inch thick thermal shield shell was not cut by the puncture bar. More detail is given in Section 2.12.3.4.5, *Test Series D6*.

2.7.4 Thermal

The 435-B package is designed to withstand the HAC 30 minute fire specified in 10 CFR §71.73(c)(4). The thermal evaluation is presented in Section 3.4, *Thermal Evaluation under Hypothetical Accident Conditions*.

2.7.4.1 Summary of Pressures and Temperatures

As shown in Table 3.1-3, the maximum internal pressure as a result of the HAC fire event is 8.2 psig. This is slightly higher than the MNOP of 5 psig conservatively assumed in Section 2.6.1.1, *Summary of Pressures and Temperatures*. A value of 10 psig will be utilized in the stress calculations which follow.

From Table 3.1-1, as a result of the HAC fire event, the maximum temperature of the containment boundary occurs in the upper torispherical head and is equal to 1,269 °F. This peak temperature occurs at the end of the fire and is located in a hypothetical puncture dent, which locally compresses the head thermal shield. A peak temperature of 1,156 °F occurs at the junction between the thermal shields on the head and bell where a narrow segment of the bell is directly exposed to ambient conditions. At an alternate puncture location just above the rain shield on the side of the package, the peak temperature is 1,127 °F (see Table 3.4-1). The peak temperatures at all of these locations represent temporary excursions which exceed the continuous-duty limit for Type 304 stainless steel of 800 °F for less than one hour. The peak temperatures of the closure flanges, closure bolts, and lower torispherical head are much lower. The peak temperature of the lodgment is 449 °F and occurs at the location where the lodgment is touching the package shell at the location of the hypothetical puncture damage on the package side, as shown in Table 3.4-1 and Figure 3.4-5. At the end of the fire, this highly localized temperature rapidly falls as energy is distributed to the rest of the lodgment structure. The peak temperature of the inner container is 972 °F, which occurs in a single rib at the location of the hypothetical puncture damage on the package side, as shown in Table 3.4-3 and Figure 3.4-12. The peak temperature of the ¼-inch thick cylindrical shell of the inner container, which controls the thermal expansion, is 432 °F, from Section 3.4.3.1, *Side Drop Damage with Shielded Device Payload.*

2.7.4.2 Differential Thermal Expansion

The following calculations demonstrate a positive clearance under HAC between the 435-B payload cavity and the payload, consisting of the lodgment or inner container. The aluminum lodgment is governing due to its higher temperature (449 °F compared to 432 °F) and larger coefficient of thermal expansion. In addition, the hot rib of the inner container may locally deform under thermal expansion and have only a negligible effect on the overall length or diameter of the inner container. Thus, the clearances applicable to the lodgment bound those that would occur when using the inner container.

The payload cavity has a nominal length of 60.30 inches with a tolerance of ± 0.25 inches, giving a minimum length of 60.05 inches. The lodgment has a nominal length of 59.50 inches with a tolerance of ± 0.25 inches, giving a maximum length of 59.75 inches, for a minimum room temperature axial clearance of 0.30 inches. The maximum length of the lodgment is calculated using the peak lodgment temperature, bounded by a value of 450 °F, which occurs at the end of the HAC fire. Since the peak temperature is highly localized, this approach is very conservative. The maximum length of the lodgment is:

$$L_L = 59.75[1 + \alpha(450 - 70)] = 60.06 \text{ inches}$$

where the coefficient of thermal expansion for the aluminum lodgment at 450 °F, $\alpha = 13.8(10^{-6})$ in/in/°F from Table 2.2-4, and the reference temperature is 70 °F. The temperature of the package shell is relatively hot, but is conservatively considered to be a minimum of 100 °F, since the ambient temperature is 100 °F during the cool down period. The increased length of the package cavity is:

$$L_C = 60.05[1 + \alpha(100 - 70)] = 60.07 \text{ inches}$$

where the coefficient of thermal expansion for Type 304 at 100 °F, $\alpha = 8.6(10^{-6})$ in/in/°F from Table 2.2-1, and the reference temperature is 70 °F. The minimum axial clearance is:

$$CLR_{axial} = L_C - L_L = 0.01 \text{ inches}$$

As noted, this minimum clearance is conservatively calculated, since it considers that the localized peak temperature of the lodgment is uniform, and considers a relatively cool temperature for the package sidewall.

The payload cavity has a nominal inner diameter of 43.5 inches with a tolerance of ± 0.3 inches, giving a minimum diameter of $D_C = 43.2$ inches. The lodgment has a nominal diameter of 42.75 inches with a tolerance of ± 0.12 inches, giving a maximum diameter of 42.87 inches, for a minimum room temperature diametral clearance of 0.33 inches. The diameter of the lodgment at the bounding, uniform temperature of 450 °F is:

$$D_L = 42.87[1 + \alpha(450 - 70)] = 43.09 \text{ inches}$$

where α is defined above. The minimum diametral clearance, conservatively neglecting any expansion of the payload cavity diameter, is:

$$CLR_{diametral} = D_C - D_L = 0.11 \text{ inches}$$

Thus, positive clearance is maintained under worst case HAC.

2.7.4.3 Stress Calculations

The 435-B containment boundary is designed as a pressure vessel. As shown in Section 2.6.1.3.1, *Stresses Due to Pressure Loading*, the stress generated in the material by internal pressure is relatively small. However, for the HAC fire event, some deformation of the structure may be present. The most penalizing damage would be for the top down free drop case, since it creates a quasi-flat end on the upper end of the package, which generates higher stress than the original torispherical shape. As shown in Figure 2.12.4-76, the top down drop creates a flat approximately 38 inches in diameter, with a smooth radius connecting it to the side wall. This will be conservatively modeled using a pressurized flat plate having the full package meridional diameter of 44 inches. From [24], Table 24, Case 10b for a fixed-edge plate, the maximum bending moment in the plate is:

$$M_{ra} = \frac{qa^2}{8} = 605 \text{ in} - \text{lb/in}$$

where the pressure, q = 10 psig, and the radius, a = 22 inches. The stress (located at the plate edge) is:

$$\sigma = \frac{6M_{ra}}{t^2} = 14{,}520 \text{ psi}$$

where the thickness, t = 0.5 inches. The stress evaluation method is found in [30]. The stress rupture value is taken from Table I-14.6A at a temperature of 1,300 °F and a duration of one hour, and is equal to 23 ksi. The allowable stress is 67% of this value, or 0.67 × 23 = 15.4 ksi. The stress from the flat plate evaluation is a bending stress, which may be designated P_b. From Article NH-3223(c), K_t = 1.25. Therefore:

$$P_L + P_b / K_t = 11{,}616 \text{ psi}$$

where P_L = 0, P_b = 14,520 psi, and K_t is defined above. The margin of safety is:

$$MS = \frac{15{,}400}{11{,}616} - 1 = +0.33$$

This evaluation is carried out with the following conservative assumptions:

1. The configuration considers a flat plate geometry which is larger than the worst case configuration calculated for the free drop impact damage. Since stress is proportional to diameter squared, this overestimates the stress by approximately 34%.
2. The rupture stress is taken at a conservative temperature (1,300 °F > 1,269 °F), which underestimates the rupture stress by approximately 8%.

3. The maximum temperature is assumed to remain constant for one hour. However, the transient temperature only peaks at 1,269 °F, and falls rapidly. In fact, the length of time for which the maximum temperature exceeds 800 °F is less than one hour.
4. The pressure of 10 psig exceeds the calculated maximum pressure of 8.2 psig, which overestimates the stress by approximately 22%. Furthermore, the peak pressure occurs at a later time than the peak temperature occurs.
5. The material of the head and sidewall of the package have a minimum yield strength of 40 ksi and minimum ultimate strength of 80 ksi, which is greater than the minimum values of 30 ksi and 75 ksi, respectively. The temperature and time to which the torispherical head is exposed is not sufficient to anneal the material (i.e., to reduce the strength to minimum). However, no adjustment was made to the ASME Code minimum rupture strength value.

Thus, it is evident that the true margin of safety is larger than 0.33. In addition, the stress must meet the Level D Service Limit in Section III, Appendix F, Article F-1331.1, of $1.5\times0.7S_u = S_u$. Since S_u for Type 304 material at a temperature of 1,300 °F, from Table NH-3225-1, is 37.7 ksi, the margin of safety is:

$$MS = \frac{37{,}700}{14{,}520} - 1 = +1.60$$

Thus, stress in the HAC fire event is not of concern.

Per Regulatory Guide 7.6, paragraph C.7, the extreme range of stress must be considered. Of all the various allowable stresses corresponding to the different conditions evaluated (including fabrication stresses and normal conditions of transport), the largest allowable stress is equal to the material ultimate strength, S_u. It is therefore conservative to assume that S_u bounds all stresses actually developed in the structure. For Type 304 stainless steel, S_u = 75,000 psi at 70 °F. The maximum possible stress intensity range is twice this value, or 150,000 psi. Applying a factor of four to account for possible stress concentrations at structural discontinuities gives a total elastic stress range of 600,000 psi. The alternating component is one-half of this value, or 300,000 psi. To account for temperature effects, this value of alternating stress is factored by the ratio of modulus of elasticity. This ratio is formed between the modulus of elasticity at room temperature (at which the test data applies directly) and the modulus of elasticity at the maximum temperature, conservatively bounded by a temperature of 1300 °F for the upper torispherical head in the HAC fire event. The adjusted stress is

$$S_{alt} = 300{,}000\frac{E_{70^\circ F}}{E_{1300^\circ F}} = 418{,}227 \text{ psi}$$

where $E_{70^\circ F} = 28.3(10^6)$ psi and $E_{1300^\circ F} = 20.3(10^6)$ psi, from Table TM-1 of the ASME Code, for Material Group G. Per Figure I-9.2 and Table I-9.2 of the ASME Code [12], the allowable value for S_{alt} at 10 cycles is 870,000 psi. The margin of safety is

$$MS = \frac{870{,}000}{418{,}227} - 1 = +1.08$$

Considering the significant conservatism used in the underlying assumptions (e.g., use of allowable stress rather than smaller actual stresses, assuming worst case stresses are fully reversing, use of the maximum factor of stress concentration), it is apparent that the actual margin of safety is larger than 1.08. Thus, the requirement of paragraph C.7 of Regulatory Guide 7.6 is met.

2.7.5 Immersion – Fissile

An immersion test for fissile material packages is required by 10 CFR §71.73(c)(5). Since the 435-B package does not transport fissile materials, this requirement does not apply.

2.7.6 Immersion – All Packages

An immersion test for all packages is required by 10 CFR §71.73(c)(6), in which a separate, undamaged specimen must be subjected an equivalent pressure of 21.7 psig. The package will be evaluated for buckling resistance of the cylindrical portion of the containment boundary using Code Case N-284-2, and the torispherical heads using ASME B&PV Code, Section III, Subsection NE-3133.4(e). Although the immersion takes place in water, the maximum NCT warm temperature of 200 °F (see Section 2.6.1.1, *Summary of Pressures and Temperatures*) is conservatively utilized.

For the cylindrical side shell, the compressive hoop stress is:

$$\sigma_\theta = p_o \frac{r_{avg}}{t} = 954.8 \text{ psi}$$

where the pressure, $p_o = 21.7$ psig, the mean shell radius, $r_{avg} = 22.0$ inches, and the thickness, $t = 0.5$ inches. The compressive axial stress is:

$$\sigma_\phi = \frac{p_o \pi r_{skirt}^2}{2\pi r_{avg} t} = 488.3 \text{ psi}$$

Where the pressure load is applied to the projected area of the top of the containment boundary, having an outer radius of $r_{skirt} = 44.5/2 = 22.25$ inches. Using Mohr's circle, the maximum shear stress is:

$$\sigma_{\phi\theta} = \frac{1}{2}\left(\sigma_\theta - \sigma_\phi\right) = 233.3 \text{ psi}$$

The possibility of buckling of the inner shell is evaluated using [13]. Consistent with Regulatory Guide 7.6, a factor of safety corresponding to ASME Code, Service Level D is employed. In this case, the applicable factor of safety is 1.34 for hypothetical accident conditions, as specified in [13]. The analysis used a modulus of elasticity of $27.5(10^6)$ psi, corresponding to 200 °F. Buckling analysis geometry and loading parameters are listed in Table 2.7-2 and results of the analysis in Table 2.7-3. As shown, all interaction parameters, including the maximum value of 0.0654, are less than unity, as required.

The buckling analysis of the torispherical head is evaluated using the technique outlined in [31]. The analysis for torispherical heads is the same as for ellipsoidal heads. Factor A is found as:

$$A = \frac{0.125}{R/T} = 0.00144$$

where the inside crown radius, R = 43.5 inches, and the head thickness, T = 0.5 inches. From ASME B&PV Code, Section II, Part D, Table HA-1, the corresponding value of factor B for a temperature of 200 °F is conservatively taken as B = 8,000. The maximum allowable external pressure is:

$$P_a = \frac{B}{(R/T)} = 92.0 \text{ psig}$$

Per Article NE-3222.2, a factor of 1.5 may be applied for Service Level D conditions, which are appropriate for HAC. The permissible external pressure is therefore 1.5 × 92.0 = 138 psig. For an external pressure of 21.7 psig, the factor of safety against buckling of the torispherical head is:

$$FS = \frac{138}{21.7} = 6.4$$

This value is significantly in excess of the minimum factor of 1.34 suggested by [13]. Therefore, the immersion test is not of concern.

2.7.7 Deep Water Immersion Test (for Type B Packages Containing More than 10^5 A_2)

For Type B packages containing an activity of more than 10^5 A_2, 10 CFR §71.61 requires that an undamaged containment system withstand an external pressure of p_o = 290 psig for a period of not less than one hour without collapse, buckling, or inleakage of water. As shown in Table 1.2-1, the payload represents a maximum activity of less than 10^5 A_2. Therefore, this requirement does not apply to the 435-B package.

2.7.8 Summary of Damage

2.7.8.1 Summary of Certification Test Damage

From the discussions presented in the foregoing sections, it is shown that the hypothetical accident sequence does not result in any adverse structural damage to the 435-B package, and that the criteria established for hypothetical accident conditions in Section 2.1.2., Design Criteria, are satisfied. Full scale certification testing of free drop and puncture drop, including prior damage imposed by the NCT free drop, has demonstrated the resistance of the 435-B package to hypothetical accident conditions. A total of six potentially worst-case HAC sequences (consisting of a NCT free drop, followed by a HAC free drop followed by one or two puncture drops) were applied to three CTUs. After each test series (in one case, after a pair of test series), the main containment O-ring seal and the vent port sealing washer were leaktight to a level of 1×10^{-7} scc/sec, air, per [4]. After all testing was complete, the metallic containment boundary was leaktight as documented in Table 2.12.3-2. Deformations of the containment boundary were only observed in the upper half of the bell in connection with direct free drop or puncture impacts. No deformations were observed in the closure flanges or in the lower torispherical head, and gross buckling did not occur. None of the deformations compromised the leaktight barrier presented by the containment boundary.

The lodgment maintained the LTSS in essentially its original position in all cases. The LTSS did not experience any lead slump or deformations or other failures that could affect its ability to shield the radioactive sources transported. Since there were no loadings or evidence of damage to the LTSS end door closures, the radioactive sources within the LTSS could not change their position relative to the lead shielding. The inner container supported the shielded device and maintained it within the confines of the inner container. The inner container absorbed most of the potential energy of the device, and protected the packaging containment boundary, while absorbing some energy in the array of external ribs.

The fire analysis assumptions regarding the post-accident configuration of the packaging were supported. Particularly, the absence of significant exposure of foam and the integrity of the thermal shield shells was demonstrated. The vent port and seal test port insulation cylinders and the rain shield remained intact and in place, with no loosening of the rain shield attachment bolts.

2.7.8.2 Summary of Analytical Evaluation Results

Analytical evaluations support the conclusions stated above. The closure bolts, considering the worst case orientation and a conservative payload CG height and payload gap, have a margin of safety of 1.04. The retention of the radioactive source in the shielded position within the Group 1 or Group 3 shielded devices was demonstrated assuming conservatively bounding free drop accelerations. Utilizing a series of conservative assumptions, the stress in the containment boundary during and after the HAC fire event was demonstrated to have a minimum margin of safety of 0.33, and the range of stress, evaluated according to Reg. Guide 7.6, has a margin of safety of 1.08. The factor of safety for immersion of the package under water is 6.4.

Therefore, the 435-B satisfies all of the requirements of 10 CFR §71.73.

Table 2.7-1 – HAC Free Drop Impact Accelerations

Free Drop	Acceleration, g[1]		Comment[2]
D1H	768		Average of four accelerometer locations
D2H	466	249	Avg. of two upper locations/avg. of two lower locations
D3H	178		Average of four accelerometer locations
D4H	374	183	Avg. of two upper locations/avg. of two lower locations
D5H	812		Average of four accelerometer locations
D6H	411	173	Avg. of two upper locations/avg. of two lower locations

Notes:
1. Resolved perpendicular to the ground.
2. Accelerometer locations are described in Section 2.12.3.2.2, *Instrumentation*.

Table 2.7-2 – Immersion Test: Geometry and Loads

	Containment boundary shell dimensions, inches	Applied stress, psi	
Inner Dia.	43.5	σ_{φ}	954.8
Outer Dia.	44.5	σ_{θ}	488.3
Length (bounding)	60.0	$\sigma_{\varphi\theta}$	233.3

Table 2.7-3 – Immersion Test: N–284–2 Results

Parameter	Value	Remarks
Capacity Reduction Factors (-1511)		
$\alpha_{\phi L}$ =	0.2397	
$\alpha_{\theta L}$ =	0.8000	
$\alpha_{\phi\theta L}$ =	0.8000	
Plasticity Reduction Factors (-1610)		
η_{ϕ} =	0.2534	
η_{θ} =	0.7249	
$\eta_{\phi\theta}$ =	0.1706	
Theoretical Buckling Values (-1712.1.1)		
C_{ϕ} =	0.6050	
$\sigma_{\phi eL}$ =	378,125 psi	
$C_{\theta r}$ =	0.0544	
$\sigma_{\theta eL} = \sigma_{reL}$ =	33,982 psi	
$C_{\theta h}$ =	0.0527	
$\sigma_{\theta eL} = \sigma_{heL}$ =	32,942 psi	
$C_{\phi\theta}$ =	0.1758	
$\sigma_{\phi\theta eL}$ =	109,882 psi	
Elastic Interaction Equations (-1713.1.1)		
σ_{xa} =	67,647 psi	
σ_{ha} =	19,667 psi	
σ_{ra} =	20,288 psi	
σ_{ta} =	65,601 psi	
Axial + Shear ⇨ Check (c):	0.0072	<1 ∴ OK (see note*)
Hoop + Shear ⇨ Check (d):	0.0471	<1 ∴ OK
Inelastic Interaction Equations (-1714.2.1)		
σ_{xc} =	17,142 psi	
σ_{rc} =	14,706 psi	
σ_{tc} =	11,194 psi	
Max(Axial,Hoop) ⇨ Check (a):	0.0649	<1 ∴ OK
Axial + Shear ⇨ Check (b):	0.0289	<1 ∴ OK
Hoop + Shear ⇨ Check (c):	0.0654	<1 ∴ OK

*Note: Elastic interaction checks (a), (b), (e), and (f) are not applicable.

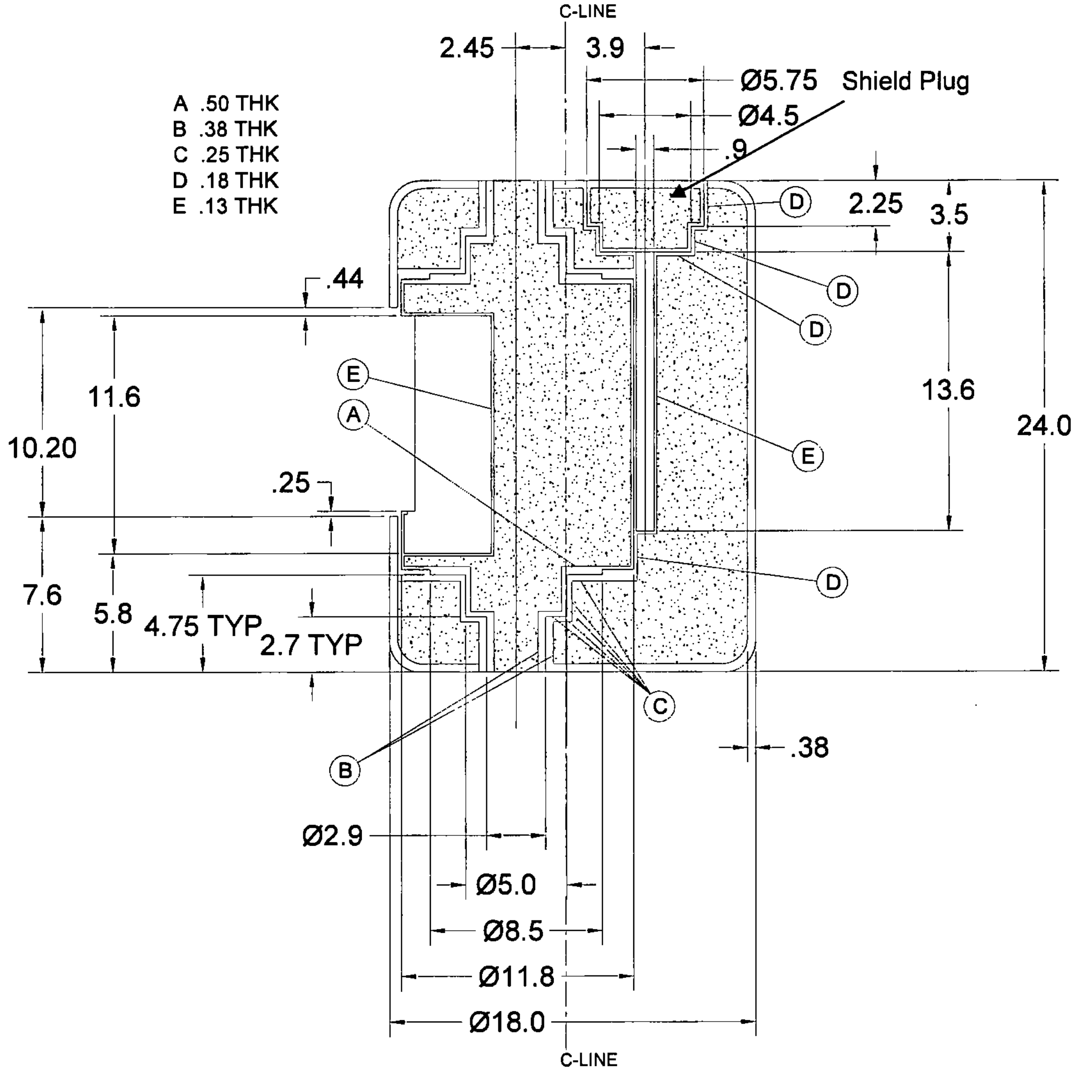


Figure 2.7-1 – Typical Shielded Device Group 1 Cross Section (Gammacell-3000)

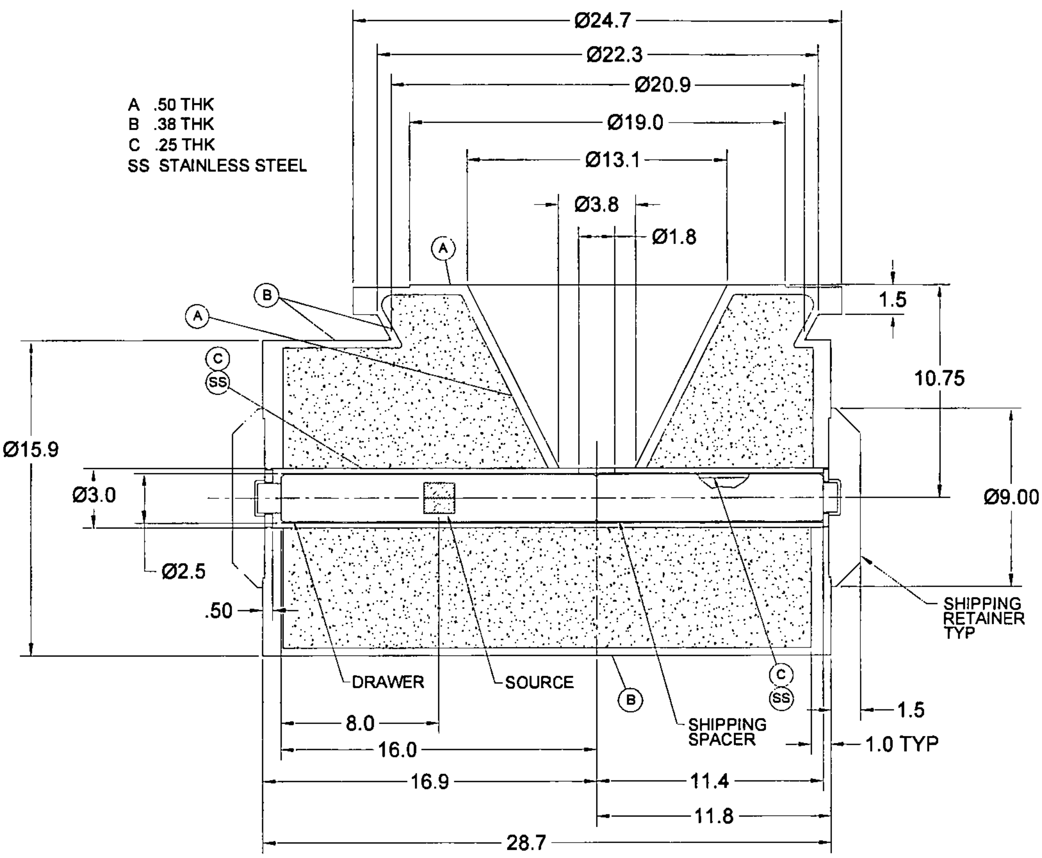


Figure 2.7-2 – Typical Shielded Device Group 3 Cross Section (GC-40)

2.8 Accident Conditions for Air Transport of Plutonium

This section does not apply, since air transport is not used for the 435-B package when transporting plutonium.

2.9 Accident Conditions for Fissile Material Packages for Air Transport

This section does not apply, since the contents of the 435-B package are fissile exempt as discussed in Chapter 6.0, *Criticality Evaluation*.

2.10 Special Form

This section does not apply, since special form is not claimed for the sources transported in the 435-B package. Most of the payloads placed into the LTSS will use special form capsules, however special form is not formally claimed for any payload.

2.11 Fuel Rods

This section does not apply, since fuel rods are not transported in the 435-B package.

2.12 Appendices

2.12.1 References

2.12.2 Certification Test Plan

2.12.3 Certification Test Results

2.12.4 Finite Element Analysis

2.12.5 Seal Performance Tests

2.12.1 References

1. Title 10, Code of Federal Regulations, Part 71 (10 CFR 71), *Packaging and Transportation of Radioactive Material*, 01–01–11 Edition.
2. U. S. Nuclear Regulatory Commission, Regulatory Guide 7.6, *Design Criteria for the Structural Analysis of Shipping Cask Containment Vessels*, Revision 1, March 1978.
3. U. S. Nuclear Regulatory Commission, Regulatory Guide 7.8, *Load Combinations for the Structural Analysis of Shipping Casks for Radioactive Material*, Revision 1, March 1989.
4. ANSI N14.5–1997, *American National Standard for Radioactive Materials – Leakage Tests on Packages for Shipment*, American National Standards Institute (ANSI), Inc.
5. U. S. Nuclear Regulatory Commission, 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)*, June 1991.
6. R. E. Monroe, H. H. Woo, and R. G. Sears, *Recommended Welding Criteria for Use in the Fabrication of Shipping Containers for Radioactive Materials*, NUREG/CR–3019, UCRL–53044, U.S. Nuclear Regulatory Commission, March 1985.
7. L. E. Fischer, W. Lai, *Fabrication Criteria for Shipping Containers,* NUREG/CR–3854, UCRL–53544, U.S. Nuclear Regulatory Commission, March 1985.
8. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, *Rules for Construction of Nuclear Facility Components*, Division 1 – Subsection NB, *Class 1 Components*, 2010 Edition.
9. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, *Rules for Construction of Nuclear Facility Components*, Division 1 – Subsection NF, *Supports,* 2010 Edition.
10. G.C. Mok, L.E. Fischer, S.T. Hsu, *Stress Analysis of Closure Bolts for Shipping Casks*, NUREG/CR–6007, UCRL–ID–110637, U.S. Nuclear Regulatory Commission, January 1993.
11. W.R. Holman, R. T. Langland, *Recommendations for Protecting Against Failure by Brittle Fracture in Ferritic Steel Shipping Containers Up to Four Inch Thick*, NUREG/CR–1815, UCRL–53013, U.S. Nuclear Regulatory Commission, August 1981.
12. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, *Rules for Construction of Nuclear Facility Components*, Appendix I, *Design Stress Intensity Values, Allowable Stresses, Material Properties, and Design Fatigue Curves*, 2010 Edition.
13. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, *Rules for Construction of Nuclear Power Plant Components*, Division 1, Class MC, Code Case N–284–2, *Metal Containment Shell Buckling Design Methods*, 2010 Edition.
14. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section IX, *Qualification Standard for Welding and Brazing Procedures, Welders, Brazers, and Welding and Brazing Operators*, 2010 Edition.

15. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, *Rules for Construction of Nuclear Facility Components*, Division 1 – Subsection NE, *Class MC Components,* Article NE–4220, 2010 Edition.
16. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, *Rules for Construction of Nuclear Facility Components*, Division 1 – Subsection NB, *Class 1 Components*, Article NB–2540, and Section V, *Nondestructive Examination*, Article 5, *Ultrasonic Examination Methods for Materials,* 2010 Edition.
17. ANSI/AWS D1.6/D1.6M:2007, *Structural Welding Code–Stainless Steel*, American Welding Society (AWS).
18. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, *Rules for Construction of Nuclear Facility Components*, Division 1 – Subsection NB, *Class 1 Components*, and Section V, *Nondestructive Examination*, Article 2, *Radiographic Examination*, 2010 Edition.
19. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, *Rules for Construction of Nuclear Facility Components*, Division 1 – Subsection NB, *Class 1 Components*, and Section V, *Nondestructive Examination*, Article 6, *Liquid Penetrant Examination*, 2010 Edition.
20. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, *Rules for Construction of Nuclear Facility Components*, Division 1 – Subsection NF, *Supports,* and Section V, *Nondestructive Examination*, Article 6, *Liquid Penetrant Examination*, 2010 Edition.
21. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, *Rules for Construction of Nuclear Facility Components*, Division 1 – Subsection NB, *Class 1 Components*, Article NB–6220, 2010 Edition.
22. Boucher, R. C., *Strength of Threads*, Product Engineering, November 27, 1961.
23. ANSI N14.23, *Design Basis for Resistance to Shock and Vibration of Radioactive Material Packages Greater Than One Ton in Truck Transport (DRAFT)*, 1980, American National Standards Institute, Inc, New York.
24. Roark's Formulas for Stress and Strain, Sixth Edition, McGraw–Hill, New York, 1989.
25. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, *Rules for Construction of Nuclear Facility Components*, Division 1 – Subsection ND, *Class 3 Components,* 2010 Edition.
26. ANSI/AWS D1.2/D1.2M:2008, *Structural Welding Code–Aluminum*, American Welding Society (AWS).
27. International Atomic Energy Agency, *Regulations for the Safe Transport of Radioactive Material*, TS-R-1.
28. F837-08, *Standard Specification for Stainless Steel Socket Head Cap Screws*, American Society for Testing and Materials (ASTM).
29. A574-11, *Standard Specification for Alloy Steel Socket Head Cap Screws*, American Society for Testing and Materials (ASTM).

30. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, *Rules for Construction of Nuclear Facility Components*, Division 1 – Subsection NH, Class 1, *Components in Elevated Temperature Service*, Article NH–3225, 2010 Edition.
31. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, *Rules for Construction of Nuclear Facility Components*, Division 1 – Subsection NE, *Class MC Components*, Article NE–3133.4(e), 2010 Edition.
32. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, *Rules for Construction of Nuclear Facility Components*, Division 1 – Appendix F, *Rules for Evaluation of Service Loadings wth Level D Service Limits*, 2010 Edition.
33. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section VIII, *Rules for Construction of Pressure Vessels*, Division 1 – Subsection A, *General Requirements*, 2010 Edition.

2.12.2 Certification Test Plan

This appendix describes the certification tests that were performed on the 435-B package. The justification for choosing the specific tests performed is presented and discussed. Since this material served for test planning purposes, the future tense is used. The results of the tests are provided in Appendix 2.12.3, *Certification Test Results.*

The licensing basis for the package will be primarily by full-scale test of Hypothetical Accident Condition (HAC) free drop and puncture. Analysis will be used for all Normal Conditions of Transport (NCT), except the NCT free drop. Analysis will also be used to determine the worst-case orientations for test, to determine the performance in orientations not tested, and for the HAC fire event.

Test data will consist of measured accelerations, measurements of the damaged configuration, and helium leak testing of the containment boundary.

2.12.2.1 Certification Objective

The objectives of the certification test program are to demonstrate the adequacy of the 435-B package and internal component design. Since the payloads provide the shielding function, they (or a generic representation) are included in the test program. The certification tests will demonstrate the performance of the package in both the NCT and HAC free drop and HAC puncture drop events. Although analysis will be used to direct the testing, primary emphasis will be placed on the test results. Free drop impact deformation and acceleration results will be used to benchmark the analysis model for use in non-tested orientations or conditions. The benchmarking analysis is provided in Appendix 2.12.4, *Finite Element Analysis.* Significant deformation or other damage to the LTSS will be used in the HAC shielding analysis. Since the LTSS has more weight and thinner outer steel shells than the shielded devices, any damage incurred by the LTSS is bounding for the devices.

The acceptance criteria for the tests is that, following the worst-case series of free drop and puncture drop events, the containment boundary and containment seals will be leaktight per the criterion of [1], i.e., a leakage rate of 1×10^{-7} scc/sec, air. In addition, the maximum combination of free drop and puncture drop deformation will be used in the thermal analysis to show that under these worst-case conditions, the elastomer O-ring seal temperature does not exceed safe limits during the HAC fire event. Finally, any deformations or damage occurring to the LTSS will not cause the HAC dose rate to exceed regulatory limits.

Several orientations will be tested to ensure that the worst-case series of free drop and puncture drop events has been considered. Due to the relative complexity of the package design and because the acceptance criteria is based on leakage rate, the certification test units will be fabricated in prototypic full-scale. Any differences which may exist between the Certification Test Units (CTUs) and a prototypic package will be described and justified in the test report.

2.12.2.2 Initial Test Conditions

2.12.2.2.1 Temperature and Pressure

For free drops where maximum impact is desired, the foam behavior must correspond to the minimum temperature of the packaging. Of the two regulations considered [2, 3], the bounding minimum temperature is -40 °F as found in [3]. At this temperature, the polyurethane foam will exhibit its maximum crush resistance and generate the maximum impact in the given orientation. Since the foam-filled impact limiter is integral with the package, the entire CTU would need to be chilled and held at this temperature for each of the relevant free drops. To avoid the need to chill such a large package to a uniform temperature of -40 °F, an equivalent foam strength may be used. The equivalent foam must exhibit essentially the same stress-strain curve as the prototypic foam, but at a somewhat higher temperature which can be achieved in certification testing. In this way, the impact obtained will be essentially the same as the impact that would be obtained using the prototypic foam at -40 °F. A foam density of 16 lb/ft^3 at a temperature of zero °F will be used. (See Section 2.12.3.3, *Certification Test Unit Configuration*, for the comparison between the strength of the foam actually used in the CTUs at the cold temperature achieved in the test, vs the maximum strength of the prototypic, 15 lb/ft^3 foam at -40 °F.)

For free drops where maximum foam crush deformation is desired, the foam behavior must correspond to the NCT warm temperature of the packaging. From preliminary thermal analysis, the bulk average foam temperature under maximum heat conditions is bounded by a temperature of 150 °F. To avoid the need to heat the package to this temperature, an equivalent foam strength may be used. The equivalent foam must exhibit essentially the same stress-strain curve as the prototypic foam, at a somewhat lower temperature. In this way, the crush deformation obtained will be essentially the same as the deformation that would be obtained using the prototypic foam at 150 °F. A foam density of 14 lb/ft^3 at a temperature of 110 °F will be used. (See Section 2.12.3.3, *Certification Test Unit Configuration*, for the comparison between the strength of the foam actually used in the CTUs at the warm temperature achieved in the test, vs the minimum strength of the prototypic, 15 lb/ft^3 foam at 150 °F.)

Since the strength of the steel will not vary greatly with temperature, any free drop tests that do not depend on foam performance, and all puncture tests, will be performed at the prevailing temperature at the time of the test.

Since the maximum normal operating pressure (MNOP) of the 435-B package is 5 psig, the hoop stress in the shell will be 220 psi. This value will not have a significant effect on the test results, and therefore the test units will not be pressurized during the tests.

2.12.2.2.2 Test Facilities and Instrumentation

The certification drop and puncture testing will be conducted using a drop pad having a mass of at least 10 times the weight of the CTU. The top of the pad must be covered by an embedded steel plate of adequate thickness such that the drop pad will represent an essentially unyielding surface. The puncture bar must be a 6-in diameter bar of mild steel, mounted perpendicular to the drop pad, and having an edge radius not exceeding 1/4-inch. The bar will be reinforced by gussets at its base and fastened securely to the pad. The length of the bar must permit the bar to do maximum damage before the package becomes supported by the drop pad, and it must be at least 8 inches long. More than one length of bar may be used. Puncture bars will not be reinforced beyond what is necessary to provide rigidity at the baseplate joint.

CTU temperature will be measured by means of thermocouples embedded in the foam. As a minimum, the region of foam expected to undergo crush deformation will be monitored.

The primary means of recording the results of the certification testing will be physical measurements and observations of the CTU before and after testing. In addition, each free drop impact (both NCT and HAC) will be recorded using active accelerometers. Since puncture drops are not governing for impact, puncture drops do not need to be instrumented.

Prior to beginning testing, during testing (if the containment seal must be disturbed), and at the end of testing of each CTU, a helium leak test will be performed on the closure containment seal, and on the vent port containment seal. At the conclusion of all tests, a helium leakage rate test will be performed on the remainder of the containment boundary. Intermediate vacuum tests on the seals may be performed to ensure continued integrity.

2.12.2.2.3 Certification Test Unit Configuration

All of the CTU components (packaging, lodgment, inner container (IC), and LTSS) will be fabricated in prototypic full-scale. The shielded device payload will be simulated by a dummy shielded device which will feature the maximum device weight and typical device dimensions. Some features of the prototypic design may be modified or omitted. Any modification or omission shall be stated and justified in the test report. Some features may be added specifically to facilitate testing, such as an auxiliary vent port, accelerometer blocks welded to the containment shell, or special lifting lugs. Care shall be exercised to prevent such modifications from affecting the outcome of the tests.

2.12.2.3 Identification of Worst-Case Test Orientations

The objectives of the certification test program are:

1. To demonstrate that the 435-B package is leaktight following the worst-case series of free drop and puncture.
2. To quantify the worst-case damage for the HAC fire event thermal analysis.
3. To support benchmarking of the computer structural model, in order to validate calculations for orientations not tested.
4. To demonstrate the general structural integrity of the lodgment. The lodgment must prevent uncontrolled movement of the LTSS in the various impact events, such that the LTSS is not free to damage the containment boundary or incur damage from the lodgment.
5. To demonstrate the general structural integrity of the LTSS. Any non-negligible damage will be accounted for in the shielding analysis.
6. To demonstrate the general structural integrity of the IC. The IC must prevent damage to the containment boundary by the shielded device.

Components of the packaging could experience potentially significant damage as follows:

1. Closure joint, including structural deformation making the O-ring ineffective as well as limiter damage leading to excessive O-ring temperature in the fire.

   Free drop impact could impart significant structural loading to the closure joint bolts. Local puncture deformation could cause leakage of the joint. Inside-out deformation from a failure of the lodgment to control the LTSS (or a failure of the IC to control the dummy device) could cause deformation in the joint. Puncture bar damage near the joint could lead to excessive O-ring temperatures in the fire event.

2. Containment boundary, either from excessive strains in the free drop impact or from the subsequent puncture.
3. Lodgment, whether from a failure to keep the LTSS from gross movement or from causing internal damage to the containment.
4. LTSS, by suffering damage from interaction with the lodgment that could reduce its shielding function.
5. IC, from a failure to keep the dummy device from causing internal damage to the containment.

Computer modeling is used to guide the selection of worst-case orientations. Preliminary runs of the type provided in Appendix 2.12.4, *Finite Element Analysis*, are used for this purpose. Only the final runs are reproduced in this SAR. In the following discussion, refer to Figure 2.12.4-43 for impact results, Figure 2.12.4-45 for foam crush results, and Figure 2.12.4-46 for containment boundary strain results.

2.12.2.3.1 Free Drops

Using the guidance of the FEA model results, the following tests are considered significant. Since the NCT drop height of four feet is over 13% of the HAC drop height of 30 feet, a NCT free drop will precede each HAC free drop, and be applied in the same orientation in order to maximize damage accumulation in the series.

Bottom down. Due to the large diameter of the flat bottom, energy can only be absorbed in the impact limiter at a relatively high force level. This drop consequently represents the largest overall impact of the package, as well as the largest impact along the lodgment or IC axis. This drop also challenges the attachment of the impact limiter to the lower flange. To obtain the maximum impact, it must be done at cold temperature. The impact of the payload will be less than that of the cask, due to the action of the internal absorber. The lodgment or IC must prevent the LTSS or dummy device from possibly damaging the containment boundary or sealing areas. This drop will be performed.

Side, cold (simultaneous head/limiter). As shown in Figure 2.12.4-43, the maximum lateral impact occurs in the simultaneous impact of the knuckle and impact limiter in the cold condition. This represents the largest impact perpendicular to the package axis. The lodgment or IC must prevent the LTSS or dummy device from possibly damaging the containment boundary or sealing areas. This drop will be performed.

CG over knuckle. Several orientations (top down, CG over knuckle, and knuckle-primary slapdowns) will require the upper torispherical head and side to absorb impact energy. The CG over knuckle orientation will require all of the drop energy to be absorbed by the head knuckle region. When combined with a puncture drop, it will produce the greatest plastic strain in the containment boundary. This drop does not have bounding impact, and interaction with the lodgment or IC is expected to be minimal. This drop will be performed.

Side, warm (simultaneous head/limiter). Figure 2.12.4-45 shows that the maximum foam crush occurs for the simultaneous side drop orientation. Under warm conditions, the foam crush would be greater than shown in the figure. This type of damage, when combined with puncture damage, will potentially represent the worst case for the subsequent HAC fire event. There is also the potential for compromise of containment if the free drop or puncture forces cause deformation of the closure joint flanges. This drop will be performed.

Free drops that will not be tested are discussed below.

CG over bottom corner. As shown in Figure 2.12.4-47, the maximum closure bolt loading occurs for the near-vertical orientation in the cold condition. This is due to the lateral action of the payload acting against the inside of the upper body. The maximum bolt load is determined by analysis in Section 2.7.1.5.1, *Maximum Closure Bolt Stress*, using the benchmarked finite element model. Therefore, this orientation does not need to be tested.

Top down. The top down orientation does not generate bounding strains or impacts. The strain in the upper torispherical head is bounded by the CG over knuckle orientation. The axial impact on the package and on the payload is bounded by the bottom down orientation. This drop does not challenge the impact limiter or containment seal. The effect of internal pressure on the deformed head in the fire event is evaluated analytically in Section 2.7.4, *Thermal*, using the benchmarked finite element model. Therefore, the vertical top down free drop does not need to be tested.

Slapdown. As shown in Figure 2.12.4-43, Figure 2.12.4-45, and Figure 2.12.4-46, no slapdown drops (either knuckle primary or impact limiter primary) represent bounding impact, foam crush, or containment boundary strain. Therefore, no slapdown drops need to be performed.

2.12.2.3.2 Puncture Drops

The spectrum of possible punctures will include impacts on prior free drop damage and on undamaged areas. The temperature of all puncture tests will be the prevailing temperature at the time of the test.

On CG over knuckle damage. As discussed above, the maximum strain in the containment boundary will occur due to a puncture impact on the upper torispherical head damage caused by the CG over knuckle drop. The puncture drop orientation of the package would be the same as for the free drop, and be directed through the CG. Since the knuckle area is somewhat thinner than the base material due to the forming process used to fabricate the torispherical head, the edge of the bar should strike just inboard of the fold to maximize the shear strain in a slightly thinner region. To demonstrate the integrity of the containment boundary under conditions of maximum strain, this puncture drop will be performed.

Oblique on bottom down damage. Puncture could occur on the bottom of the package, where the foam is relatively thin, and may be somewhat thinner due to bottom down drop deformation. Although the foam is thinnest on the package axis, a greater risk of perforation of the impact limiter shell will occur with an angled puncture orientation. Such an orientation would also bring the puncture damage closer to the thermally sensitive flange area. This puncture drop will be performed.

On side drop (warm) damage – IL shell. Puncture could occur on the side drop impact limiter warm damage area. The minimum remaining foam thickness will result from the warm side drop case. The worst case puncture would be aimed approximately at the closure flange, through the package CG, with an oblique angle impact for the greatest opportunity of perforation of the impact limiter shell. This puncture test could create damage relevant to the thermal analysis, as well as challenge the integrity of the closure flanges. This puncture drop will be performed.

Side puncture on the tube sheet region. Puncture could occur on the region around the top of the bolt tubes, tube sheet, and rain shield. The bar will be aimed at right angles to the package axis, within a small distance to the CG. An attempt to aim at the CG would require inclination of the package axis and render the target area too small to hit with adequate certainty in the actual test. The difference in damage will be small since the offset of the puncture axis from the CG will be approximately only six inches. The puncture will primarily impact the outer edge of the tube sheet and rain shield. The damage may show the maximum package side wall deformation, the ability of the rain shield to remain largely intact (i.e., limit the damage to a small region), and may produce damage relevant to the thermal analysis. This puncture drop will be performed.

On the side drop damage to the knuckle. Puncture could occur on the damage to the top head knuckle from the side drop. The bar will be aimed to strike on the top side of the damage with the bar axis through the CG. This puncture drop will be performed.

On the side thermal shield. A puncture could occur on the side thermal shield area and cause damage local to the puncture. The bar will be aimed through the CG with an oblique angle to the surface to increase the chance of ripping into the shield, which could produce damage relevant to the thermal analysis. This puncture drop will be performed.

Other possible punctures are as follows:

On the impact limiter, not on prior damage. Since the puncture bar will advance nearest the flange and seals when applied on prior damage as discussed above, puncture drops not on prior damage are not governing and do not need to be performed.

On the bolt tube area, puncture bar directed toward the bottom of the package. A puncture drop impact could be applied, either parallel to and adjacent to the package side onto the rain shield, or onto the rain shield perpendicular to the 30° inclined top surface of the impact limiter. However, the line of force would be directed mainly toward the package bottom, and thus substantially away from the package CG, and damage from this orientation is likely to be minimal. Therefore, this test does not need to be performed.

Adjacent to the lifting boss. Due to the strength of the torispherical head design, no significant damage is expected from a puncture drop adjacent to the lifting boss. Therefore this test does not need to be performed.

2.12.2.4 Summary of Certification Tests

Based on the discussions in Section 2.12.2.3, *Identification of Worst Case Orientations*, the planned certification tests for the 435-B package are summarized below and in Table 2.12.2-1. Free drops are depicted in Figure 2.12.2-1 and puncture drops in Figure 2.12.2-2.

The test sequence utilizes three separate CTUs, designated CTU #1, CTU #2, and CTU #3. All three CTUs are identical except for payload, polyurethane foam, and thermal shield configuration. CTU #1 and #2 contain a lodgment and LTSS (one LTSS test model will be re-used for both units). CTU #1 and #2 feature a simplified rather than a prototypic side thermal shield since no tests performed on these units will affect the side thermal shield. CTU #2 includes a head thermal shield, since the CG-over-knuckle drop and a subsequent puncture drop test occurs on the region covered by the head thermal shield. CTU #3 contains an IC and dummy payload with wood blocking. CTU #3 includes a prototypic side thermal shield, but no head thermal shield. A summary of the configuration of the thermal shields on the test units is given in Table 2.12.2-2. Each test unit will be tested in two free drop orientations and two or three puncture orientations. The complete test series consists of six, 4-foot NCT free drops, six, 30-foot HAC free drops (in the same orientation as the NCT drops), and seven, 40-inch puncture drops.

The free drops and punctures may be performed in the order given in Table 2.12.2-1 or a different order if necessary. All free drops on CTU #1 and #3 shall be performed with the bulk average temperature of the equivalent (16 lb/ft^3) foam at approximately zero °F or less. The side drop on CTU #2 shall be performed with the bulk average temperature of the equivalent (14 lb/ft^3) foam at approximately 110 °F or greater, per the discussion given in Section 2.12.2.2.1, *Temperature and Pressure*. Interference of damage between test series is expected to be negligible. The temperature of CTU #2 for the CG over knuckle drop does not need to be controlled.

2.12.2.4.1 Tests on CTU #1

Two free drop orientations and two puncture drop orientations will be performed on CTU #1.

Free Drop, Flat Bottom Down (D1N and D1H on CTU #1). CTU #1 will be tested in the bottom end drop orientation at cold temperature. The purpose of this test is to demonstrate:

- The attachment of the impact limiter to the lower flange
- The ability of the internal absorber to absorb most of the payload energy
- The ability of the lodgment to prevent excessive movement of the LTSS

Expected results: Very modest deformation of the foam below the containment vessel, and significant deformation of the internal absorber. The LTSS will retain its general position, and damage to the lodgment will be acceptable. The impact limiter will remain attached to the lower flange, with no distortion of the flange sealing area. Containment will be leaktight.

Puncture on the bottom down impact damage from D1 (P1 on CTU #1). This puncture will occur on the bottom face of the impact limiter with the package axis inclined approximately 30° from the vertical. The purpose is to demonstrate acceptability of potentially bounding, thermally-relevant impact limiter damage. Azimuth is not important.

Expected results: The ¼-inch shell represents essentially 100% of the Bechtel TOP-9A [4] recommendation. Experience with other puncture tests on foam impact limiters shows that perforation is unlikely at this thickness level, and none is expected.

Open the package after completing tests D1N, D1H, and P1, and evaluate the need to replace the lower absorber with a new component. Evaluate the ability of the lodgment to sustain a governing side impact and repair or replace as necessary, before proceeding to test series D2.

Free Drop, Side (D2N and D2H on CTU #1). CTU #1 will be tested in the orientation where the knuckle and impact limiter contact the ground simultaneously, at cold temperature. The azimuth orientation will be with the vent port at the top (i.e., impact is 180° from the vent port) which will place lodgment ribs equally straddling the impact point. The purpose of this test is to demonstrate:

- Acceptable behavior of the impact limiter and containment under maximum lateral impact
- The ability of the lodgment to prevent excessive movement of the LTSS

Expected results: Lateral deformation of both the knuckle and the impact limiter, and possible outward deformation of the sidewall. The LTSS will retain its general position, and damage to the lodgment will be acceptable. Containment will be leaktight.

Puncture on the knuckle damage from D2 (P2 on CTU #1). This puncture will occur with the puncture bar axis through the CG, and placed to impact on the top side of the head adjacent to the damage (which is on the side of the knuckle) as shown in Figure 2.12.2-2. The azimuth location will be the same as the side drop (D2).

Expected results: A dent approximately 1 – 2 inches deep. Little or no payload interaction. Containment will be leaktight.

Tests on CTU #1 are complete.

2.12.2.4.2 Tests on CTU #2

Two free drop orientations and two puncture drop orientations will be performed on CTU #2.

Free Drop, CG over Top Knuckle (D3N and D3H on CTU #2). CTU #2 will be tested with the CG over the upper knuckle at prevailing temperature. The purpose is to impart the maximum bending strain in the knuckle region for subsequent puncture, which could affect containment. In addition, it will demonstrate the ability of the head thermal shield to maintain sufficient integrity for thermal performance in the HAC fire. The azimuth orientation (point of first contact) should be opposite to the vent port, which places it halfway between lodgment ribs. Since this impact does not include foam, the temperature of the foam is not important.

Expected results: A large flat on the top end, biased toward one side with a significant buckle in the knuckle region. The head thermal shield will not be ripped open or torn off. The internal absorber will crush locally, but the lodgment will not move significantly relative to the package interior. This will represent the maximum bending strain in the containment due to free drop. Containment will be leaktight.

Free Drop, Side (D4N and D4H on CTU #2). CTU #2 will be tested in the orientation where the knuckle and impact limiter contact the ground simultaneously, identical to tests D2N and D2H on CTU #1. This test shall be done at warm temperature, with the azimuth orientation having the vent port at the bottom. The lodgment ribs will be equally straddling the impact point. The purpose of this test is to create the maximum strain in the foam, which occurs near to the closure joint flanges. The maximum damage will also occur right at the vent port.

Expected results: Maximum foam strain will occur from this impact, which will be combined with puncture for maximum potential damage. Containment will be leaktight.

Puncture on the CG over top knuckle impact damage from D3 (P3 on CTU #2). This puncture will nominally occur in the same orientation as the associated free drop, with the puncture axis through the CG of CTU #2. The purpose is to demonstrate that the containment can sustain the worst case plastic strain and remain leak tight, and demonstrate the ability of the head thermal shield to maintain sufficient integrity for thermal performance in the HAC fire. The location of the impact should be approximately 2 – 3 inches from the outside edge of the larger fold as shown in Figure 2.12.2-3, so as to maximize local shear loading and maximum strain. Optionally, this test could be performed immediately after test D3H.

Expected results: A dent approximately 1 – 2 inches deep. Little or no payload interaction. The head thermal shield may locally shear through but will not be torn off. Containment will be leaktight.

Puncture on the impact limiter side damage from D4 (P4 on CTU #2). This puncture will occur on the side drop crush damage on the impact limiter with the puncture bar aimed at the flange and the package CG. The angle of the package axis to the horizontal is approximately 35°. The azimuth will be the same as free drop D4. The purpose of this test is to demonstrate:

- Acceptability of potentially bounding, thermally-relevant impact limiter damage
- Containment is maintained following the worst case puncture near the closure flange

Expected results: A dent will occur at the puncture site, but no perforation of the shell is expected. The damage will be compared to other cases for thermal consequences and the worst case will be included in the thermal analysis. Containment will be leaktight.

Tests on CTU #2 are complete.

2.12.2.4.3 Tests on CTU #3

Two free drop orientations and three puncture drop orientations will be performed on CTU #3. The purpose of CTU #3 is to test the behavior of the IC with the dummy payload and blocking. The governing drops for the payload will be the maximum impact, which are the same ones that were used for the lodgment/LTSS tests in CTU #1. Therefore, the free drop orientations will be the same as for CTU #1.

Free Drop, Flat Bottom Down (D5N and D5H on CTU #3). CTU #3 will be tested in the bottom end drop orientation at cold temperature. The purpose of this test is to demonstrate the ability of the IC to adequately control the dummy device.

Expected results: The same package responses as for D1N and D1H on CTU #1. The dummy device may change position, but no unacceptable damage to the package will occur. The package will be leaktight.

Puncture on the bottom down impact damage from D5 (P6 on CTU #3). This puncture will be identical to puncture P1 on CTU #1. The results will be the same.

Open the package after completing tests D5N, D5H, and P6, and evaluate the need to replace the lower absorber, the IC, or the blocking with new components before proceeding to test series D6.

Free Drop, Side (D6N and D6H on CTU #3). CTU #3 will be tested in the orientation where the knuckle and impact limiter contact the ground simultaneously, at cold temperature. The azimuth orientation will be with the vent port at the top. The purpose of this test is to demonstrate the ability of the IC to adequately control the dummy device.

Expected results: The same package responses as for CTU #1. The dummy device may change position, but no unacceptable damage to the package will occur. The package will be leaktight.

Puncture on package side on the tube sheet (P5 on CTU #3). This puncture will occur with the puncture bar perpendicular to the package axis, and placed essentially centered on the tube sheet and rain shield region as shown in Figure 2.12.2-4. The bar will be directed as near as practical to the CG. (Trying to aim directly at the CG may invalidate the test because a slight error in the impact point could cause the puncture bar to miss the tube sheet altogether.) The azimuth location will be at the vent port.

Expected Results: The tube sheet and adjacent bolt tubes will be crushed. The rain shield will be locally deformed, but will remain globally in proper position. The vent port shield will be trapped in its tube. The side wall may deform inward. Containment will be leaktight.

Puncture on the thermal shield (P7 on CTU #3). This puncture will occur with the puncture bar axis through the CG with the package axis at 30° to the horizontal, head down, as shown in Figure 2.12.2-2. The azimuth is not important.

Expected results: A dent approximately 1 – 2 inches deep. Some tearing of the outer or inner thermal shields is possible. Containment will be leaktight.

Tests on CTU #3 are complete.

2.12.2.5 Acceptance Criteria

The following are the acceptance criteria for certification testing of the 435-B package:

1. Each CTU, at the conclusion of all drop and puncture testing, shall remain leaktight per [1], as demonstrated by helium leakage rate testing.
2. The maximum damage to the package from the single worst-case free drop and puncture test sequence must fall within the bounding assumptions used in the HAC fire thermal analysis. Alternatively, the worst post-test configuration will form the basis for a conservative thermal analysis.
3. After all testing, including the worst-case puncture onto the rain shield/bolt tube region, the vent port insulation cylinder must be retained either by the rain shield or by other deformation, such as deformation of the vent port tube.
4. The lodgment shall control the displacement of the LTSS, and the IC must control the dummy device, such that the CTU remains leaktight.
5. The LTSS must remain intact, and deformations must be negligible relative to the shielding function. Alternatively, the LTSS damage, including lead slump if any, will form the basis for a conservative shielding analysis.

Table 2.12.2-1 – Summary of Certification Tests

No.	Test Description	CTU/Payload	Foam Density & Temperature	Purpose of Test & Expected Damage
D1N D1H	Bottom end drop	#1 (LTSS)	16 lb/ft^3, Cold	Maximum end impact, internal absorber crush, lodgment performance
D2N D2H	Side (simultaneous)	#1 (LTSS)	16 lb/ft^3, Cold	Maximum lateral impact, impact limiter, lodgment performance
D3N D3H	CG over knuckle	#2 (LTSS)	Not controlled	Plastic strain, challenge to containment
D4N D4H	Side (simultaneous)	#2 (LTSS)	14 lb/ft^3, Warm	Maximum foam crush, combine with worst case puncture
D5N D5H	Bottom end drop	#3 (IC)	16 lb/ft^3, Cold	Maximum axial impact for payload
D6N D6H	Side (simultaneous)	#3 (IC)	16 lb/ft^3, Cold	Maximum lateral impact for payload
P1	On bottom end drop (D1) damage	#1 (LTSS)	Not controlled	Possible governing thermal damage
P2	On side knuckle (D2) damage	#1 (LTSS)	Not controlled	Plastic strain, challenge to containment
P3	On CG over knuckle (D3) damage	#2 (LTSS)	Not controlled	Plastic strain, challenge to containment
P4	On side drop (D4) damage	#2 (LTSS)	Not controlled	Possible governing thermal damage, challenge to containment
P5	On rain shield/tube sheet region	#3 (IC)	Not controlled	Deformation of tube sheet, rain shield, and side wall, possible governing thermal damage
P6	On bottom end drop (D5) damage	#3 (IC)	Not controlled	Possible governing thermal damage
P7	On side thermal shield	#3 (IC)	Not controlled	Obtain bounding damage to shield for thermal analysis

Table 2.12.2-2 – Summary of Certification Test Unit Thermal Shield Configuration

CTU	Thermal Shields	Comments
1	Simulated side shield, no head shield	Neither type of thermal shield is relevant to the tests performed on this unit.
2	Simulated side shield, prototypic head shield	CG-over-knuckle free drop and related puncture will test the prototypic head thermal shield.
3	Prototypic side shield, no head shield	Puncture on side of package tests the prototypic side thermal shields.

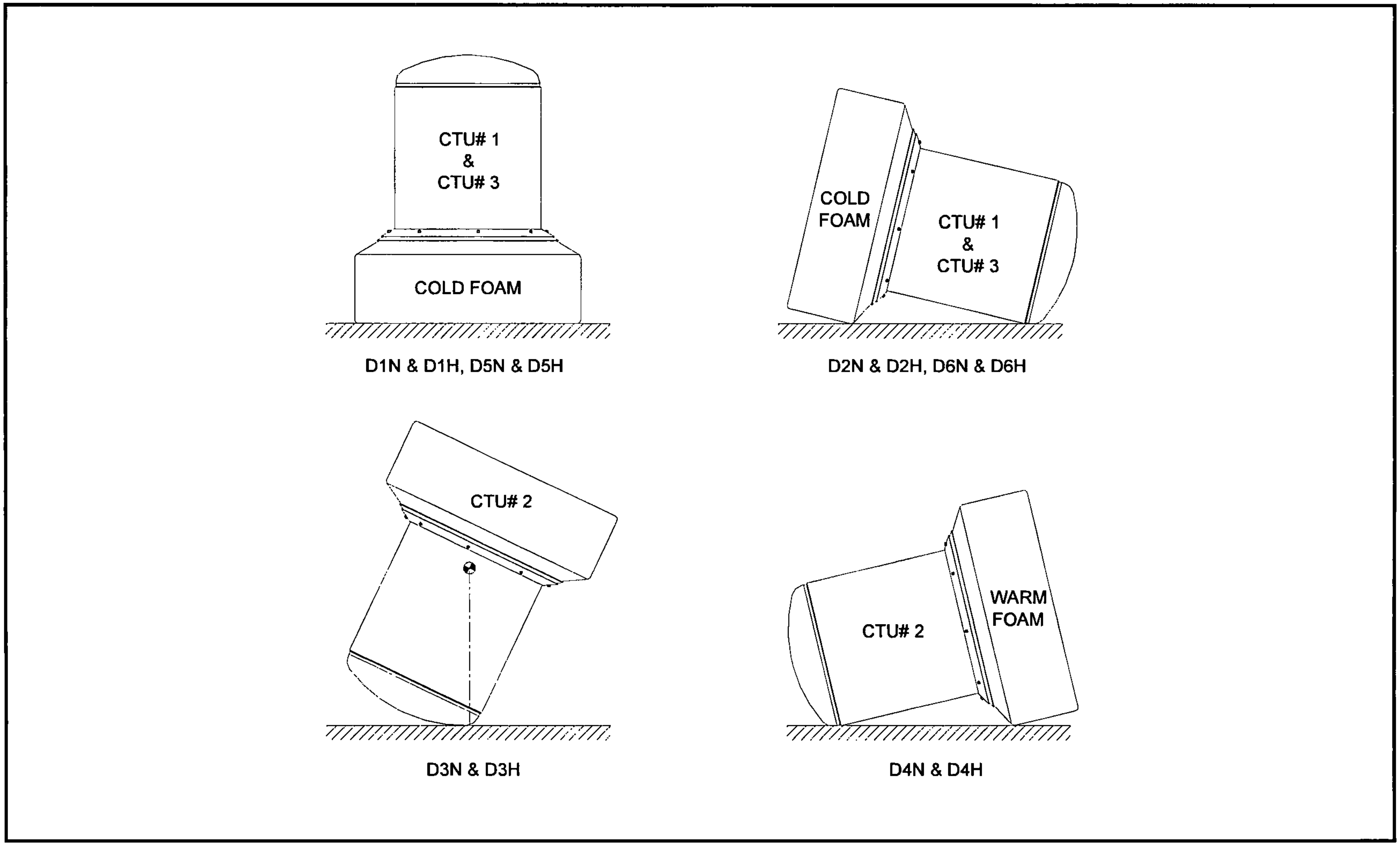


Figure 2.12.2-1 – 435-B Free Drop Orientations

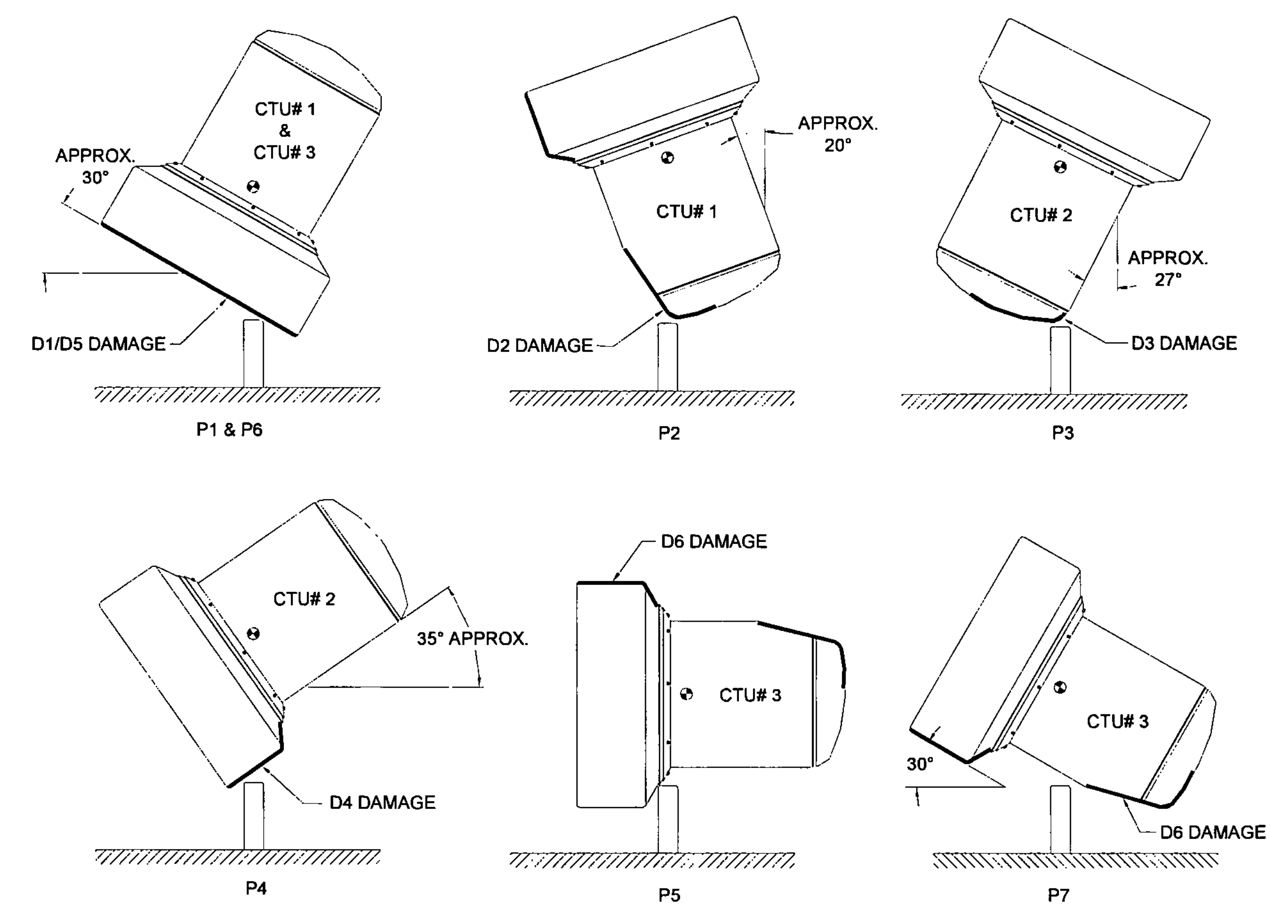


Figure 2.12.2-2 – 435-B Puncture Drop Orientations

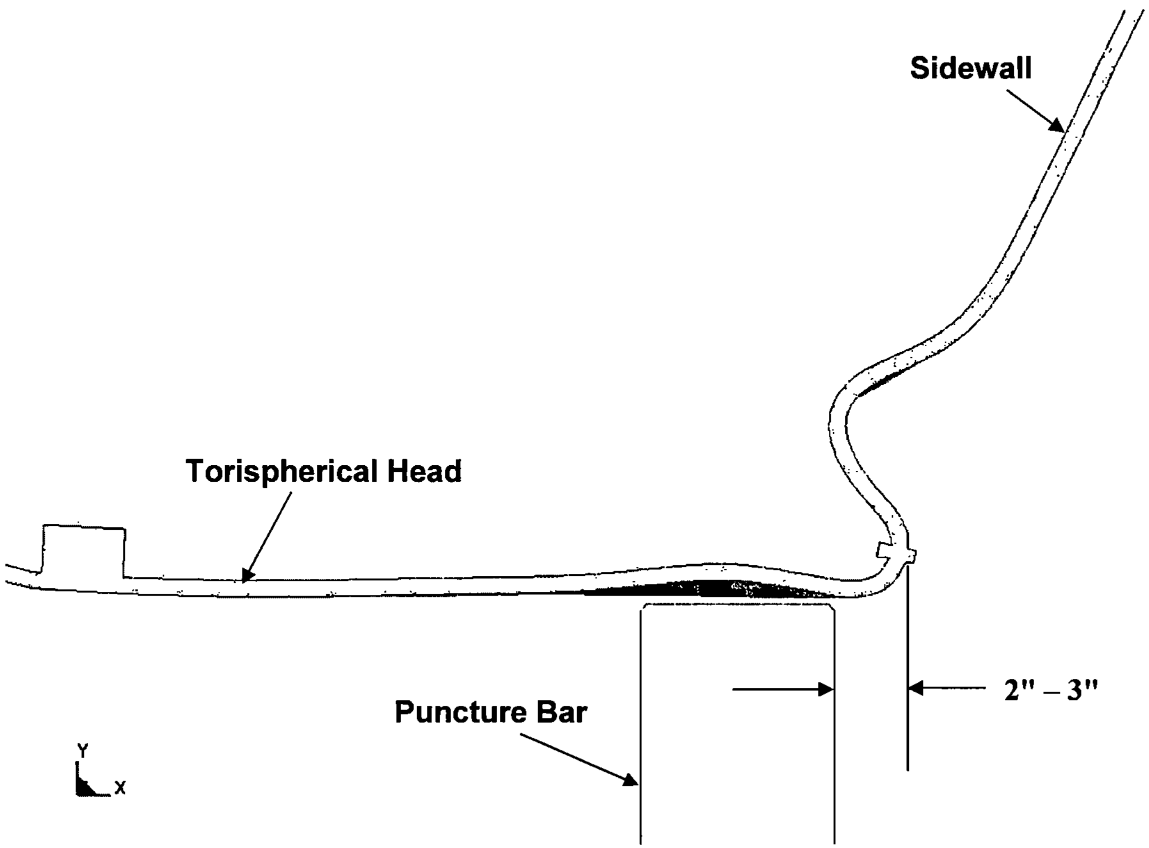


Figure 2.12.2-3 - Puncture Drop Orientation Detail for P3

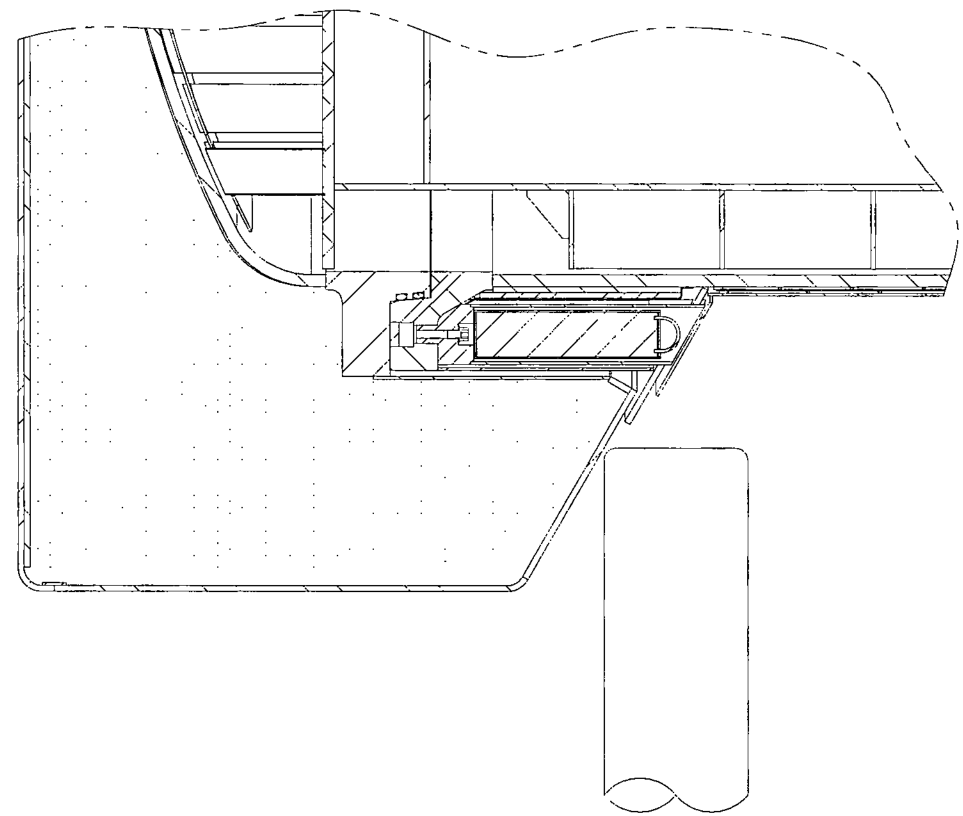


Figure 2.12.2-4 - Puncture Drop Orientation Detail for P5

2.12.2.6 References

1. ANSI N14.5-1997, *American National Standard for Radioactive Materials – Leakage Tests on Packages for Shipment*, American National Standards Institute (ANSI), Inc.
2. Title 10, Code of Federal Regulations, Part 71 (10 CFR Part 71), *Packaging and Transportation of Radioactive Material*, 01-01-11 Edition.
3. International Atomic Energy Agency, *Regulations for the Safe Transport of Radioactive Material*, TS-R-1.
4. Bechtel Power Corporation, *Design of Structures for Missile Impact*, BC-TOP-9A, Rev. 2, 9/1974.

2.12.3 Certification Test Results

This appendix presents the results of the certification testing of the 435-B package that addresses the performance requirements of 10 CFR 71 [1]. This material summarizes the information presented in the certification test report [2].

2.12.3.1 Introduction

Demonstration of the compliance of the design of the 435-B package with the requirements of 10 CFR §71.73 was primarily achieved using formal certification testing. Analysis was used for all NCT events except the free drop, and for the HAC thermal case. Analysis using a model benchmarked against test results was also used to evaluate certain orientations that were not tested. The NCT and HAC free drop events and HAC puncture event were demonstrated by testing. This appendix describes the results of the free drop and puncture testing, including post-test measurements and evaluations. The testing utilized three, full-scale certification test units (CTUs). Testing was performed to a written procedure which was based on the test plan presented in Appendix 2.12.2, *Certification Test Plan*. A total of six NCT free drops, six HAC free drops, and seven HAC puncture drop tests were performed on the units. The primary success criterion was that, subsequent to all free drop and puncture testing, the CTU containment boundary, including the main containment seal and vent port seal, be leaktight per ANSI N14.5 [3]. Other supporting data, including accelerations and physical measurements, was collected as described herein.

2.12.3.2 Test Facilities and Instrumentation

2.12.3.2.1 Test Facilities

Testing was performed at Lampson International LLC in Pasco, Washington, beginning November 28, 2011. The drop pad weighed approximately 110,000 lb, including a 2-inch thick, embedded steel plate impact surface. The pad therefore represented an essentially unyielding surface for the CTUs, which weighed between approximately 9,650 and 9,775 lb. The puncture bar assembly was made of ASTM A36 steel, 6 inches in diameter, 24 inches long, with an edge radius of 0.22 to 0.25 inches. The bar was affixed to a steel baseplate and welded to the drop pad for puncture drop testing.

Eight free drops were performed with the impact limiter polyurethane foam in the cold condition. A refrigerated trailer was present onsite to chill the CTUs prior to testing. Thermocouples were inserted in 1/4-inch diameter holes in each CTU, 9 inches deep, through the plastic plugs on the side of the CTUs. Three thermocouples were used for each test article, located 120° apart. Two free drops were performed with the impact limiter foam at warm temperature. A combination of heating blankets and warm ambient air inside an enclosure were used to warm the foam. Two free drops were performed using the prevailing temperature of the CTU. All puncture tests used prevailing temperature.

2.12.3.2.2 Instrumentation

Accelerometers were used to record the impact of each free drop. Accelerations of the puncture drops were not recorded. For axial or near-axial drop orientations, the measurement axis of the accelerometers was axial. For the near-horizontal side drops, the measurement axis was transverse to the cask axis.

Two axial and two transverse mounting positions were provided at each end of the cask. The measurement axes were as close to the cask surface as possible, and the mounting blocks were rigidly welded to the cask. The mounting location and orientation of each accelerometer is shown in Figure 2.12.3-1. The transverse accelerometers at each end were all mounted on the same axial plane with their axes parallel. The two accelerometers located at the azimuth of the seal test port were designated T/U (at test port, upper location) and T/L (at test port, lower location). The two accelerometers located 180° away from the first set were designated OT/U and OT/L, where the 'O' indicates 'opposite', i.e., 180° away from the first set.

The raw data was conditioned and low-pass filtered at a cutoff frequency of 500 Hz. Per the guidance given in TS-G-1.1, *Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material*, an appropriate cutoff frequency range is found from:

$$f_c = [100 \text{ to } 200] \times \left(\frac{100}{m}\right)^{\frac{1}{3}} = 280 \text{ to } 560 \text{ Hz}$$

Where m is the mass of the package in metric tonnes (10,100 lb equals 4.59 metric tonnes). From this, a reasonable cutoff frequency of 500 Hz is chosen. Further reduction of accelerometer data is discussed in Section 2.12.3.4, *Free Drop and Puncture Drop Test Results.*

2.12.3.3 Certification Test Unit Configuration

The three CTUs were fabricated in prototypic full scale in accordance with the drawings in Appendix 1.3.3, *Packaging General Arrangement Drawings*, except as noted and justified below. CTU #1 used a LTSS payload and lodgment #1. CTU #2 used the same LTSS payload and lodgment #2. CTU #3 used an Inner Container (IC) and Dummy Payload. The weights of the CTUs are given in Table 2.12.3-1.

1. CTU #1 and CTU #3 had slightly higher density (nominally 16 lb/ft^3) polyurethane foam installed in the impact limiter compared to the prototypic foam density (nominally 15 lb/ft^3). The higher density foam, when chilled to a temperature of 0 °F as discussed in Section 2.12.2.2, *Initial Test Conditions*, has crush properties essentially equal to those of the prototypic foam at a temperature of -40 °F. The temperature of -40 °F is conservatively below the cold environment temperature of -20 °F found in [1], and corresponds to the minimum environment temperature found in [4]. In this way, the crush strength of the foam in CTUs #1 and #3 at the target test temperature of 0 °F would accurately simulate the higher strength of the prototypic foam at a temperature of -40 °F. The comparison of the stress-strain curves for the two foam densities at cold temperature is given in Figure 2.12.3-2. The production foam (15 lb/ft^3) is shown for -40 °F and includes a +10% manufacturing strength tolerance and a dynamic adjustment. The test foam (16 lb/ft^3) is shown for the actual manufactured strength, the actual test temperature of -10 °F, and a dynamic adjustment. The properties of the production foam are developed in Appendix 2.12.4, *Finite Element Analysis.*
2. CTU #2 had slightly lower density (nominally 14 lb/ft^3) polyurethane foam installed in the impact limiter compared to the prototypic foam density (nominally 15 lb/ft^3). The lower density foam, when heated to a temperature of 110 °F as discussed in Section 2.12.2.2, *Initial*

Test Conditions, has crush properties essentially equal to those of the prototypic foam at a temperature of 150 °F. The temperature of 150 °F is slightly above the foam bulk average temperature under the hot environment conditions presented in Chapter 3, *Thermal Analysis*. In this way, the crush strength of the foam in CTU #2 at the target test temperature of 110 °F accurately simulated the lower strength of the prototypic foam at a temperature of 150 °F. The comparison of the stress-strain curves for the two foam densities at elevated temperature is given in Figure 2.12.3-2. The production foam (15 lb/ft^3) is shown for 150 °F and includes a -10% manufacturing strength tolerance and a dynamic adjustment. The test foam (14 lb/ft^3) is shown for the actual manufactured strength, the actual test temperature of 117 °F, and a dynamic adjustment. The properties of the production foam are developed in Appendix 2.12.4, *Finite Element Analysis*.

3. CTU #1 and CTU #2 had simulated thermal shields installed on the side of the packages instead of prototypic thermal shields. A fully prototypic thermal shield on the cylindrical side was installed on CTU #3, since a puncture test was performed directly on the shield of that unit only in order to test its integrity. But since the presence of a thermal shield on the side of CTUs #1 and #2 did not have any significant effect on the tests performed on those units, it was not necessary to include prototypic thermal shields. The simulated shield consisted of a single layer of 0.105-inch thick stainless steel, essentially the full length of the side shield region, without stand-off wires, in order to partially make up the weight of the full shield. It was welded using intermittent welds to the cask shell, and its vertical seam was a lap joint using intermittent welds. As such, it represented less structural strength than a prototypic shield, which has uninterrupted welds to the body and a full bevel weld vertical seam. Note also that the inner, 0.060" thick thermal shield was conservatively not included with the simulated shields. To account for the effect of the stack-up of steel strips that is used at the top end of the prototypic thermal shield (an area which was deformed in the side drop events), an equivalent strip of 5/16-inch thick stainless steel was welded to the location of the top and lower ends of the prototypic shield. Thus, the simulated thermal shields on CTUs #1 and #2 represented a package having somewhat less structural strength on the side than the prototypic model, while including the hard point that could increase containment boundary strain in a side impact.
4. CTU #1 and CTU #3 did not have a thermal shield on the upper torispherical head. A prototypic head thermal shield was installed on CTU #2, since the tests on that unit included the free drop and puncture drop impact on the head. Since the thermal shield provides added structure to the torispherical head of the package, the effect of the absence of the head shield on CTUs #1 and #3 is conservative. Since the weight of the head thermal shield is relatively small (~ 67 lb), it was not necessary to make up the weight of the missing shield.
5. Because the testing performed on the CTUs was structural and not thermal, it was not necessary to provide a prototypic finish to the internal surfaces of the thermal shields used on CTU #2 (top head shield) and #3 (side shield). The finishes specified for the prototypic package are provided only to reduce heat transfer by radiation. The surface finish used on the CTUs was as-received.
6. To facilitate leak testing during the certification test series, an auxiliary vent port was placed in each CTU on the side near the top head joint, in an azimuth location that prevented significant damage to the 1-inch NPT hole. The presence of the hole did not have a significant effect on any of the tests.

7. In order to facilitate rigging and lifting the CTUs, the threaded hole on the top of the upper head was increased to 1-8 UNC thread and a correspondingly large swivel hoist ring was used. The prototypic hole is ¾-10 UNC, and is used only to lift the top assembly (the bell). The larger hole and hoist ring allowed for safe lifting of the entire package. This difference had no effect on any tests. To further facilitate rigging, carbon steel plates having a threaded hole were attached by welding to the lower sides of the impact limiter. These plates were distant from the deformation of the impact limiter in each case, and had no effect on any tests.
8. To record impact accelerations of the free drops, four accelerometers were used with each drop. To mount the accelerometers, Type 304 stainless steel blocks, 1-inch cubic in size, were mounted to the package as shown in Figure 2.12.3-1. The mounting locations required small cutouts to be made in the prototypic (CTU #3) and simulated (CTU #1 and #2) side thermal shields. The blocks and cutouts had no effect on any of the tests.
9. To record the temperature of the polyurethane foam, three thermocouple wires were used in holes that were placed in the three plastic melt-out plugs on the side of the impact limiter. The holes were 9 inches deep and 1/4 inches in diameter. This depth placed the thermocouples at essentially the volumetric center of the foam body. Two additional holes were placed through the steel shell, at the same height, on CTU #2. These holes did not have a significant effect on the crush behavior of the impact limiters in any drop or puncture event.
10. Due to flange distortion during fabrication, the vent and test ports became misaligned to the package axis. They were repaired by placing new ports in a block welded to the flange. The prototypic design uses the same welded block, except the block is configured such that no flange counter bore is necessary. In addition, the prototypic design has a 50% larger vent hole diameter, a different configuration in the flange, and an additional weld. Because both designs depend for strength on the same 3/16-inch all-around fillet weld between the block and the flange, they have the same resistance to damage. The as-tested and prototypic designs are compared in Figure 2.12.3-3. Furthermore, during testing, no significant loadings were transmitted to the vent or test port regions, as demonstrated by the relatively large distance between the port areas and external damage areas. Therefore the difference in the port designs had no effect on the test results.
11. To ensure that the lodgment was azimuthally oriented properly for the worst-case damage to occur, two aluminum tabs were welded to the lower internal impact limiter assemblies at a distance of 14 inches from the center of the plate. The tabs are not used on the prototypic package. Since their purpose was to ensure the test damage was maximized, their presence in the test units was conservative.
12. The lid of the IC features three radial ribs. In the prototypic design, the ribs are welded to the inner sheet of the lid using intermittent fillet welds. Instead, a continuous fillet weld was used on the test articles. Since the lid of the IC did not experience significant deformation in any of the tests, this discrepancy had no effect on test results.
13. The CTUs did not have any caps over the guide pin holes in the upper flange. The caps in the prototypic design keep the region surrounding the bolt access tubes closed to the environment. The lack of these caps (two) had no effect on the test results.

14. The CTUs did not have a lead-in chamfer on the bell opening. This had no effect on the test results.
15. The CTU used three melt-out plugs on the outer circumference of the external impact limiter. The prototypic quantity is six melt-out plugs. This difference had no effect on the test results.
16. The length of the containment and test O-rings was 44.6 inches for CTU #1 and #3, and 44.1 inches for CTU #2. The prototypic length is 44.1 inches. The small difference in length (0.5 inches for CTU #1 and #3) had no effect on the test results.
17. The outer diameter of the lodgment and IC used in the CTUs was nominally 43.0 inches. The prototypic nominal diameter is 42.75 inches, or a difference of 0.25 inches. In addition, the height of the lower corner of the lodgment was nominally 8.0 inches from the base (see drawing 1916-01-02-SAR, sheet 2, zone A-3/4). The prototypic nominal dimension is 10.0 inches. These small differences did not have a significant effect on the test results.
18. The LTSS payload used in CTU #1 and CTU #2 differed in several particulars from a prototypic model, however, the differences were not material to the test results. The test LTSS used a solid steel central barrel, without any drawers. The test LTSS did not have operating hinges for the end doors, having instead welded steel blocks that simulated the size, shape, attachment, and location of the prototype hinges. The internal security plates were installed loose instead of bolted in place. None of these differences had any effect on the result of any of the tests.

The IC in CTU #3 contained a dummy shielded device and wood blocking/dunnage. The dummy device is shown in Figure 2.12.3-39. The body is a pipe, 20 inches in diameter, and the overall length is 34 inches. It had a weight of 3,570 lb, essentially equal to the maximum device weight limit of 3,500 lb. The dunnage was of two kinds: pallets and end caps. The pallets were made from 4×4 lumber attached to a disc of ½-inch thick plywood. The end caps were made of 1-1/8-inch thick plywood sheets. One end cap (with test damage) is shown in Figure 2.12.3-38. Starting from the bottom of the IC, the stackup of dunnage was as follows: one pallet; one end cap (hollow end up); dummy device; one end cap (hollow end down); and two pallets on top.

2.12.3.4 Free Drop and Puncture Drop Test Results

Results of the free drop and puncture drop tests are given below. Tests on the three CTUs were arranged in six series of two on each CTU, consisting of one, 4-ft NCT free drop followed by one, 30-ft HAC free drop, and concluded by at least one, 40-inch puncture drop test. Thus there were a total of six, 4-ft NCT free drop tests, six, 30-ft HAC free drop tests and seven 40-inch puncture drop tests. The test series were performed in the order D1 (D1N, D1H, & P1), D5 (D5N, D5H, & P6), D2 (D2N, D2H, & P2), D3 (D3N, D3H, & P3), D6 (D6N, D6H, P5 & P7), and D4 (D4N, D4H, & P4). The tests are depicted in Figure 2.12.2-1 and Figure 2.12.2-2 and summarized in Table 2.12.2-1 from Appendix 2.12.2, *Certification Test Plan.* Photographs of each test, including post-test examinations, are given in Figure 2.12.3-4 through Figure 2.12.3-49. Low pass filtered accelerometer time histories are given below in Section 2.12.3.6, *Filtered Accelerometer Time Histories*. The acceleration peak values are then resolved to a value that is perpendicular to the ground. Due to the necessity of mounting some accelerometers with their mounting threads facing upwards and others with the threads facing downwards, both positive and negative signals were recorded. However, all results shown in the following summaries are given as positive. Since the data was collected orthogonal to the cask axes, the resultant of the average of the peak acceleration data in the oblique impact cases is as follows.

For free drop tests D1 and D5, which were vertical bottom-down drops, the accelerometers were mounted with their measurement axes parallel to the impact direction. Therefore, the accelerometer readings require no adjustment.

For tests D2, D4, and D6, which were identical side drops in which the upper knuckle and impact limiter corner contacted the pad simultaneously, the cask axis was inclined at an angle of 13° to the ground. The accelerometers were mounted with their measuring axes transverse to the cask axis. The accelerometer reading is divided by the cosine of 13° to obtain the impact which occurred perpendicular to the ground.

For test D3, which was the c.g.-over-knuckle free drop, the accelerometers were mounted with their measurement axes parallel to the cask axis. The accelerometer reading is divided by the cosine of 27°, which corresponds to the recorded angle between the cask axis and the vertical, to obtain the impact perpendicular to the ground.

All puncture drop tests were performed from a height of 40 inches above the top of the 24-inch long puncture bar. The bar remained securely attached to the drop pad during the test, and was not observed to experience permanent deformation. The radius became damaged from contact with the CTUs and was re-dressed prior to further use.

For each test, the temperature of the polyurethane foam (for test D3, the exposed steel surface on the top) was recorded, depending on which was relevant to the test impact. As discussed in Section 2.12.3.3, *Certification Test Unit Configuration*, the cold temperature target for the bulk of the polyurethane foam was 0 °F, and the warm temperature target was 110 °F. The temperature of the steel and of the foam for puncture drops was accepted at the prevailing temperature and recorded at the time of the test.

After the completion of each series of 4-ft, 30-ft, and puncture drop tests (with the single exception of the D3 series), the CTUs were opened for internal inspection. Each time this was done, a helium leakage rate test with a criteria of leak tight per [3] was performed to test the integrity of the main containment O-ring seal and vent port containment sealing washer. (All leakage rate tests mentioned in this SAR used the same leak tight criteria from [3].) This was followed by a measurement of the removal torque of the closure bolts and inspections of the internal components. Removal torque was measured using a dial-type torque wrench loaded in the counter-clockwise direction. Loading was manually increased until the reversal torque reached a maximum, which was recorded. The torque was not removed from any bolt until all of the bolts had been checked. Note that, due to the inclined angle of the threads, the removal torque is somewhat less than the application torque. Trials have shown that bolt removal torque will be between 2/3 and 3/4 of the application torque for joints that have not undergone drop testing. Thus an even lower value would be expected from impact tested joints. It was noted during removal that some of the bolt washers were scored. Subsequently, care was taken to lubricate not only the threads but also the washers during reassembly. Prior to resuming tests (if any), the components of the CTU were cleaned, reassembled according to drawing requirements, and leakage rate tested.

At the conclusion of all free drop and puncture testing, each CTU was subjected to a helium leakage rate test of the containment boundary. All surface obstructions, such as, for example, the head thermal shield, or the sheet enclosing the bolt tube region, were removed or cut open to ensure free access of helium to the entire bell and upper heavy flange surface. On the base, the impact limiter foam was not removed before leakage rate testing. Since the base containment boundary (consisting of the lower torispherical head and lower heavy flange) did not experience any recorded deformations, and in light of the fact that the material (ASTM Type 304 stainless steel) is capable of very large strains before fracture and is not subject to low-strain cracking, the presence of a crack or fissure resulting from any of the tests is not credible. Therefore testing with the polyurethane foam in place was acceptable. The integrated leak rates for each containment boundary are summarized in Table 2.12.3-2.

2.12.3.4.1 Test Series D1

Test series D1 was performed on CTU #1 and consisted of a 4-ft NCT and a 30-ft HAC free drop in the bottom-down orientation, with the axis vertical, followed by a puncture drop test on the flat bottom of the impact limiter, with the cask axis inclined at 30° from the vertical. The tests were designated D1N, D1H, and P1 for the 4-ft, 30-ft, and puncture drops, respectively. The free drop orientation (identical for D1N and D1H) is shown in Figure 2.12.3-4. The polyurethane foam temperature readings for test D1N were -10.0 °F, -11.3 °F, and -11.2 °F, and for test D1H, -9.0 °F, -9.5 °F, and -10.4 °F. Accelerometer results are shown in the table below.

Accelerations, Free Drop Test D1					
Location	**T/U**	**T/L**	**OT/U**	**OT/L**	**Avg. ⊥**
Test D1N	316g	315g	353g	330g	**329g**
Test D1H	856g	815g	696g	705g	**768g**

Both of these impacts imparted no visible damage to the CTU. The only external measurement taken at the time of the drops was the overall height. The height after D1N was 83-7/16 inches, compared to an as-fabricated height of 83-3/4 inches, for an apparent decrease of 5/16 inches. The same measurement taken after the D1H drop was the same as for the D1N drop, seeming to indicate no further compression of the impact limiter. It appears anomalous that a small drop height would produce more deformation than a larger one. In fact, the actual changes in overall height of the package were probably too small to be accurately measured using the techniques used. In any case, the external deformation was negligible. As discussed below, energy was absorbed internally.

After the D1H free drop, a ¼-inch diameter hole was drilled at the center of the bottom sheet of the impact limiter and through the foam to the lowest point on the lower torispherical head. After subtracting a total of 0.66 inches for the steel shell, the insulating paper, and an observed gap, the thickness of the foam was measured to be 3.9 inches. Since a pre-test measurement of this dimension was not made, the post-test result must be compared to the fabricated nominal dimension, which was 3.4 inches. Since this value is less than the post-test result, it is postulated that an unobserved gap was created between the torispherical head lower surface and the inner surface of foam by the impact. In any case, it appears that the crush of foam in the free drop events was very small. The package after the D1H drop is shown in Figure 2.12.3-5.

The puncture drop P1 orientation is shown in Figure 2.12.3-6. The axis of the puncture bar was directed through the c.g. at an oblique angle of 29.5° to the bottom surface. The temperatures of the foam were 12.1 °F, 12.7 °F, and 15.2 °F. The bar made a dent 3-1/8 inches deep and cut a small, approximately 1.5-inch wide perforation in the bottom sheet. (This was, incidentally, the only exposure of polyurethane foam from any of the drops or puncture tests.) The puncture damage is shown in Figure 2.12.3-7.

After Test Series D1 was complete, CTU #1 was disassembled for inspection. Prior to disassembly, a leak test was performed on the containment closure and vent port seals as discussed above. The results showed no detectable leak. The average removal torque of the closure bolts was 150 ft-lb, with a low value of 60 ft-lb and a high of 230 ft-lb. Initial installation torque was 300 ft-lb.

There was no sign of any weld failure or distress of the welds connecting the impact limiter to the lower flange. The only deformation of the lodgment was a slight bowing of the angle segments connecting the bottom ribs, caused by contact with the deformed plate of the lower internal impact limiter. The lodgment was still flat on the bottom. The total deformation of the lower internal impact limiter tubes, based on measurements of the lodgment relative to the lower brackets, was 1.43 inches downward, achieved by buckling of the tubes. The lower internal impact limiter top view is shown in Figure 2.12.3-8 and the underside view, showing the buckling of the tubes, in Figure 2.12.3-9. The upper internal impact limiter was not significantly damaged. Two of the lodgment toggle clamps became unclamped, and one was damaged. The LTSS was not damaged or deformed.

After Test Series D1 inspection was complete, CTU #1 was reassembled using all the same components. The closure bolts were tightened to drawing requirements and leakage rate tested.

2.12.3.4.2 Test Series D5

Test series D5 was performed on CTU #3 and consisted of a 4-ft NCT and a 30-ft HAC free drop in the bottom-down orientation, with the axis vertical, followed by a puncture drop test on the flat bottom of the impact limiter, with the cask axis inclined at 30° from the vertical. (Note: the D5 series was identical to the D1 series.) The tests were designated D5N, D5H, and P6 for the 4-ft, 30-ft, and puncture drops, respectively. The free drop orientation (identical for D5N and D5H) is shown in Figure 2.12.3-10. The polyurethane foam temperature readings for test D5N were -5.3 °F, -4.5 °F, and -6.5 °F, and for test D5H, -2.9 °F, -2.1 °F, and -3.0 °F. Accelerometer results are shown in the table below.

Accelerations, Free Drop Test D5					
Location	**T/U**	**T/L**	**OT/U**	**OT/L**	**Avg. ⊥**
Test D5N	256g	256g	206g	203g	**230g**
Test D5H	797g	794g	855g	802g	**812g**

Like the D1 series, neither of these impacts imparted any visible damage to the CTU. The only external measurement taken at the time of the drops was the overall height. The height after D5N was 83-15/32 inches, compared to an as-fabricated height of 83-1/2 inches, for an apparent decrease of 1/32 inches. The same measurement taken after the D5H drop was 83-5/16 inches, for a further apparent decrease of 5/32 inches. The actual changes in overall height of the package were probably too small to be accurately measured using the techniques used. In any case, the external deformation was negligible. As discussed below, energy was absorbed internally.

After the D5H free drop, a ¼-inch diameter hole was drilled at the center of the bottom sheet of the impact limiter and through the foam to the lowest point on the lower torispherical head. After subtracting a total of 0.54 inches for the steel shell, the insulating paper, and an observed gap, the thickness of the foam was measured to be 4.0 inches. Since a pre-test measurement of this dimension was not made, the post-test result must be compared to the fabricated nominal dimension, which was 3.4 inches. Since this value is less than the post-test result, it is postulated that an unobserved gap was created by the impact between the torispherical head lower surface and the inner surface of foam. In any case, it appears that the crush of foam in the free drop events was very small. The package after the D5H drop is shown in Figure 2.12.3-11.

The puncture drop P6 orientation is shown in Figure 2.12.3-12. The axis of the puncture bar was directed through the c.g. at an oblique angle of 30.0° to the bottom surface. The temperatures of the foam were +1 °F and -1 °F, with one thermocouple not reading. The bar made a dent 1-9/16 inches deep without perforating the impact limiter shell or exposing any foam. The puncture damage is shown in Figure 2.12.3-13.

After Test Series D5 was complete, CTU #3 was disassembled for inspection. Prior to disassembly, a leak test was performed on the containment closure and vent port seals as discussed above. The results showed no detectable leak. The average removal torque of the closure bolts was 138 ft-lb, with a low value of 80 ft-lb and a high of 190 ft-lb.

There was no sign of any weld failure or distress of the welds connecting the impact limiter to the lower flange. The IC showed a downward deformation of the bottom structure by approximately 0.9 inches, along with some dents in the IC sidewall from impact with the dummy payload. Inside the IC, the lower wood dunnage was significantly crushed. The upper dunnage was not crushed, but the 'donut' section of the dunnage became unattached from the 'disk' portion. Two views of the damaged lower dunnage are given in Figure 2.12.3-14 and Figure 2.12.3-15. The dummy payload was not damaged. The IC rested firmly on the bottom internal impact limiter. The deformation of the lower internal impact limiter tubes was considerably less than in the D1 (lodgment) case, since there was significant energy absorption in the wood dunnage and some further deformation in the bottom structure of the IC. The upper internal impact limiter was not significantly damaged.

After Test Series D1 inspection was complete, CTU #3 was reassembled using a new IC, dunnage, and dummy payload, but using the same internal impact limiters. The closure bolts were tightened to drawing requirements and leakage rate tested.

2.12.3.4.3 Test Series D2

Test Series D2 was performed on CTU #1 and consisted of a 4-ft NCT and a 30-ft HAC free drop in the side orientation (where the impact limiter corner and the knuckle contacted simultaneously), followed by a puncture drop test on the knuckle in the region damaged by the free drop tests. The tests were designated D2N, D2H, and P2 for the 4-ft, 30-ft, and puncture drops, respectively. The free drop orientation (approximately 13° from horizontal, and identical for D2N and D2H) is shown in Figure 2.12.3-16. The free drop impact occurred on the opposite side of the package from the vent port. The polyurethane foam temperature readings for test D2N were -9.0 °F, -9.4 °F, and -9.5 °F. Due to the short time interval between tests D2N and D2H, and to the cold ambient temperature, the foam temperatures for test D2H were negligibly different from those recorded for test D2N, and well below the target value of 0 °F. Accelerometer results are shown in the table below.

Accelerations, Free Drop Test D2								
Location	T/U	T/L	OT/U	OT/L	Avg. Upper	Avg. Lower	Resolved ⊥ Upper	Resolved ⊥ Lower
Test D2N	154g	84g	154g	110g	154g	97g	**158g**	**100g**
Test D2H	449g	225g	459g	260g	454g	243g	**466g**	**249g**

The damage consisted of flat spots on the impact limiter and knuckle. After the D2H drop, the combined damage from both the NCT and HAC drops were as follows: the impact limiter flat was 25-1/4 inches long (along cask axis) and 33-1/4 inches wide (orthogonal). The knuckle flat was 12 inches long and 18 inches wide. At the height of the weld seam at the top of the cylindrical side of the impact limiter (essentially the lower impact point), the radial crush distance was 4-3/8 inches, using measurements based on the cask body O.D. Since the crush occurred with the cask axis at an angle of 13° to the ground, the crush in the direction of impact was 4-3/8 × cos(13) = 4.27 inches. (The crush at the knuckle was significantly less). An approximation of the amount of foam remaining was obtained by drilling a hole perpendicular to the flat damage surface, 17.5 inches from the bottom of the limiter. The bottom of the hole was approximately at the nearest point of hard flange material to the impact. The distance of foam, less the ¼-inch thick shell, was 5.94 – 0.25 = 5.69 inches. It was noted that all of the rain shield bolts were snug. The package after the D2H drop is shown in Figure 2.12.3-17.

Puncture drop P2 orientation is shown in Figure 2.12.3-18. The package was suspended essentially upside down over the puncture bar. The axis of the puncture bar was aimed at the knuckle at the location of the free drop damage and directed at the c.g. of the package. The temperature of the steel surface near the impact point was 31.4 °F. The puncture bar left a six-inch diameter impression at impact, the center of which was approximately 16 inches radially from the package centerline. The dent was ¾-inches deep. There was no evidence of cracking in the containment boundary material. Note that this test was conservative since the 0.105-inch thick head thermal shield was not present. The puncture damage is shown in Figure 2.12.3-19.

After Test Series D2 was complete, CTU #1 was disassembled for inspection. Prior to disassembly, a leak test was performed on the containment closure and vent port seals as discussed above. The results showed no detectable leak. The average removal torque of the closure bolts was 154 ft-lb, with a low value of 50 ft-lb and a high of 250 ft-lb.

The upper internal impact limiter was not crushed significantly, but the aluminum plate was somewhat buckled in the region of impact. The lower internal impact limiter, somewhat crushed in test series D1, did not experience significant additional damage. One guide pin in the base, located at the impact point, was slightly bent. Since the flange was not deformed, this likely occurred due to a misalignment between the bell and base during final disassembly. The side impact caused some minor radial deformations of the bell side wall of 1/8 inches maximum at locations which corresponded to the main structural members of the lodgment.

The lodgment was not significantly damaged, and the LTSS was essentially still in the original location. One toggle clamp was broken. The eight clevises connecting the two halves of the lodgment were intact. All eight bolts were slightly bent, occurring most likely during the D1 end impact. The LTSS was essentially undamaged, showing some surface waviness of approximately 1/8 inches on the impact side, corresponding to the main structural members of the lodgment. Internal damage from the D2 series is shown in Figure 2.12.3-20 and Figure

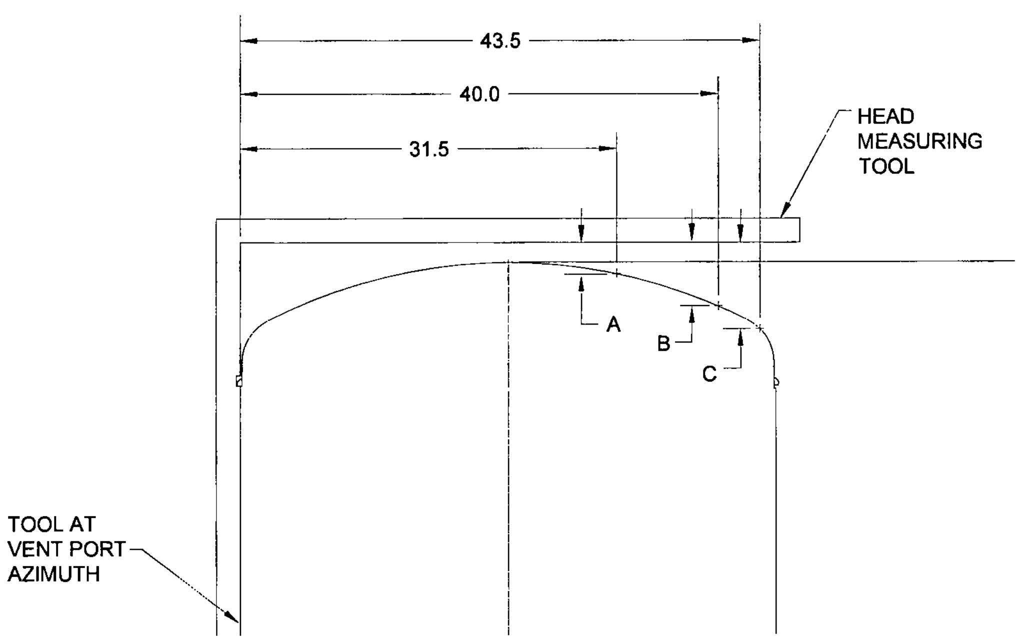
2.12.3-21. After all testing and disassembly, the containment boundary of CTU #1 was helium leakage rate tested. The maximum leakage rate was $2.9(10^{-8})$ He-cc/sec against a criteria of $2.2(10^{-7})$ He-cc/sec. Thus the package, after two complete series of free drop and puncture tests, was leaktight.

2.12.3.4.4 Test Series D3

Test series D3 was performed on CTU #2 and consisted of a 4-ft NCT and a 30-ft HAC free drop in the c.g.-over-top knuckle orientation, followed by a puncture drop through the c.g., directly on the free drop damage. The tests were designated D3N, D3H, and P3 for the 4-ft, 30-ft, and puncture drops, respectively. The free drop orientation (identical for both D3N and D3H) is shown in Figure 2.12.3-22. The package was oriented 27° from the vertical as shown. CTU #2 had the thermal shield installed on the upper torispherical head. The temperature of the outer shield shell was approximately 50 °F, based on the overnight environment temperature, the relatively short exposure to the cold ambient, and the thermal delay caused by the head shield. Accelerometer results are shown in the table below.

Accelerations, Free Drop Test D3						
Location	**T/U**	**T/L**	**OT/U**	**OT/L**	**Avg.**	**Resolved ⊥**
Test D3N	108g	No signal	106g	113g	109g	**122g**
Test D3H	162g	No signal	164g	152g	159g	**178g**

The damage consisted of a flat spot on the torispherical head, offset towards one side. After the D3H drop, the combined damage from both the NCT and HAC drops was a flat spot 21 inches long in the radial direction and 33-1/2 inches long in the circumferential direction. Another characterization showed the change in vertical location of the surface, illustrated in the figure below. Results are provided in the table below.



	Axial measurement, inches (after D3H)		
Location	**Pre-test**	**Post-test**	**Change (deformation)**
A	2-7/8	4.0	1-1/8
B	5-3/8	9-13/16	4-7/16
C	6-15/16	11-1/4	4-5/16

The package after the D3H drop is shown in Figure 2.12.3-23.

The puncture drop P3 orientation is shown in Figure 2.12.3-24. The axis of the puncture bar was directed through the c.g. of the package with the impact point (outermost edge) of the bar located at 3 inches from the outer edge of the buckle as shown in Figure 2.12.3-25. The package was oriented at the same angle as for the free drops. The internal lodgment ribs were placed to straddle the puncture impact, thus minimum support to puncture was afforded by internal structures. The bar made a dent approximately 1-3/8 inches deep, based on a straight edge laid across the entire damaged surface. The thermal shield shell did not tear or perforate, and there were no weld failures of the shield. The nominally 0.102-inch diameter wires in the puncture damage were somewhat flattened by the impact. Some of the intermittent welds attaching the simulated side thermal shield cracked, but the simulated shield was not displaced. The puncture damage is shown in Figure 2.12.3-25 and Figure 2.12.3-26. After the D3 test series, a vacuum was placed on the containment seal in the test annulus in lieu of a full helium leakage rate test, according to the test procedure. A vacuum of $7.5(10^{-4})$ Torr was sustained, indicating a leaktight containment seal. A full helium leakage rate test of the containment and vent port seals was performed following Test Series D4. The closure bolts were not retightened or nor was the vent port disturbed between the D3 and D4 series of tests.

2.12.3.4.5 Test Series D6

Test Series D6 was performed on CTU #3 and consisted of a 4-ft NCT and a 30-ft HAC free drop in the side orientation (identical to the free drop orientation of Series D2), followed by two puncture drop tests: one on the side on the prototypic side thermal shield, and one on the side on the bolt tube/rain shield region. The tests were designated D6N, D6H, P7 and P5 for the 4-ft, 30-ft, thermal shield puncture drop, and bolt tube puncture drops, respectively. The free drop orientation (approximately 13° from horizontal, and identical for D6N and D6H) is shown in Figure 2.12.3-27. The free drop impact occurred on the opposite side of the package from the vent port. The polyurethane foam temperature readings for test D6N were -3.5 °F, -4.0 °F, and -3.0 °F. Due to the short time interval between tests D6N and D6H, and to the cold ambient temperature, the foam temperatures for test D6H were negligibly different from those recorded for test D6N, and were thus below the target temperature of 0 °F. Accelerometer results are shown in the table below.

Accelerations, Free Drop Test D6								
Location	T/U	T/L	OT/U	OT/L	Avg. Upper	Avg. Lower	Resolved ⊥ Upper	Resolved ⊥ Lower
Test D6N	158g	75g	166g	78g	162g	77g	**166g**	**79g**
Test D6H	395g	159g	404g	178g	400g	169g	**411g**	**173g**

Like Test Series D2, the damage consisted of flat spots on the impact limiter and knuckle. After the D6H drop, the combined damage from both the NCT and HAC drops were as follows: the impact limiter flat was 21-3/4 inches long (along cask axis) and 30 inches wide (orthogonal). The knuckle flat was 11-1/4 inches long and 14-1/2 inches wide. At the height of the weld seam at the top of the cylindrical side of the impact limiter (essentially the lower impact point), the radial crush distance was 3-1/8 inches, using measurements based on the cask body O.D. Since the crush occurred with the cask axis at an angle of 13° to the ground, the crush in the direction of impact was 3-1/8 × cos(13) = 3.04 inches. (The crush at the knuckle was significantly less). An approximation of the amount of foam remaining was obtained by drilling a hole perpendicular to the flat damage surface, 17.5 inches from the bottom of the limiter. The bottom of the hole was approximately at the nearest point of hard flange material to the impact. The distance of foam, less the ¼-inch thick shell, was 7.0 – 0.25 = 6.75 inches. (This measurement was essentially confirmed after dissecting the impact limiter). It was noted that all of the rain shield bolts were snug. The package after the D6H drop is shown in Figure 2.12.3-28.

Puncture drop P7 orientation is shown in Figure 2.12.3-29. It occurred at the same azimuth as the free drops, i.e., opposite the vent port. The package was suspended over the puncture bar with the axis inclined at 30°, impact limiter up, and the axis of the puncture bar was aimed through the c.g. of the package. The temperature of the outermost thermal shield steel surface was 21.5 °F. The puncture bar struck the package approximately halfway up the cylindrical side and left an oblique dent 1-7/8 inches deep (measured on the outside). The 0.105-inch thick, outermost thermal shield was not ripped by the puncture bar, and there was no exposure of the inner thermal shield. The P7 puncture damage is shown in Figure 2.12.3-30.

Puncture drop P5 orientation is shown in Figure 2.12.3-31. It occurred at the azimuth of the vent port. The package was suspended essentially horizontally, with the puncture bar axis aiming perpendicularly to the package axis, slightly towards the bottom end from the c.g. This orientation was chosen to ensure that the puncture bar impact would occur on the tube sheet/rain shield region. Due to the difficulty in achieving a perfect impact location, trying to aim at the c.g. would present too large a risk of missing the desired impact point, given that the angle between the puncture bar and impact limiter slanted top surface was a very small acute angle. It was therefore judged that a horizontal package orientation represented the best choice for maximum damage. The puncture bar hit the slanted top of the impact limiter, and skidded up until it struck the tube sheet, which it deformed radially by ½-inches. The buckling of the ¼-inch thick tube sheet essentially stopped the impact progress, until the package bounced off of the bar and a secondary impact with the side thermal shield occurred. The rain shield was locally very slightly bent. The deformation of the top of the limiter caused the vent port tube opening to collapse onto the vent port insulation cylinder, which needed to be pried out. The P5 puncture damage is shown in Figure 2.12.3-32 and Figure 2.12.3-33. The dent in the vent port tube that trapped the vent port cylinder is shown in Figure 2.12.3-34. The vent port insulation cylinder was held securely in position by both the fully intact rain shield as well as the collapsed tube.

After Test Series D6 was complete, CTU #3 was disassembled for inspection. Prior to disassembly, a leak test was performed on the containment closure and vent port seals as discussed above. The results showed no detectable leak. The average removal torque of the closure bolts was 157 ft-lb, with a low value of 40 ft-lb and a high of 290 ft-lb.

The upper internal impact limiter was not crushed significantly, but the aluminum plate was somewhat buckled in the region of impact. The lower internal impact limiter was not significantly damaged. The P7 puncture dent, measured radially from the inside, was 1-1/2 inches high. An internal view of the dent is shown in Figure 2.12.3-35. A slightly different view is given in Figure 2.12.3-36, which shows the impression made on the inner surface of the containment boundary by the IC ribs, demonstrating that the puncture bar struck just adjacent to the ribs. Thus the bar was not supported by the IC ribs. The damage caused by the secondary bounce onto the bar in test P5, measured radially from the inside, was 9/16 inches high.

Since the IC was locked into the CTU #3 bell by the puncture sidewall damage, it was necessary to cut the bottom out and remove the IC wall by piecemeal cutting. The dummy payload cut through the IC wall somewhat in one location in the side drop (see Figure 2.12.3-37), but any buckling of the egg-crate reinforcements of the outside of the IC were minimal. The dummy payload did not engage more than one or two of the plywood sheets in the dunnage (top and bottom), and these sheets were significantly damaged in the side drop (see Figure 2.12.3-38). The balance of the dunnage was undamaged. The dummy payload was undamaged as shown in Figure 2.12.3-39. Two of the six bolts holding on the IC lid sheared off.

After all testing and disassembly, the containment boundary of CTU #3 was helium leakage rate tested. The maximum leakage rate was $1.9(10^{-7})$ He-cc/sec against a criteria of $2.2(10^{-7})$ He-cc/sec. Thus the package, after two complete series of free drop and puncture tests, was leaktight.

2.12.3.4.6 Test Series D4

Test Series D4 was performed on CTU #2 and consisted of a 4-ft NCT and a 30-ft HAC free drop in the side orientation (identical to the free drop orientations of Series D2 and D6), followed by a puncture drop test on the cylindrical side of the impact limiter through the c.g. The tests were designated D4N, D4H, and P4 for the 4-ft, 30-ft, and puncture drop, respectively. The free drop orientation (approximately 13° from horizontal, and identical for D4N and D4H) is shown in Figure 2.12.3-40. The free drop impact occurred at the vent port. The polyurethane foam temperature readings for test D4N were 118 °F and 120 °F. In contrast to the cold test cases, these readings were taken approximately 12 inches on either side of the impact point, at the regular depth of 9 inches. At a depth of 4.5 inches, the D4N temperatures were 112 and 120 °F. For test D4H, the corresponding temperatures at 9 inches were 116 and 119 °F, and at 4.5 inches, 90 and 116 °F. (The 90 °F temperature reading is doubtful.) Accelerometer results are shown in the table below.

Accelerations, Free Drop Test D4								
Location	T/U	T/L	OT/U	OT/L	Avg. Upper	Avg. Lower	Resolved ⊥ Upper	Resolved ⊥ Lower
Test D4N	144g	74g	130g	82g	137g	78g	**141g**	**80g**
Test D4H	356g	168g	372g	187g	364g	178g	**374g**	**183g**

Like Test Series D2 and D6, the damage consisted of flat spots on the impact limiter and knuckle. After the D4H drop, the combined damage from both the NCT and HAC drops were as follows: the impact limiter flat was 25-1/2 inches long (along cask axis) and 33 inches wide (orthogonal). The knuckle flat was 11-1/2 inches long and 18-1/2 inches wide. At the height of the weld seam at the top of the cylindrical side of the impact limiter (essentially the lower impact point), the radial crush distance was 4-13/16 inches, using measurements based on the cask body O.D. Since the crush occurred with the cask axis at an angle of 13° to the ground, the crush in the direction of impact was 4-13/16 × cos(13) = 4.68 inches. (The crush at the knuckle was significantly less). A measure of the amount of foam remaining was not obtained until after the puncture drop was complete. It was noted that all of the rain shield bolts were snug. The package after the D4H drop is shown in Figure 2.12.3-41.

Puncture drop P4 orientation is shown in Figure 2.12.3-42. It occurred on the free drop damage on the impact limiter (thus, at the vent port azimuth) with the bar aimed through the c.g. of the package. The measured angle of the package axis was 36° to the horizontal. The polyurethane foam temperature was 114 °F at 9 inches deep, and 99 °F at 4.5 inches deep. The puncture bar struck the package approximately 7-1/2 inches up the side from the flat bottom and skidded approximately 3-1/2 inches before stopping. There was no fissure or perforation of the impact limiter shell and no exposure of foam. The maximum depth of the puncture dent was 1-1/2 inches. The P4 puncture damage is shown in Figure 2.12.3-43.

After Test Series D4 was complete, CTU #2 was disassembled for inspection. Prior to disassembly, a leak test was performed on the containment closure and vent port seals as discussed above. The results showed no detectable leak. The average removal torque of the closure bolts was 101 ft-lb, with a low value of 0 ft-lb (found on two adjacent bolts) and a high of 270 ft-lb. Note that the closure bolts were not re-tightened between Test Series D3 and D4, and therefore these residual torques resulted from two complete test series.

Upon disassembly, the test O-ring seal was observed to be cut over an approximately 3-inch length. Since the leakage rate test was successful, it is presumed that this cut occurred during removal of the bell from the base. Since the bell and base were difficult to separate, the bell was not drawn off slowly but fell, with a sudden misalignment of the base to the bell, at which time the seal likely became cut by the sharp edge of the bell.

As expected, the tubes located at the impact of test D3 were crushed flat, and the plate of the upper internal impact limiter was buckled from both the D3 and D4 impacts. The pattern of tube crushing is shown in Figure 2.12.3-44. The deformation of the package due to Test Series D3 is shown in Figure 2.12.3-45 and Figure 2.12.3-46, where the head thermal shield has been locally cut away to expose the containment boundary. The lower internal impact limiter had little damage. The lodgment showed some buckling of the radial plate adjacent to the impact of the D3 test, but little other damage (see Figure 2.12.3-47). The LTSS was supported in essentially its original position. Note that the LTSS was thoroughly tested in Test Series D1 and D2. The only additional damage to the LTSS from Test Series D3 and D4 was some shallow deformations (approximately 1/8 inches or less) due to support from the lodgment's circular plates in the side (D4) free drops.

In the region of the D4 and P4 damage, the impact limiter was cut away on the plane of the free drop and puncture drop and measurements of the foam thickness made. The minimum depth of foam (not including the shell and gap), measured perpendicular to the outer surface of the foam to the hard flange upper corner, was 5-1/8 inches, and is shown in Figure 2.12.3-48. The distance from the bottom of the P4 puncture damage to the hard flange lower corner was 6-1/4 inches, and is shown in Figure 2.12.3-49.

After all testing and disassembly, the containment boundary of CTU #2 was helium leakage rate tested. The maximum leakage rate was $1.1(10^{-7})$ He-cc/sec against a criteria of $2.2(10^{-7})$ He-cc/sec. Thus the package, after two complete series of free drop and puncture tests, was leaktight.

2.12.3.5 Summary of Test Results

Certification testing was performed on the 435-B packaging design using three full scale CTUs. A total of six, 4-ft NCT free drops, six, 30-ft HAC free drops, and seven puncture drops were performed on the test units. After all tests, the CTUs were helium leaktight. Free drop accelerations were recorded for use in finite element model benchmarking and other structural analyses. The deformations of the packaging that could have an effect on performance in the HAC fire event were recorded. The deformations of the LTSS or the dummy shielded device were negligible, such that no change in the shielding performance is expected.

Table 2.12.3-1 – Certification Test Unit Weight, lb

	CTU #1	CTU #2	CTU #3
Base	2,280	2,216	2,285
Bell	2,315	2,394	2,435
Lodgment	512	508	1,110②
LTSS	4,460	4,460	3,870③
Total①	**9,642**	**9,653**	**9,775**

Notes:

1. Total weight includes 75 lb for closure bolts, washers, and rain shields.
2. Weight of inner container (IC).
3. CTU #3 used a dummy device weighing 3,570 lb and wood blocking weighing 300 lb. Tests D5N, D5H, and P6 used IC #1, and tests D6N, D6H, P5, and P7 used IC #2. Both ICs, when fully assembled, weighed the same.

Table 2.12.3-2 – Summary of Containment Boundary Integrated Leakage Rate Tests②

Test Unit	Leakage Rate, He-cc/sec①	Pass/Fail
CTU #1	$2.9(10^{-8})$	Pass
CTU #2	$1.1(10^{-7})$	Pass
CTU #3	$1.9(10^{-7})$	Pass

Notes:

1. Leak tight criteria is $2.2(10^{-7})$ He-cc/sec, which is equivalent to $1.0(10^{-7})$ std-cc/sec, air.
2. Containment seal and vent port seals were leak tight (No Detectable Leak) whenever checked (after test series D1, D2, D4, D5, and D6). After test series D3, a hard vacuum was sustained in lieu of a helium leakage rate test. The containment and vent port seals were not disturbed until after the next drop test series (D4) and subsequent helium leakage rate test had been successfully performed.

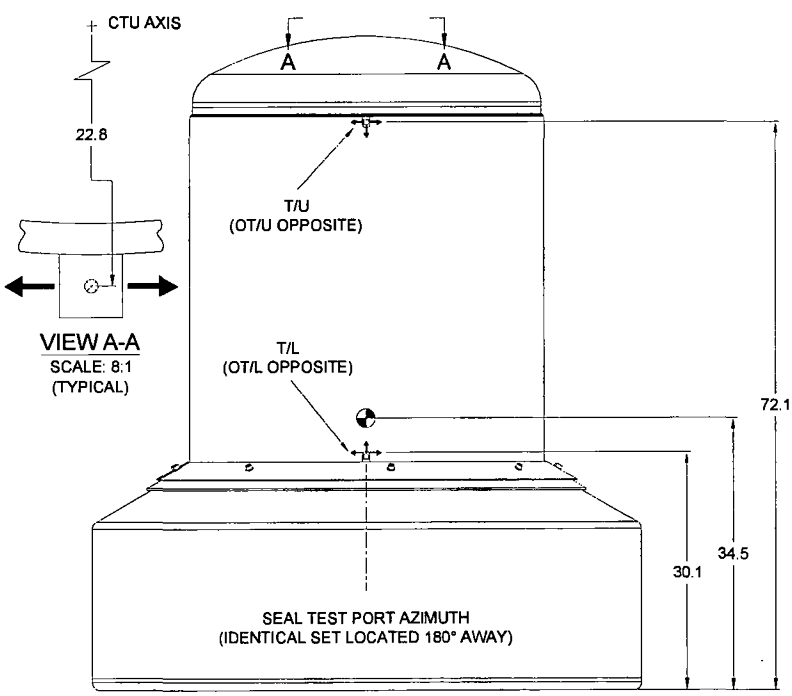


Figure 2.12.3-1 – Accelerometer Mounting

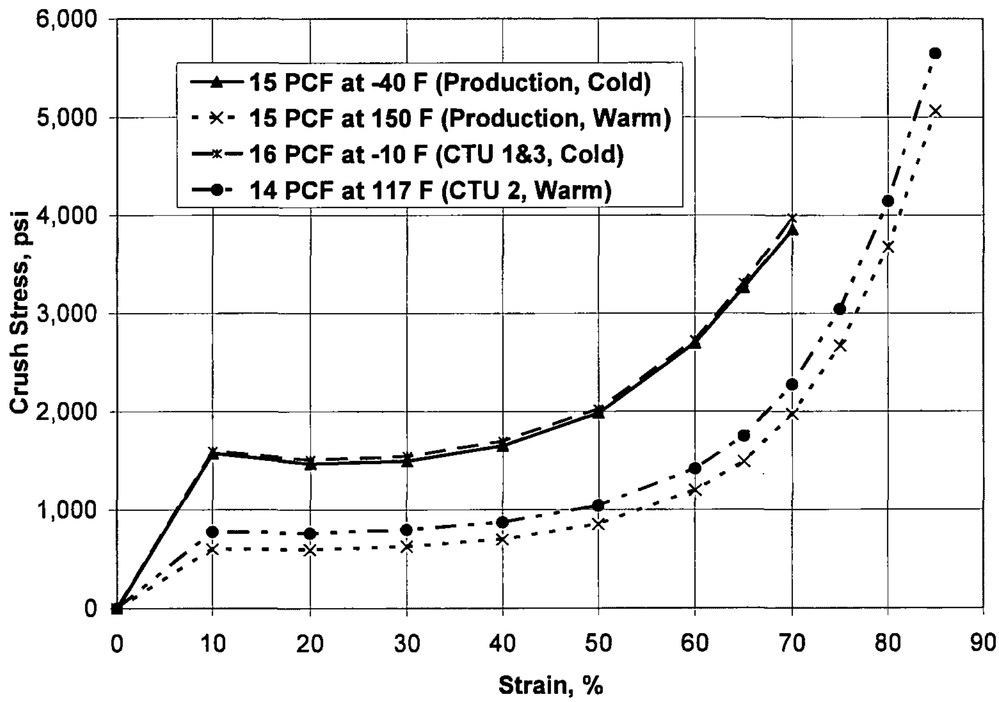


Figure 2.12.3-2 – Comparison of Foam Stress-Strain at Cold and Warm Conditions

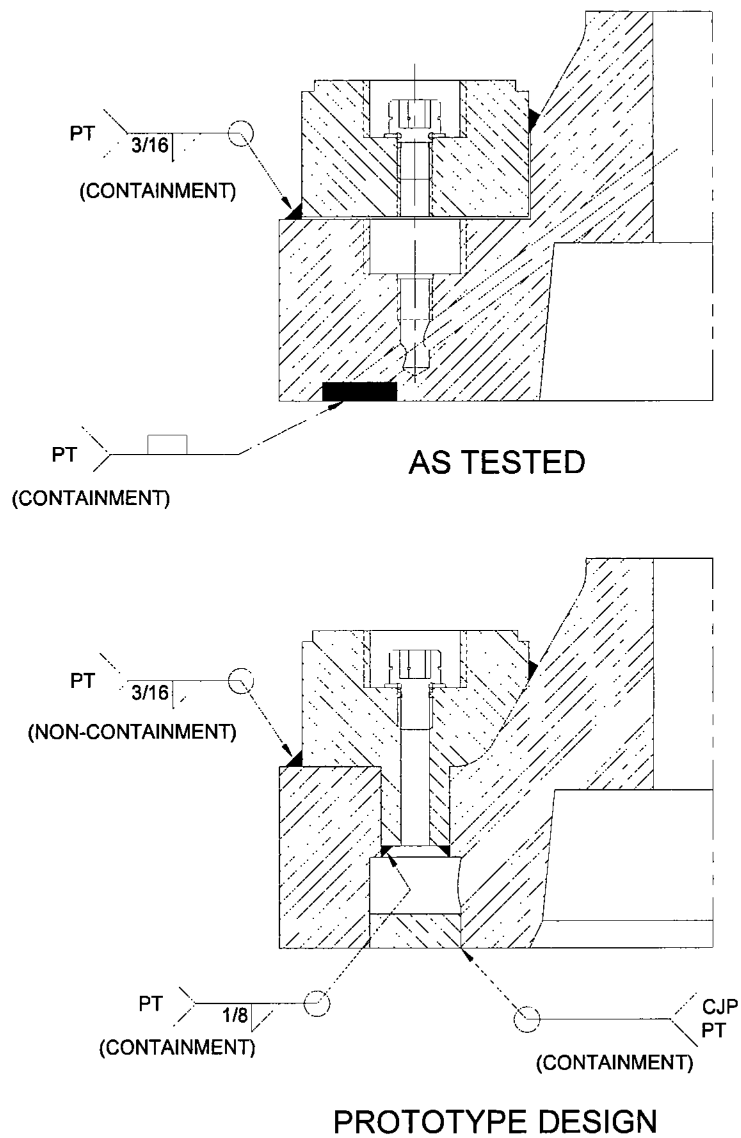


Figure 2.12.3-3 – Vent/Test Port Configuration Differences (Vent Port Shown)

Figure 2.12.3-4 – Free Drop Test D1N/D1H Orientation

Figure 2.12.3-5 – CTU #1 Condition After Free Drop Test D1H

Figure 2.12.3-6 – Puncture Drop Test P1 Orientation

Figure 2.12.3-7 – Damage to Impact Limiter Bottom Due to Puncture Drop Test P1

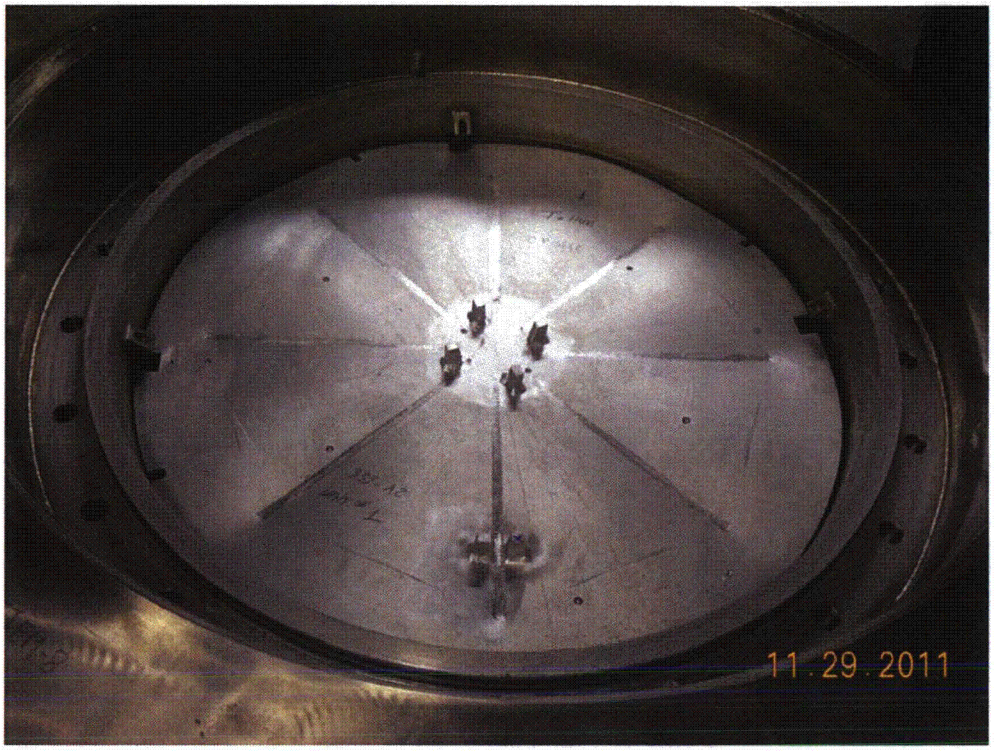


Figure 2.12.3-8 – Lower internal impact limiter, After D1 Series

Figure 2.12.3-9 – Lower internal impact limiter, View From Beneath, After D1 Test Series

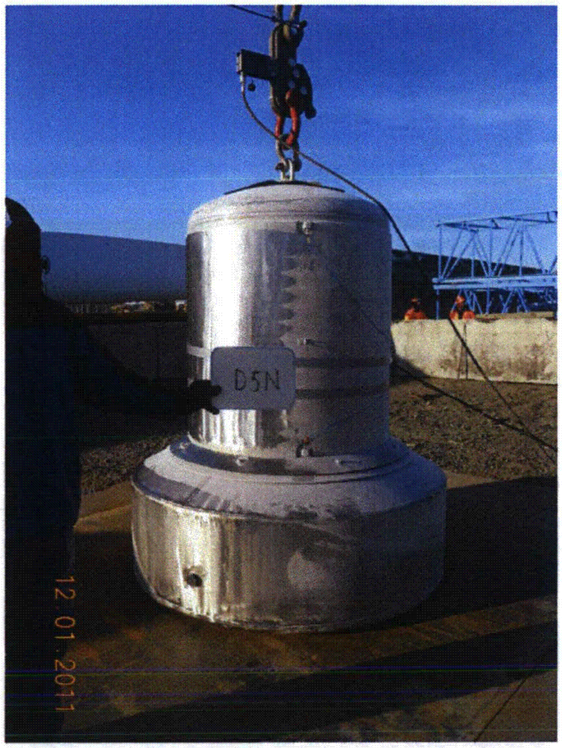


Figure 2.12.3-10 – Free Drop Test D5N/D5H Orientation

Figure 2.12.3-11 – CTU #3 Condition After Free Drop Test D5H

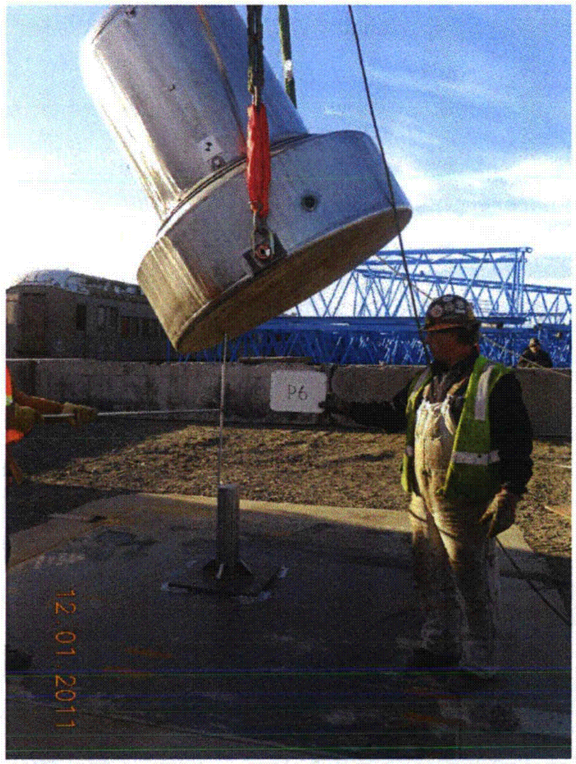


Figure 2.12.3-12 – Puncture Drop Test P6 Orientation

Figure 2.12.3-13 – Damage to Impact Limiter Bottom Due to Puncture Drop Test P6

Figure 2.12.3-14 – Inner Container Lower Dunnage After D5 Test Series

Figure 2.12.3-15 – Detail of Lower Dunnage Damage After D5 Test Series

Figure 2.12.3-16 – Free Drop Test D2N/D2H Orientation

Figure 2.12.3-17 – CTU #1 Condition After Free Drop Test D2H

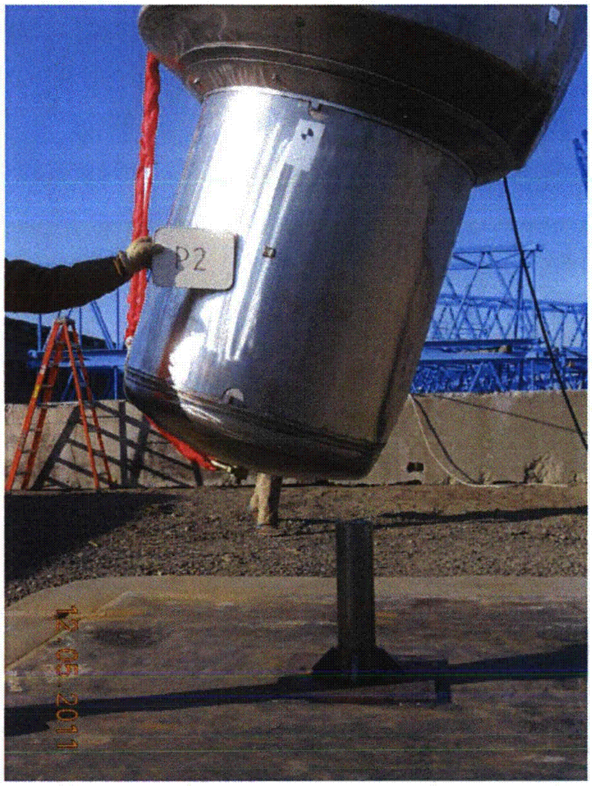


Figure 2.12.3-18 – Puncture Drop Test P2 Orientation

Figure 2.12.3-19 – Damage to Package Top Due to Puncture Drop Test P2

Figure 2.12.3-20 – General Condition of Lodgment & LTSS After D1 and D2 Test Series

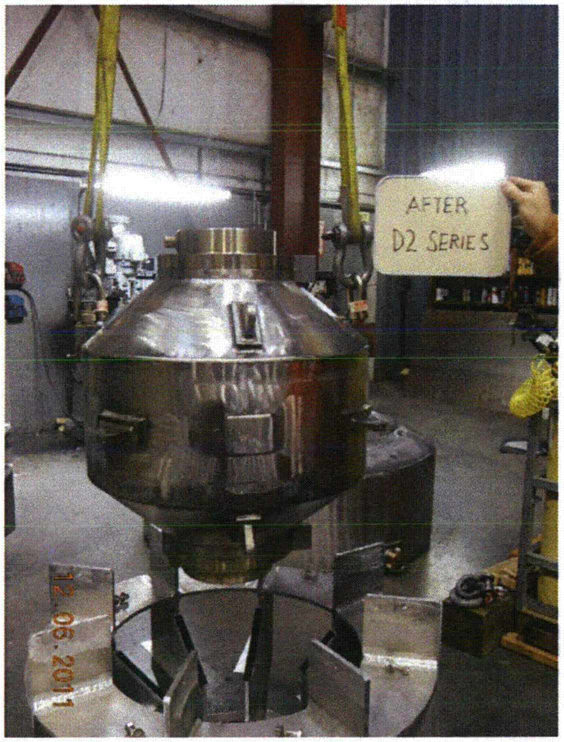


Figure 2.12.3-21 – Condition of LTSS After D1 and D2 Test Series

Figure 2.12.3-22 – Free Drop Test D3N/D3H Orientation

Figure 2.12.3-23 – CTU #2 Condition After Free Drop Test D3H

Figure 2.12.3-24 – Puncture Drop Test P3 Orientation

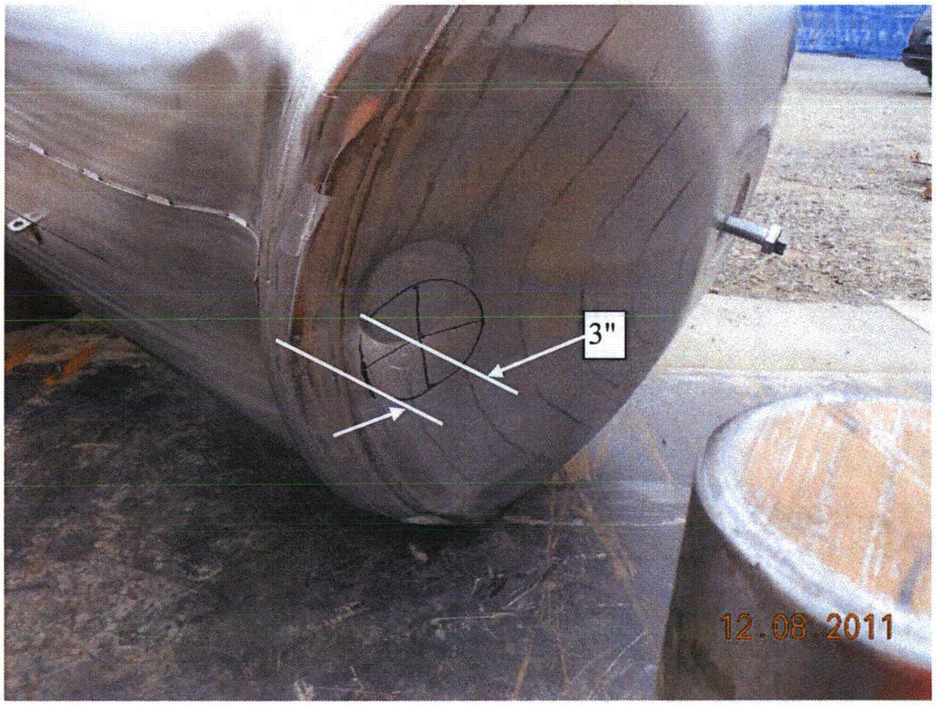


Figure 2.12.3-25 – Damage to Package Top Due to Puncture Drop Test P3

Figure 2.12.3-26 – Detail of Puncture Test P3 Damage

Figure 2.12.3-27 – Free Drop Test D6N/D6H Orientation

Figure 2.12.3-28 – CTU #3 Condition After Free Drop Test D6H (Also Showing P7)

Figure 2.12.3-29 – Puncture Drop Test P7 Orientation

Figure 2.12.3-30 – Damage to Package Side Due to Puncture Drop Test P7

Figure 2.12.3-31 – Puncture Drop Test P5 Orientation

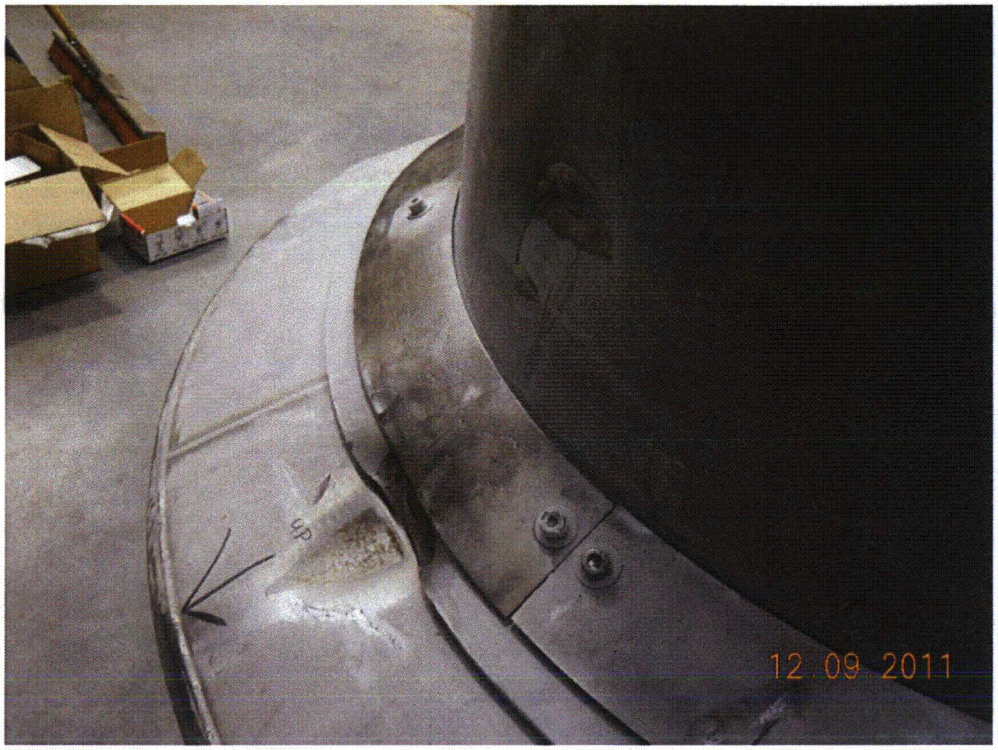


Figure 2.12.3-32 – Damage to Package Side Due to Puncture Drop Test P5

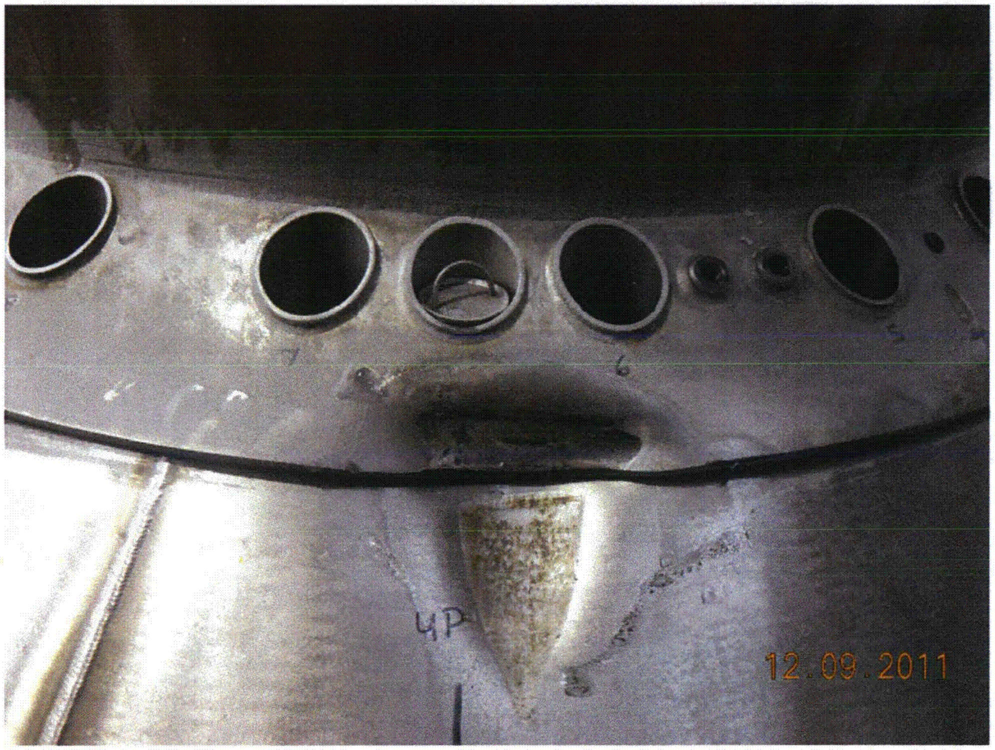


Figure 2.12.3-33 – Detail of Puncture Test P5 Damage (Rain Shield Removed)

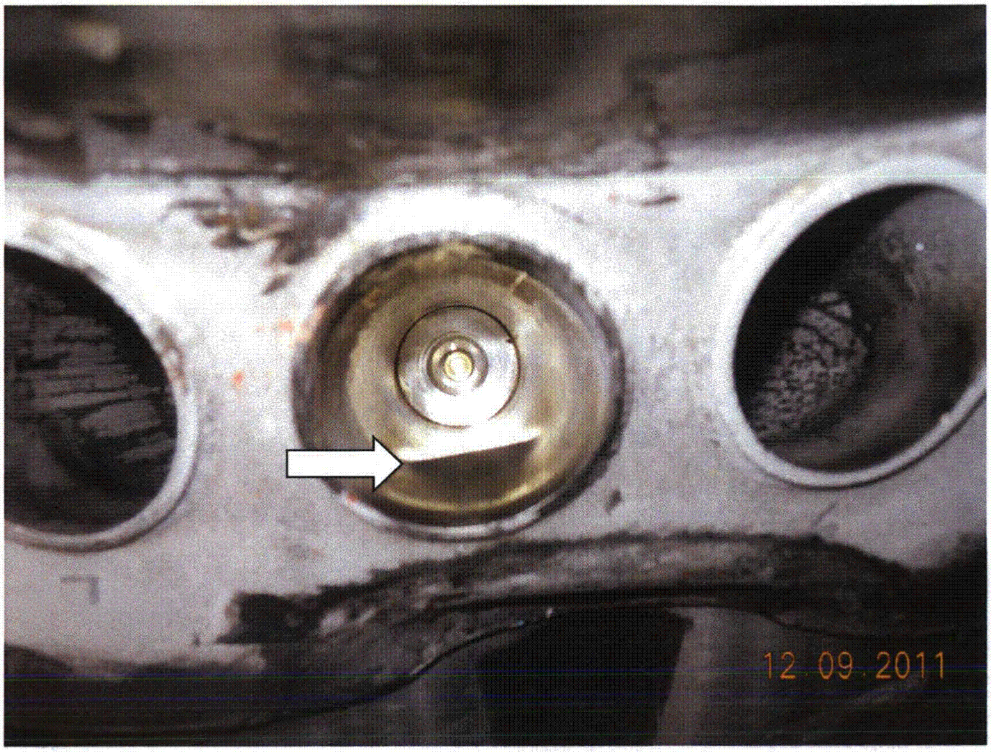


Figure 2.12.3-34 – Puncture Test P5 Damage Showing Internal Dent in Vent Port Tube

Figure 2.12.3-35 – Internal View of Damage from Puncture Test P7

Figure 2.12.3-36 – Internal View of Damage from Puncture Test P7, Detail

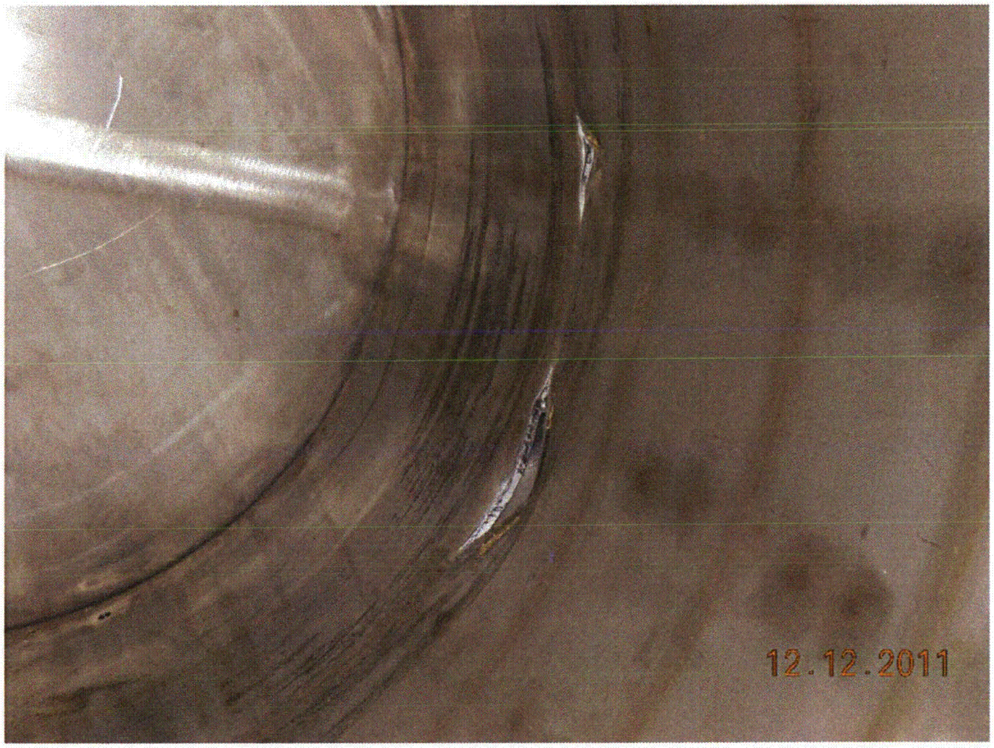


Figure 2.12.3-37 – Cut in Inner Container (IC) Wall Due to Dummy Payload Side Impact

Figure 2.12.3-38 – Dunnage After D6 Test Series

Figure 2.12.3-39 – Dummy Payload After D6 Test Series

Figure 2.12.3-40 – Free Drop Test D4N/D4H Orientation

Figure 2.12.3-41 – CTU #2 Condition After Free Drop Test D4H (Also Showing P4)

Figure 2.12.3-42 – Puncture Drop Test P4 Orientation

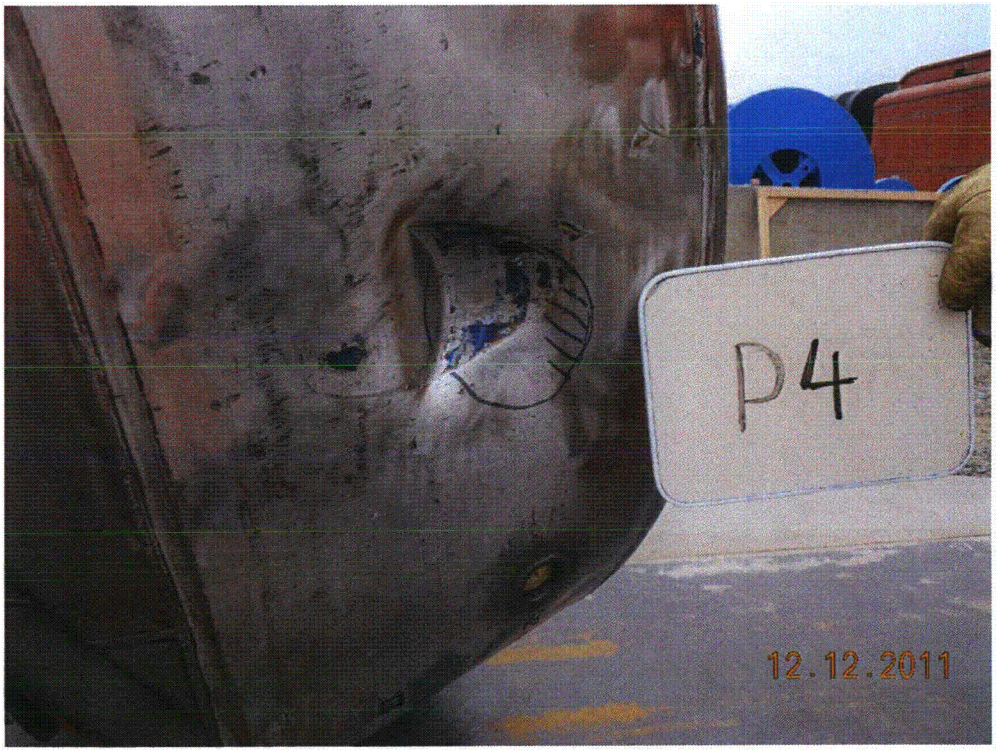


Figure 2.12.3-43 – Damage to Impact Limiter Side Due to Puncture Drop Test P4

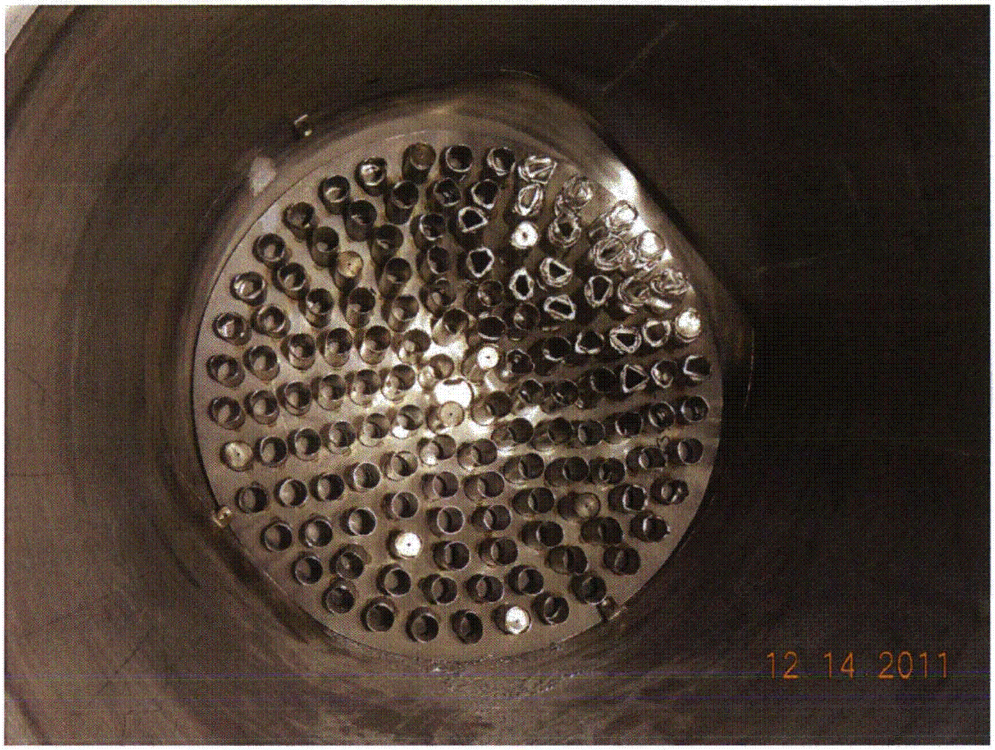


Figure 2.12.3-44 – Crushed Internal impact limiter Tubes (Upper) Due to Free Drop D3

Figure 2.12.3-45 – View of Damage Due to Test Series D3, Head Shield Cut Away (arrow indicates puncture bar impact location)

Figure 2.12.3-46 – View of Damage Due to Test Series D3

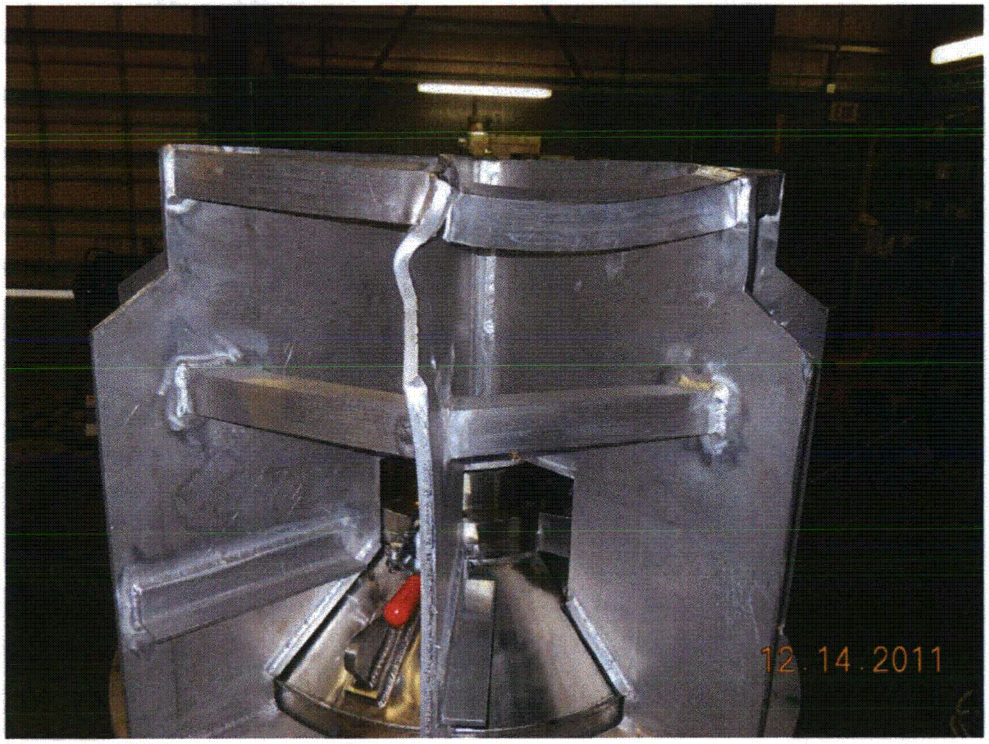


Figure 2.12.3-47 – Damage to Lodgment After Test Series D3 and D4

Figure 2.12.3-48 – Minimum Foam Remaining After Free Drop D4H

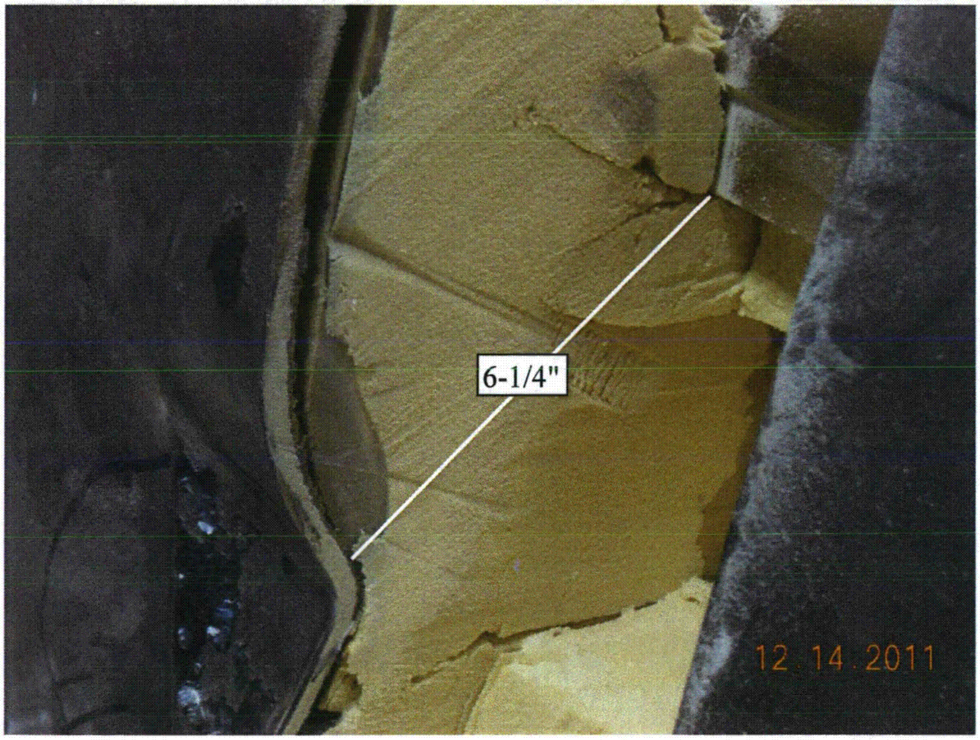
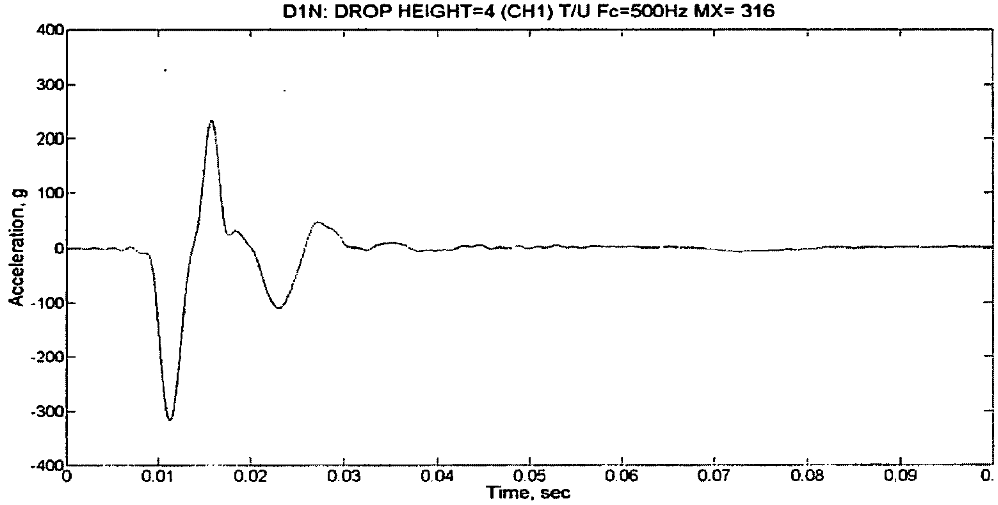
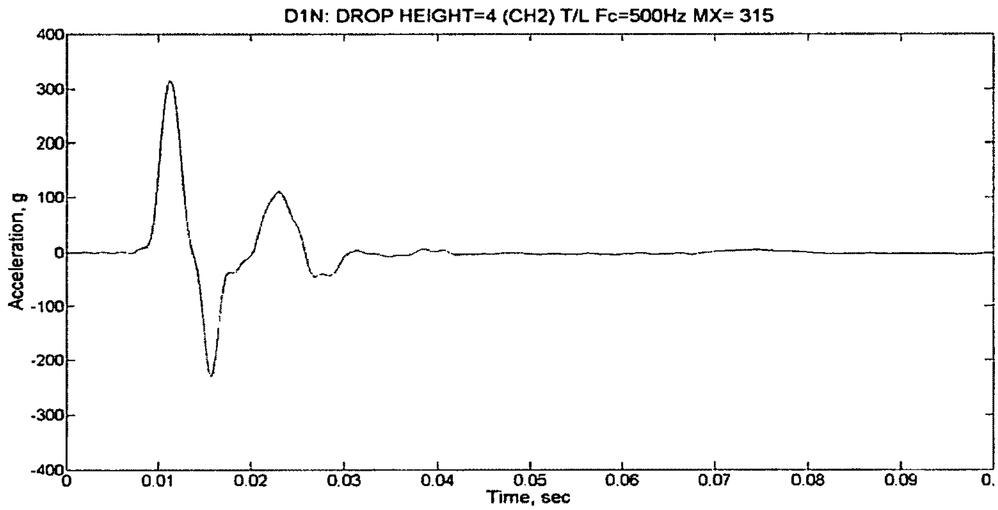


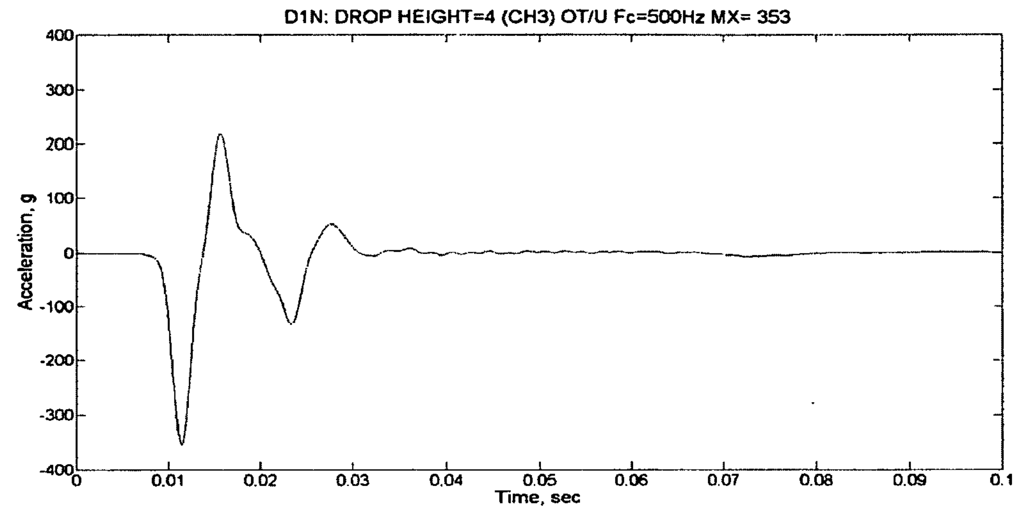
Figure 2.12.3-49 – Minimum Foam Remaining After Puncture P4

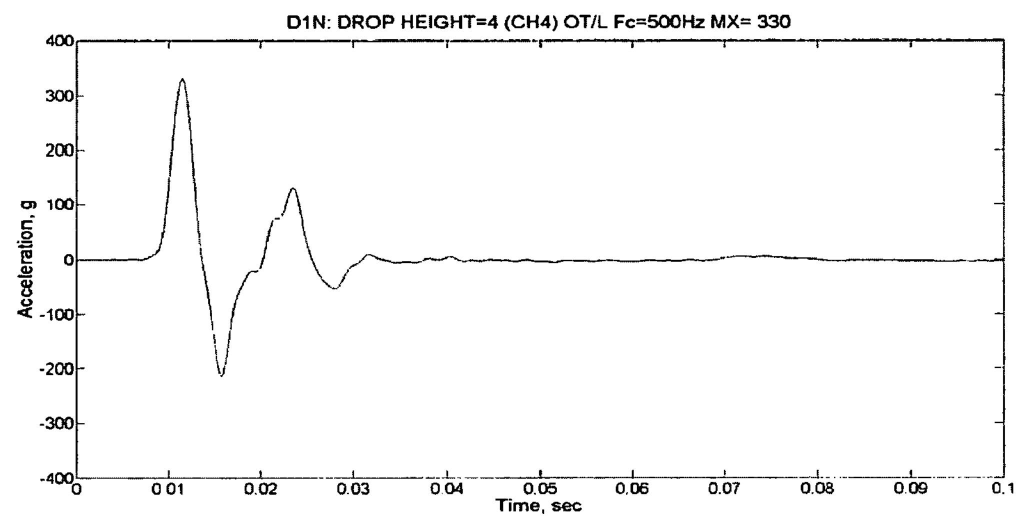
2.12.3.6 Filtered Accelerometer Time Histories

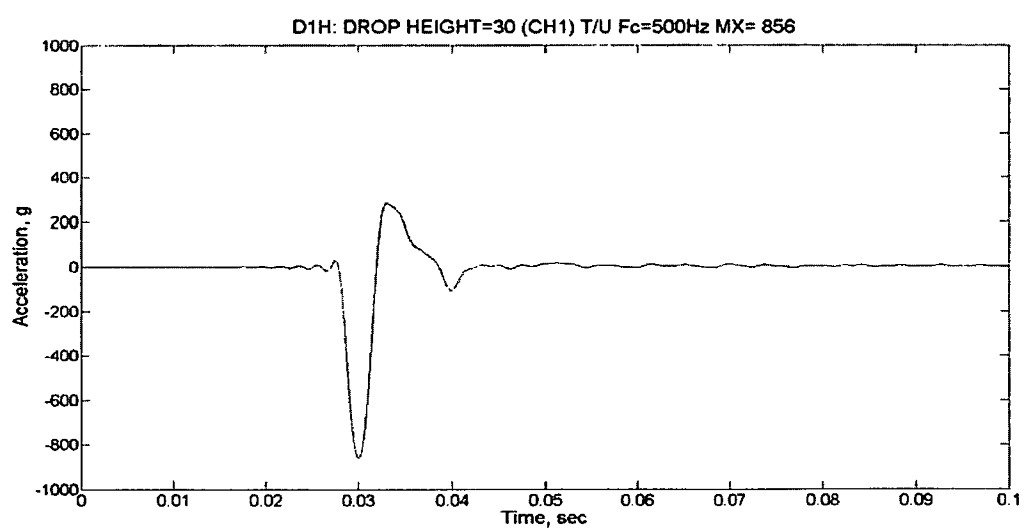
Accelerometer time history plots are provided below. Information identifying each plot is given above the figure as: drop test I.D.; drop height in ft; channel no.; location on CTU (see Section 2.12.3.2.2, *Instrumentation*, for description); filter cutoff frequency (500 Hz in all cases); and peak value, g.



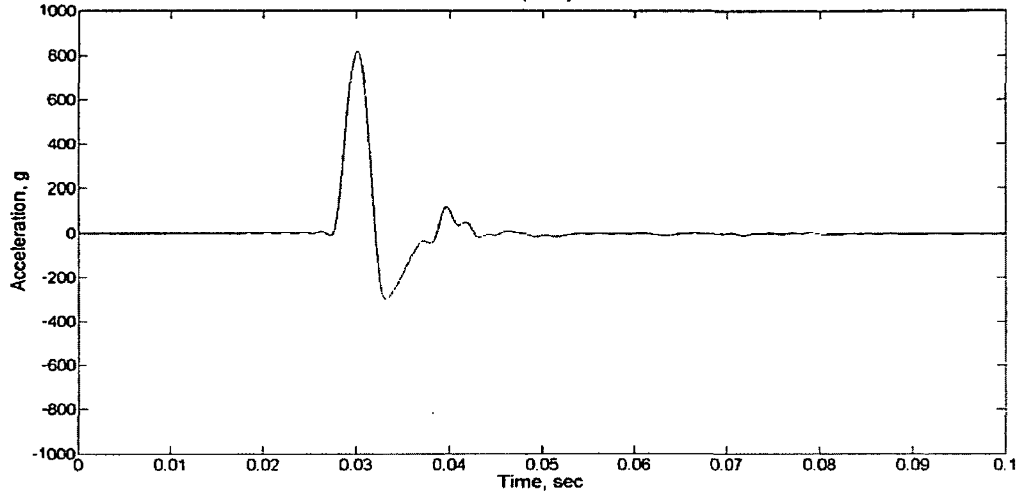



D1N: DROP HEIGHT=4 (CH3) OT/U Fc=500Hz MX= 353
Acceleration, g
Time, sec

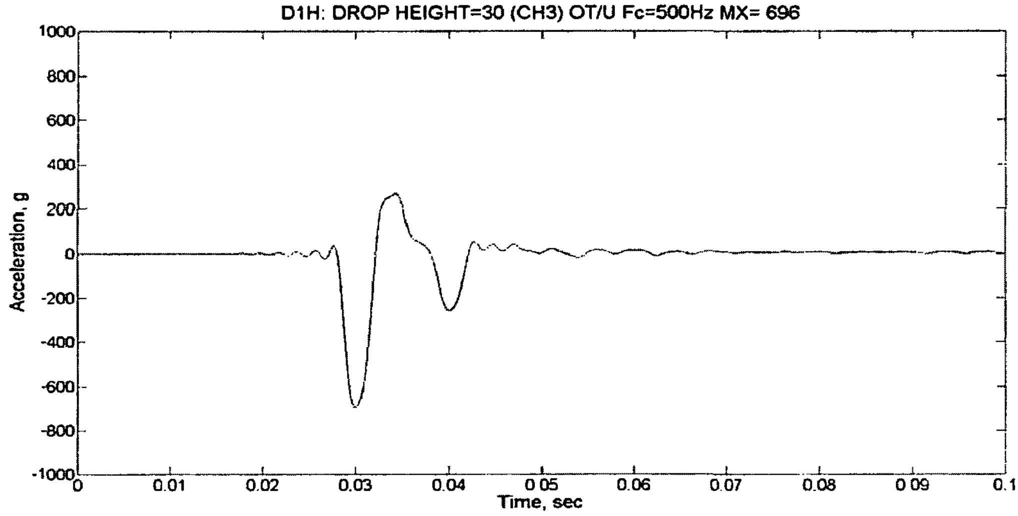

D1N: DROP HEIGHT=4 (CH4) OT/L Fc=500Hz MX= 330
Acceleration, g
Time, sec


D1H: DROP HEIGHT=30 (CH1) T/U Fc=500Hz MX= 856
Acceleration, g
Time, sec

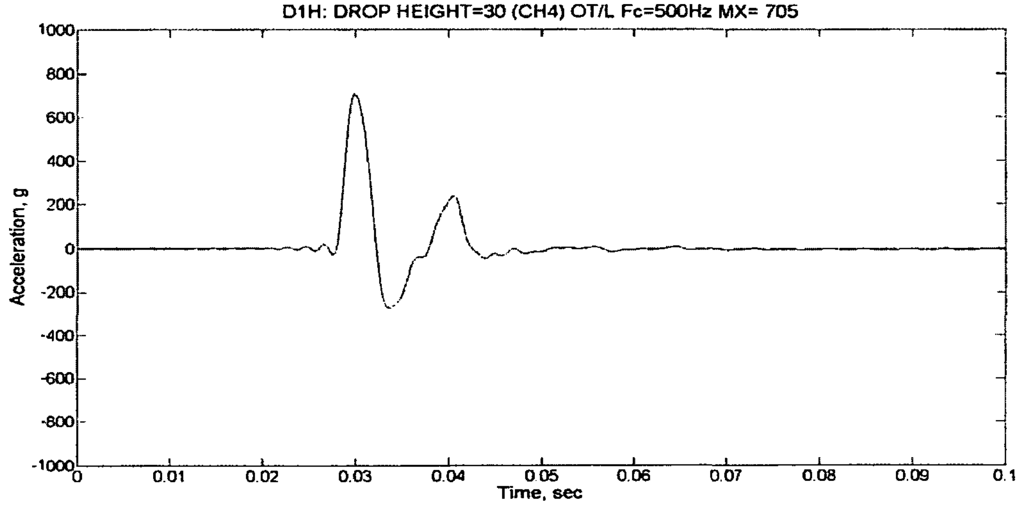
D1H: DROP HEIGHT=30 (CH2) T/L Fc=500Hz MX= 815

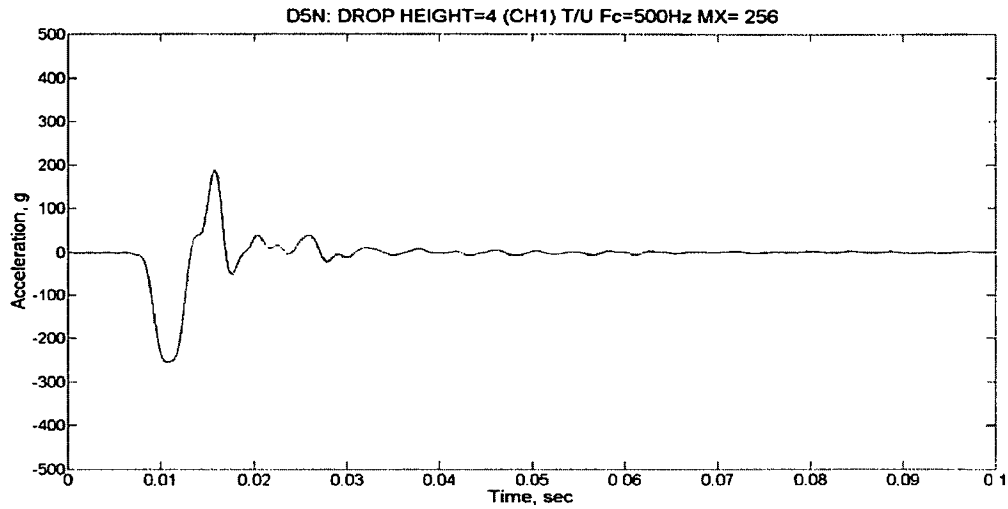


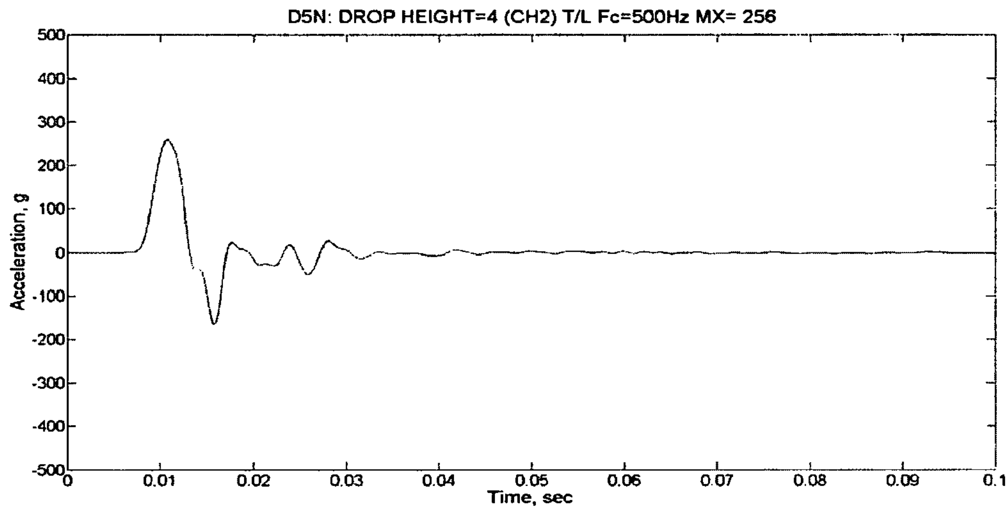
D1H: DROP HEIGHT=30 (CH3) OT/U Fc=500Hz MX= 696

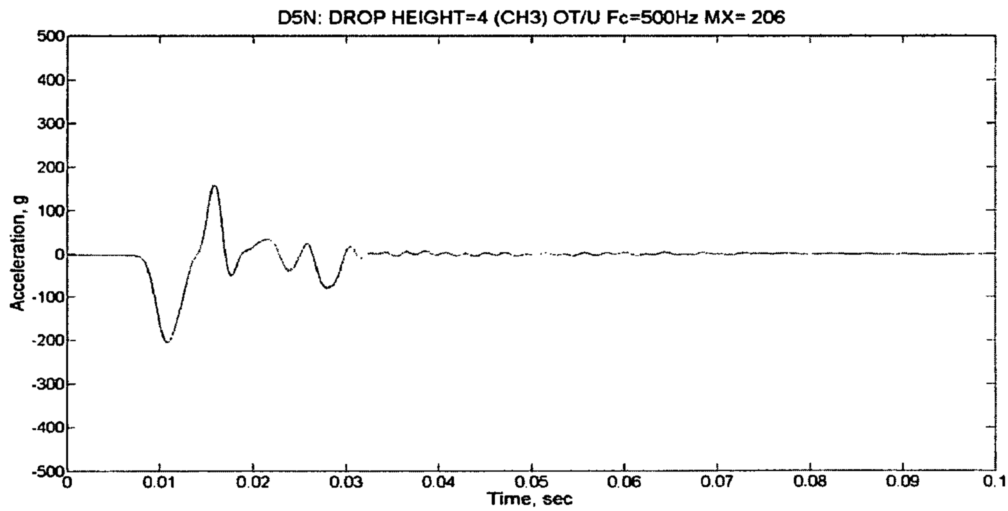


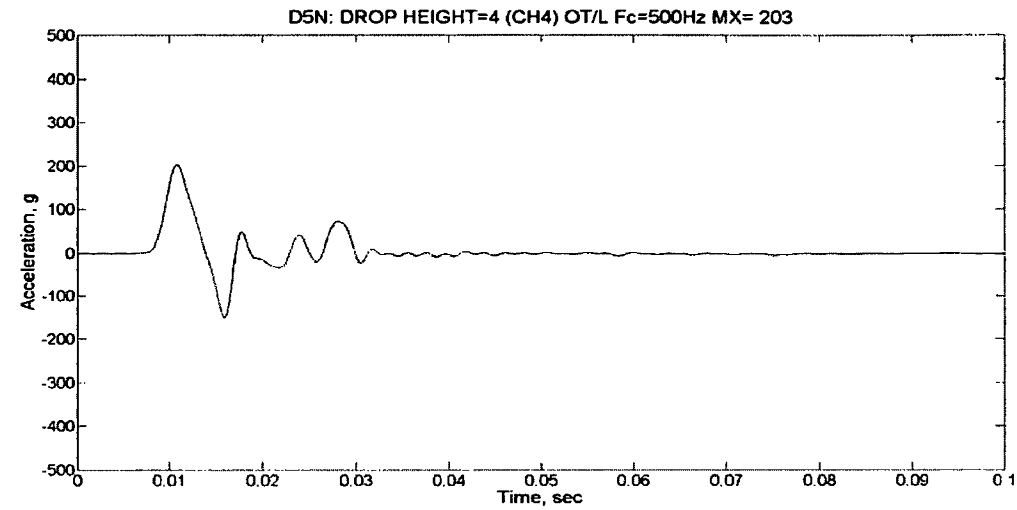
D1H: DROP HEIGHT=30 (CH4) OT/L Fc=500Hz MX= 705

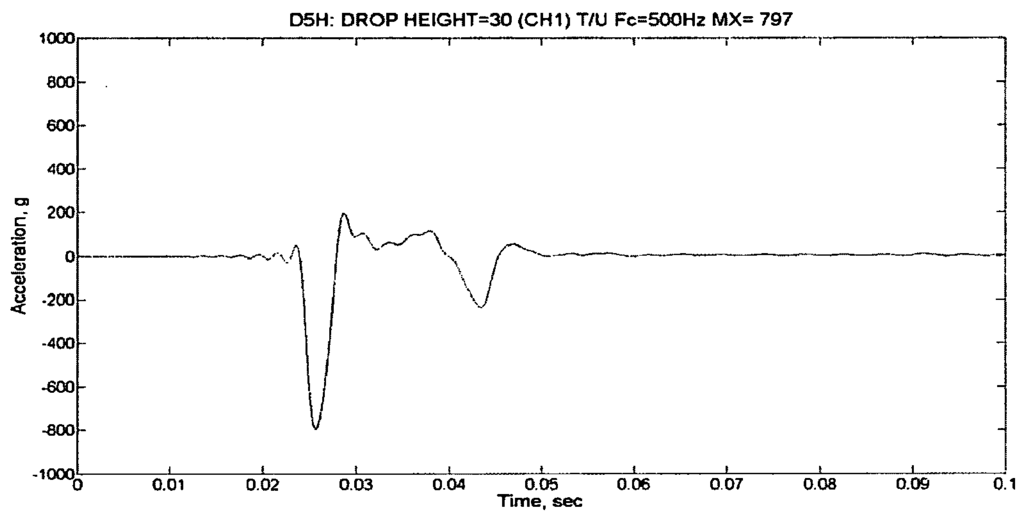


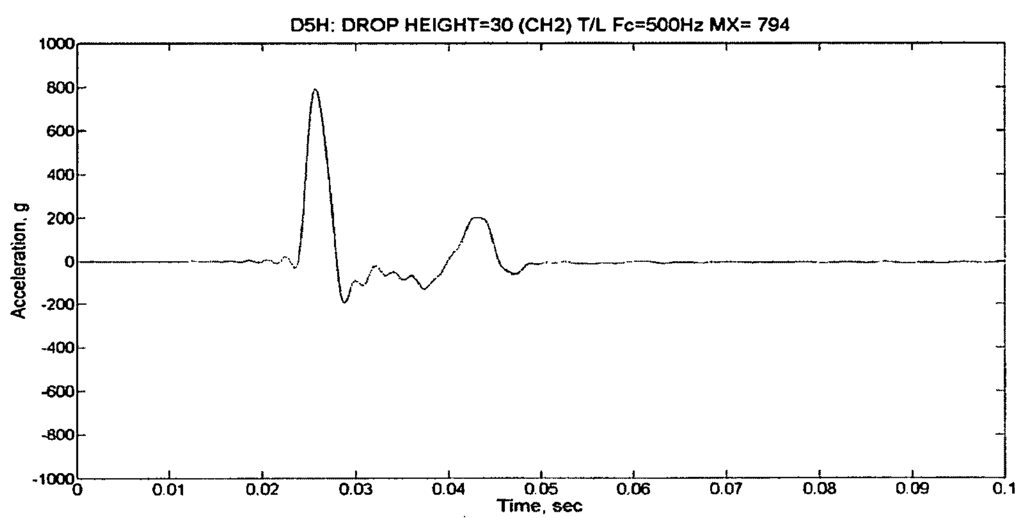

D5N: DROP HEIGHT=4 (CH1) T/U Fc=500Hz MX= 256
Acceleration, g
Time, sec

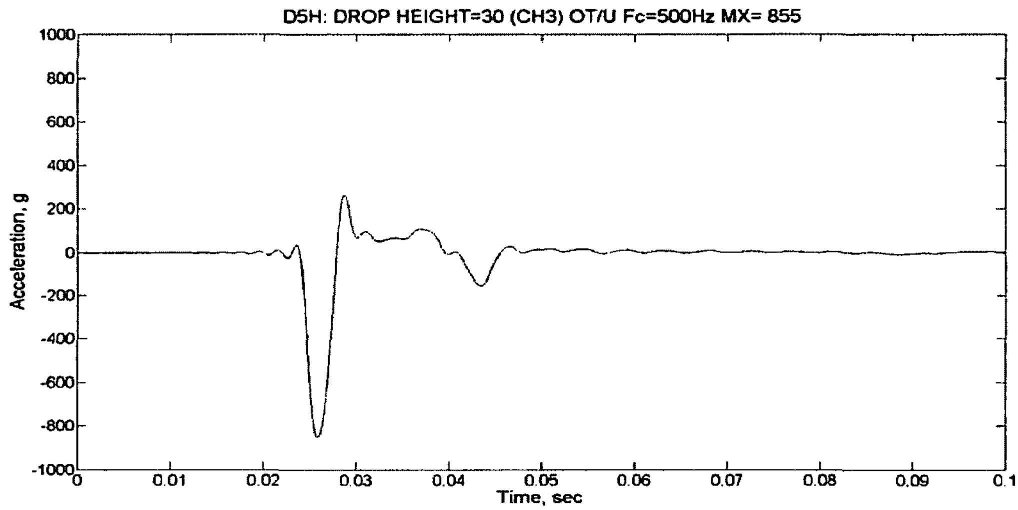

D5N: DROP HEIGHT=4 (CH2) T/L Fc=500Hz MX= 256
Acceleration, g
Time, sec

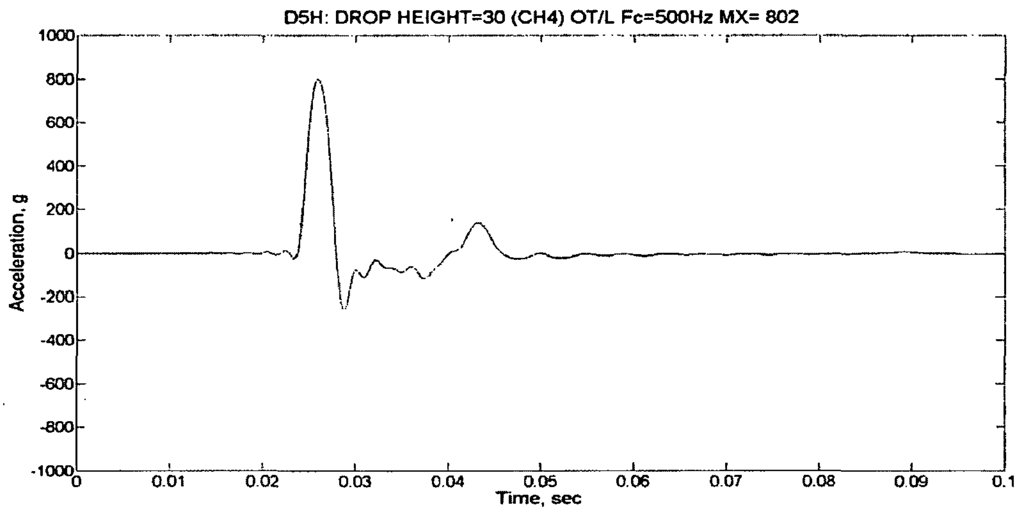

D5N: DROP HEIGHT=4 (CH3) OT/U Fc=500Hz MX= 206
Acceleration, g
Time, sec

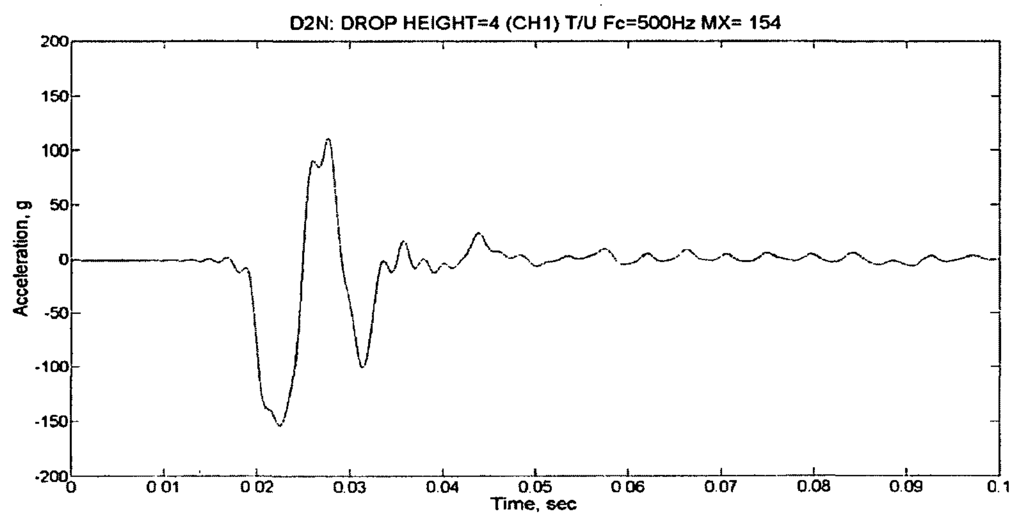

D5N: DROP HEIGHT=4 (CH4) OT/L Fc=500Hz MX= 203
Acceleration, g
Time, sec

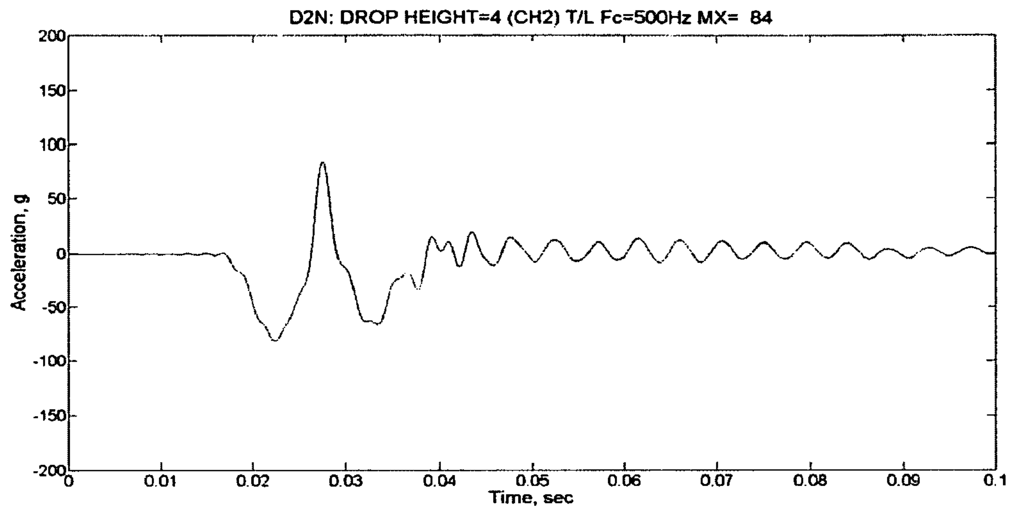

D5H: DROP HEIGHT=30 (CH1) T/U Fc=500Hz MX= 797
Acceleration, g
Time, sec

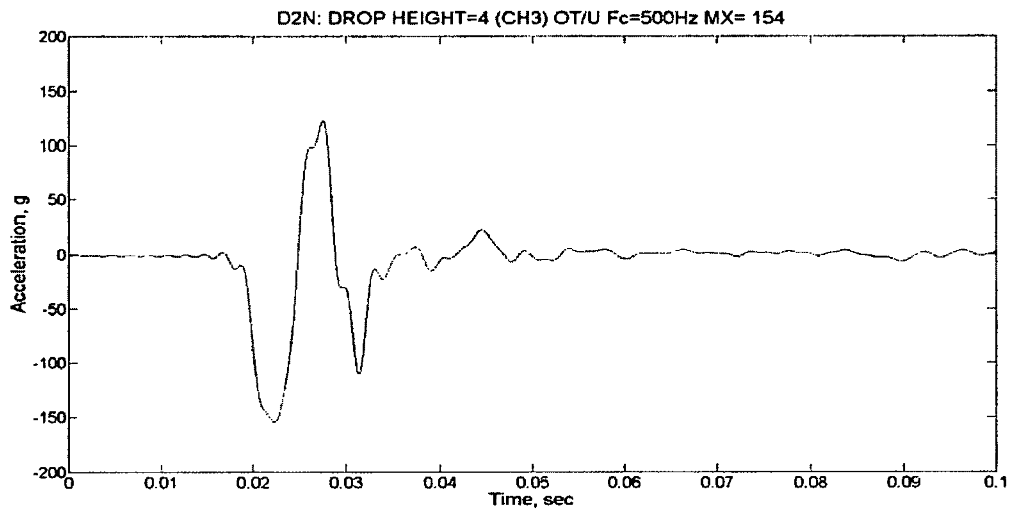

D5H: DROP HEIGHT=30 (CH2) T/L Fc=500Hz MX= 794
Acceleration, g
Time, sec

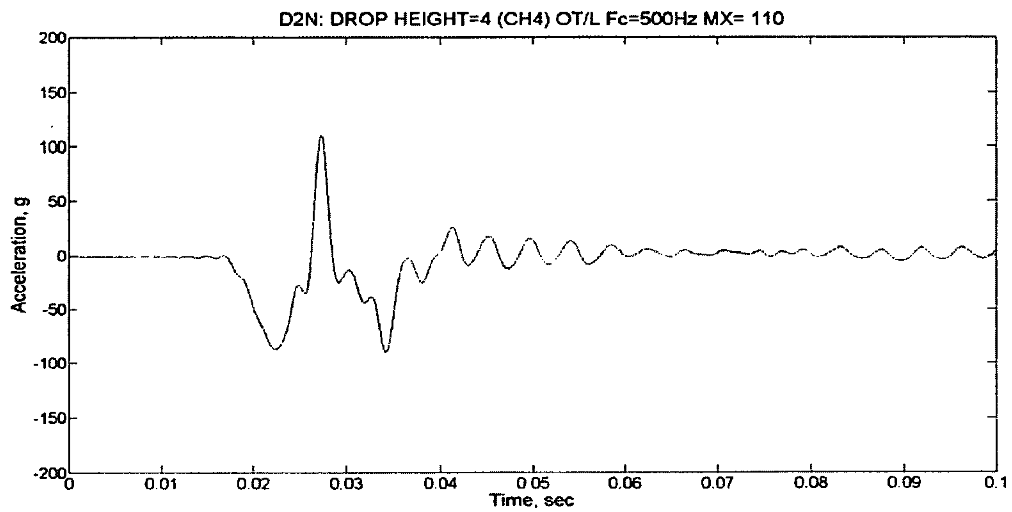

D5H: DROP HEIGHT=30 (CH3) OT/U Fc=500Hz MX= 855
Acceleration, g
Time, sec

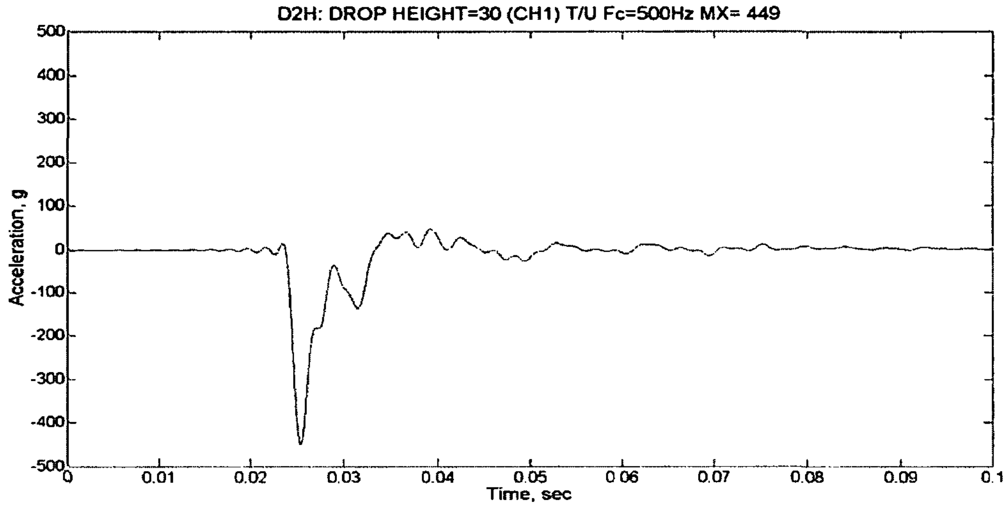

D5H: DROP HEIGHT=30 (CH4) OT/L Fc=500Hz MX= 802
Acceleration, g
Time, sec

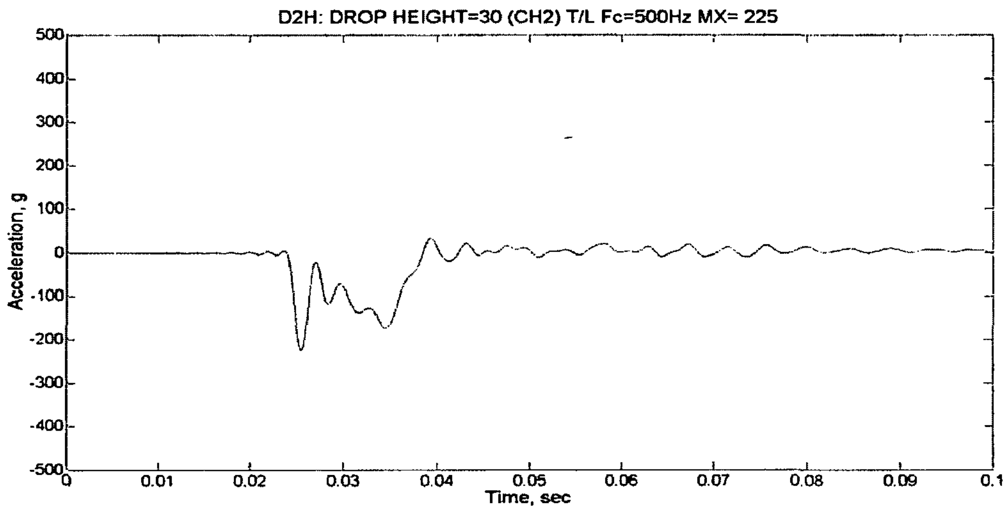

D2N: DROP HEIGHT=4 (CH1) T/U Fc=500Hz MX= 154
Acceleration, g
Time, sec

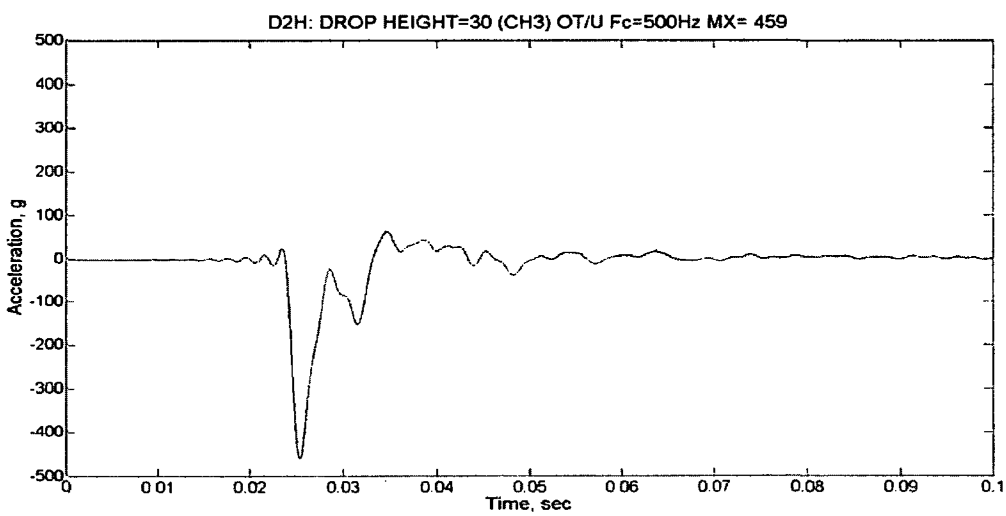

D2N: DROP HEIGHT=4 (CH2) T/L Fc=500Hz MX= 84
Acceleration, g
Time, sec

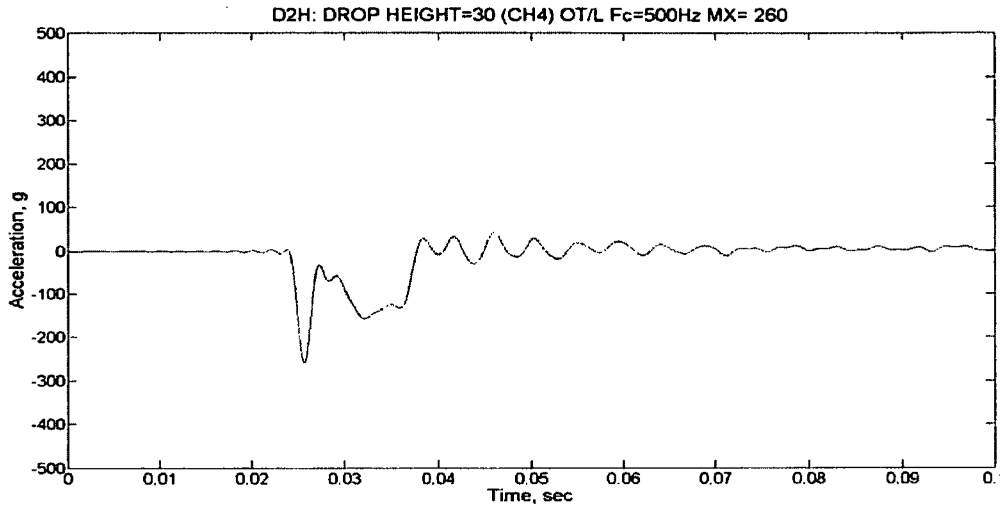

D2N: DROP HEIGHT=4 (CH3) OT/U Fc=500Hz MX= 154
Acceleration, g
Time, sec

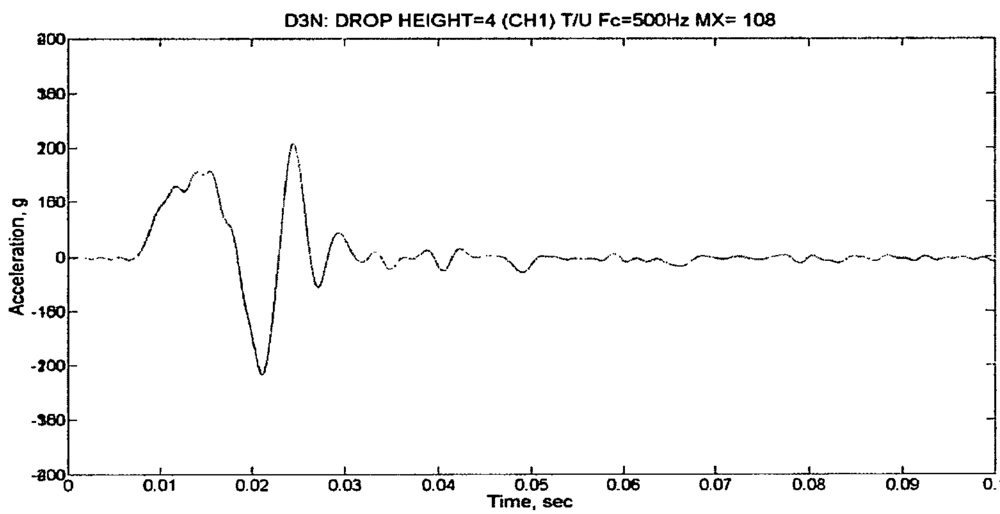

D2N: DROP HEIGHT=4 (CH4) OT/L Fc=500Hz MX= 110
Acceleration, g
Time, sec

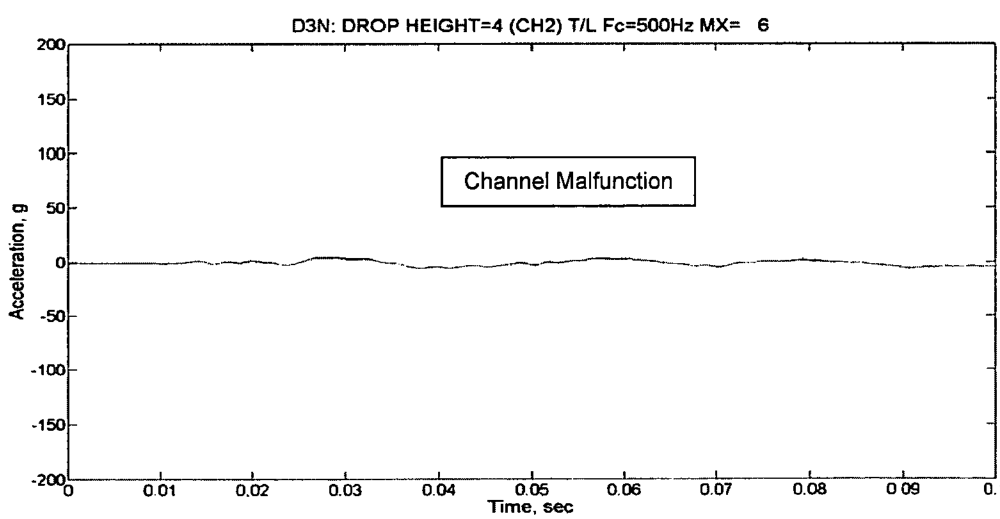

D2H: DROP HEIGHT=30 (CH1) T/U Fc=500Hz MX= 449
Acceleration, g
Time, sec

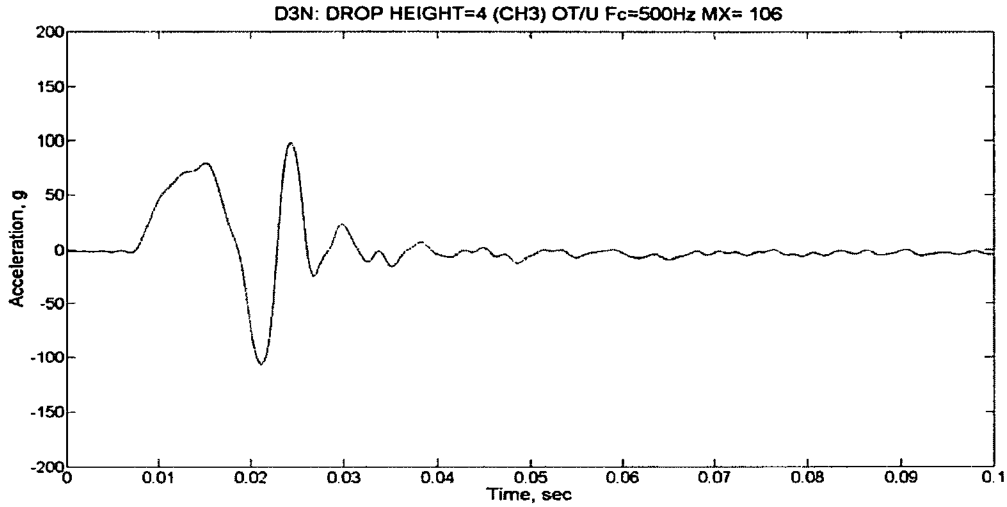

D2H: DROP HEIGHT=30 (CH2) T/L Fc=500Hz MX= 225
Acceleration, g
Time, sec

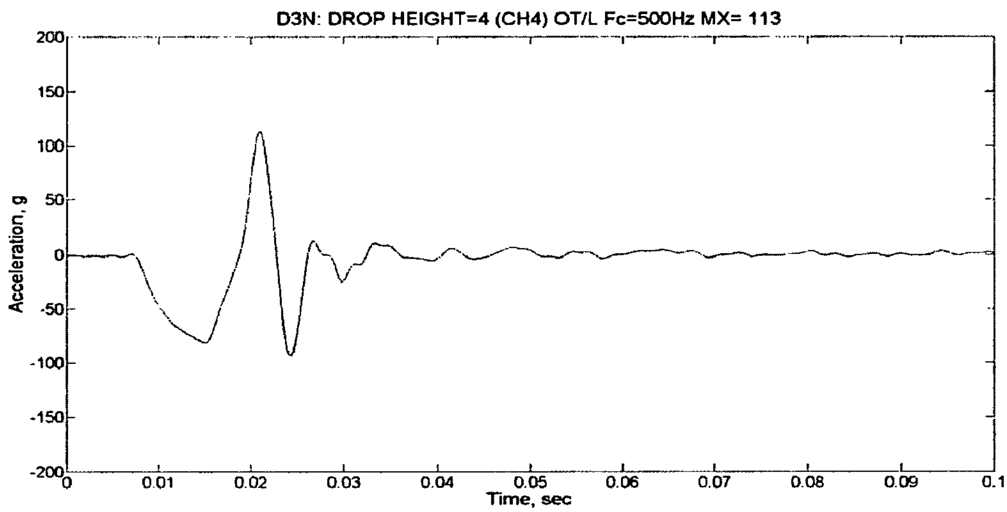

D2H: DROP HEIGHT=30 (CH3) OT/U Fc=500Hz MX= 459
Acceleration, g
Time, sec

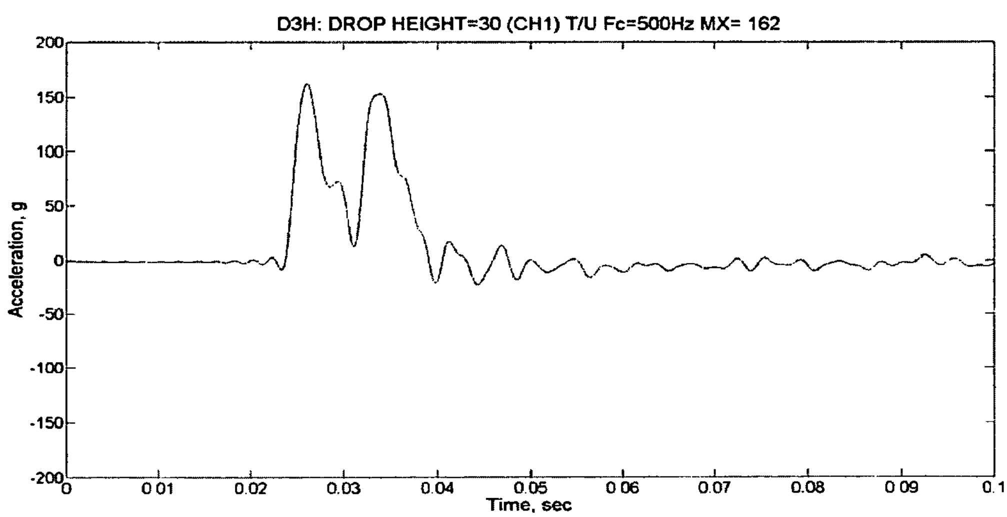

D2H: DROP HEIGHT=30 (CH4) OT/L Fc=500Hz MX= 260
Acceleration, g
Time, sec

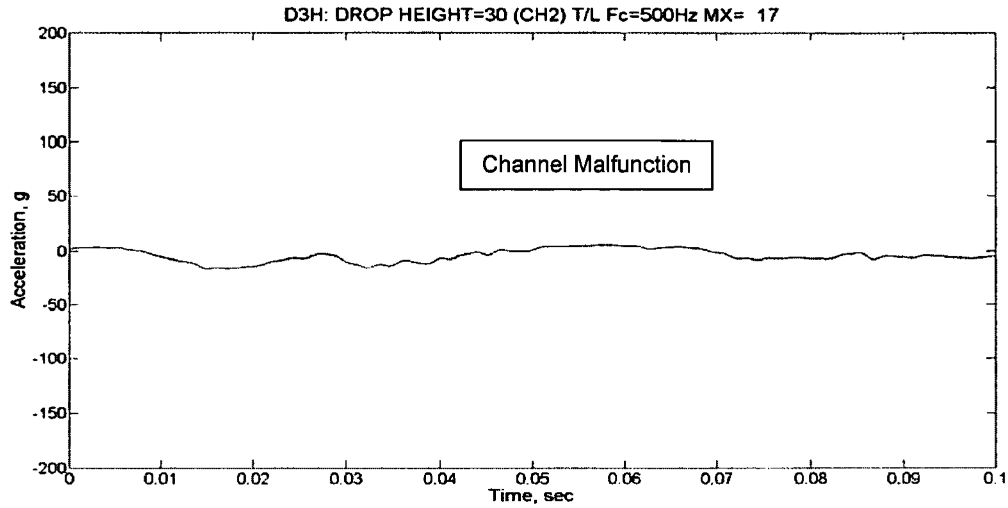

D3N: DROP HEIGHT=4 (CH1) T/U Fc=500Hz MX= 108
Acceleration, g
Time, sec

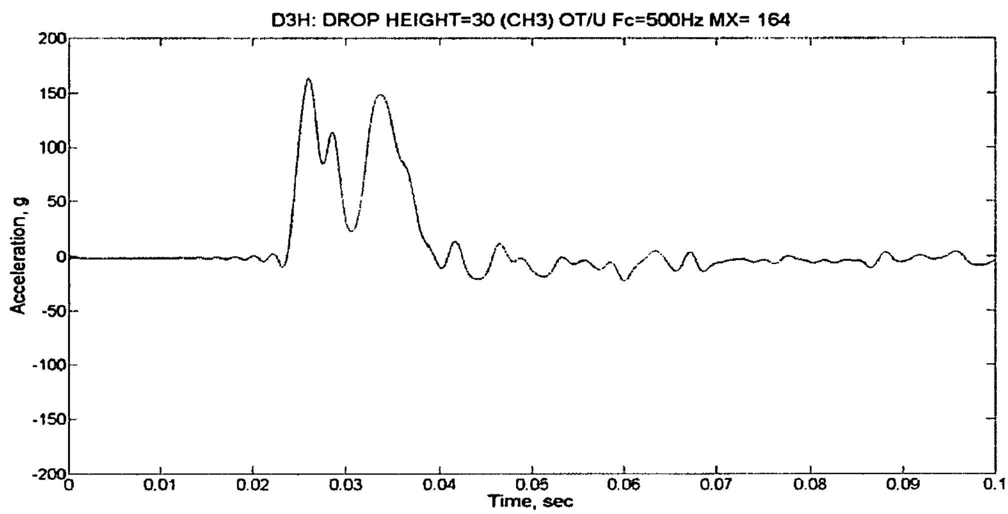

D3N: DROP HEIGHT=4 (CH2) T/L Fc=500Hz MX= 6
Channel Malfunction
Acceleration, g
Time, sec

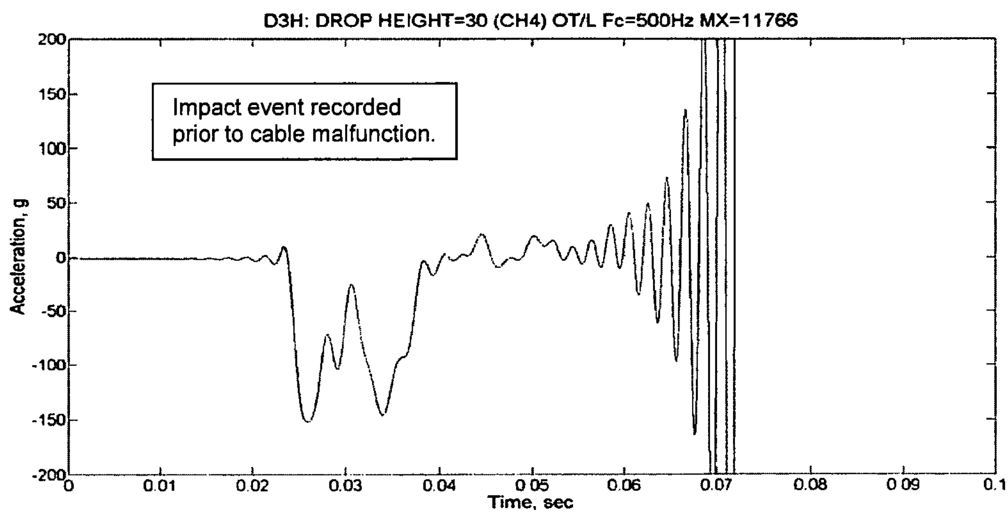

D3N: DROP HEIGHT=4 (CH3) OT/U Fc=500Hz MX= 106
Acceleration, g
Time, sec
200
150
100
50
0
-50
-100
-150
-200
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1

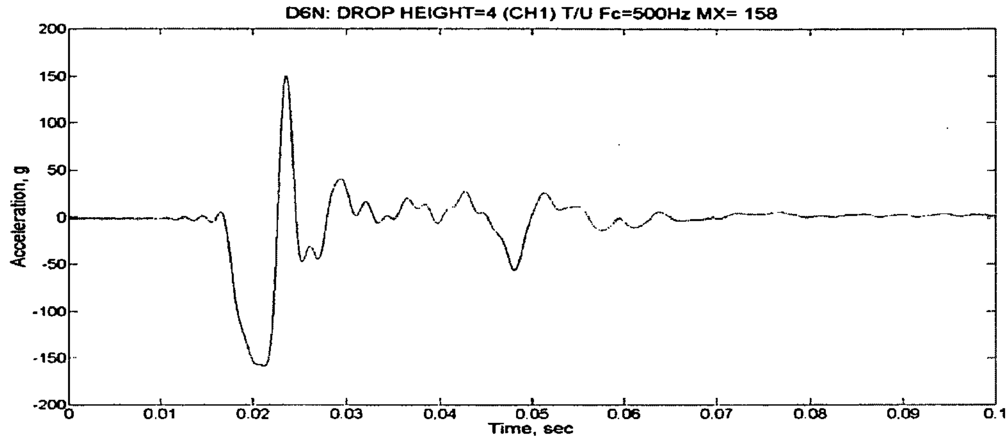

D3N: DROP HEIGHT=4 (CH4) OT/L Fc=500Hz MX= 113
Acceleration, g
Time, sec
200
150
100
50
0
-50
-100
-150
-200
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1

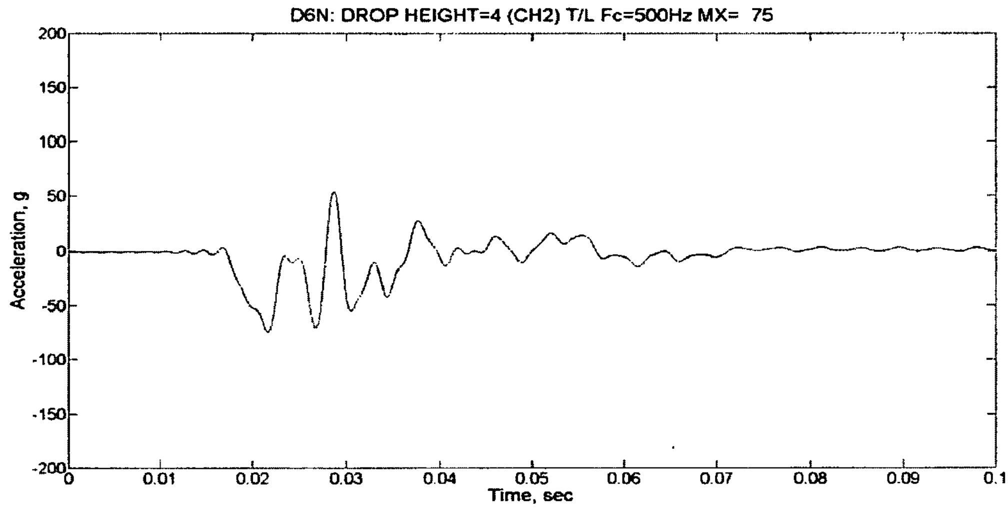

D3H: DROP HEIGHT=30 (CH1) T/U Fc=500Hz MX= 162
Acceleration, g
Time, sec
200
150
100
50
0
-50
-100
-150
-200
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1

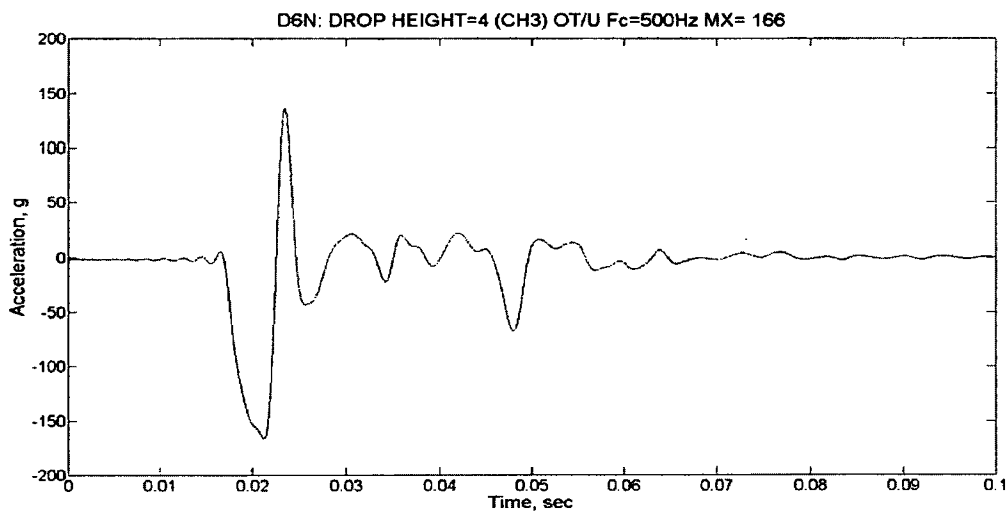

D3H: DROP HEIGHT=30 (CH2) T/L Fc=500Hz MX= 17
Channel Malfunction
Acceleration, g
Time, sec

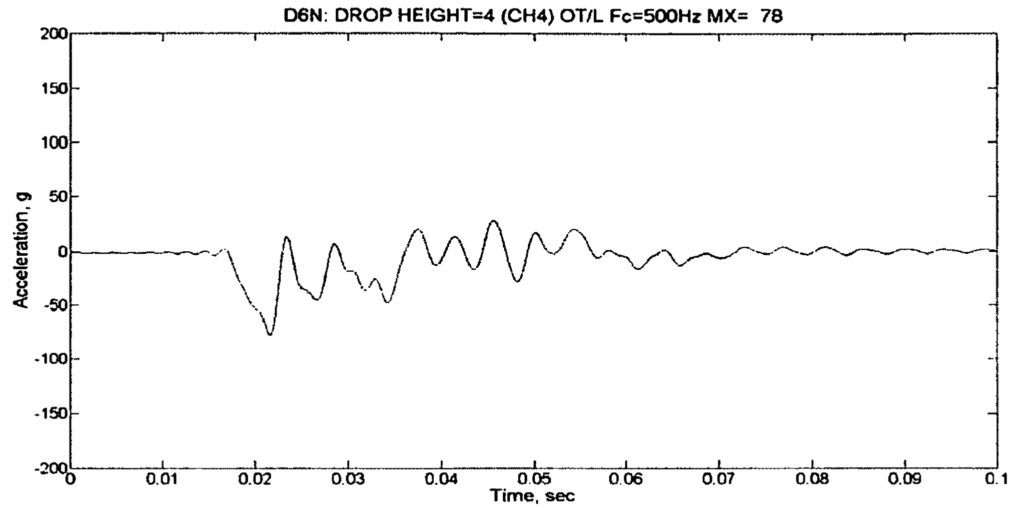

D3H: DROP HEIGHT=30 (CH3) OT/U Fc=500Hz MX= 164
Acceleration, g
Time, sec

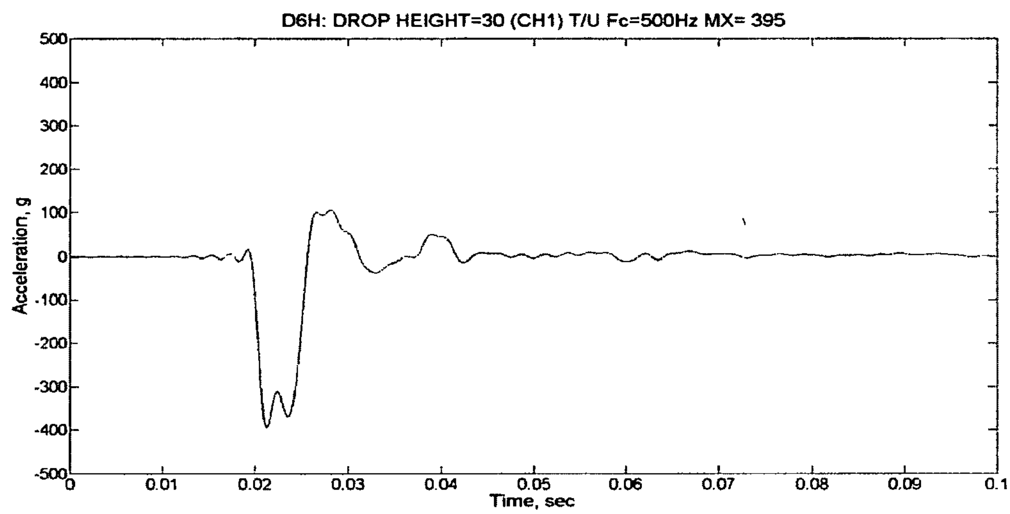

D3H: DROP HEIGHT=30 (CH4) OT/L Fc=500Hz MX=11766
Impact event recorded
prior to cable malfunction.
Acceleration, g
Time, sec

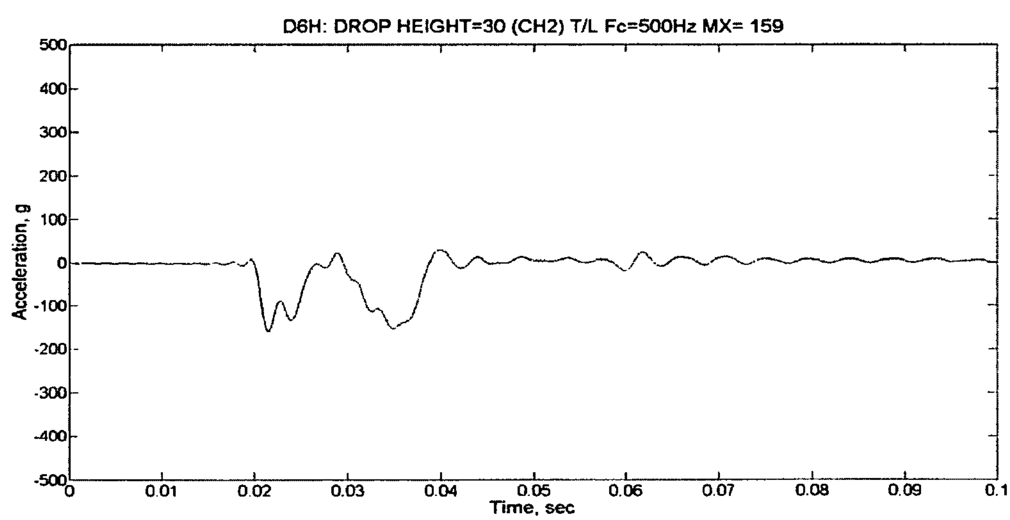

D6N: DROP HEIGHT=4 (CH1) T/U Fc=500Hz MX= 158
Acceleration, g
Time, sec

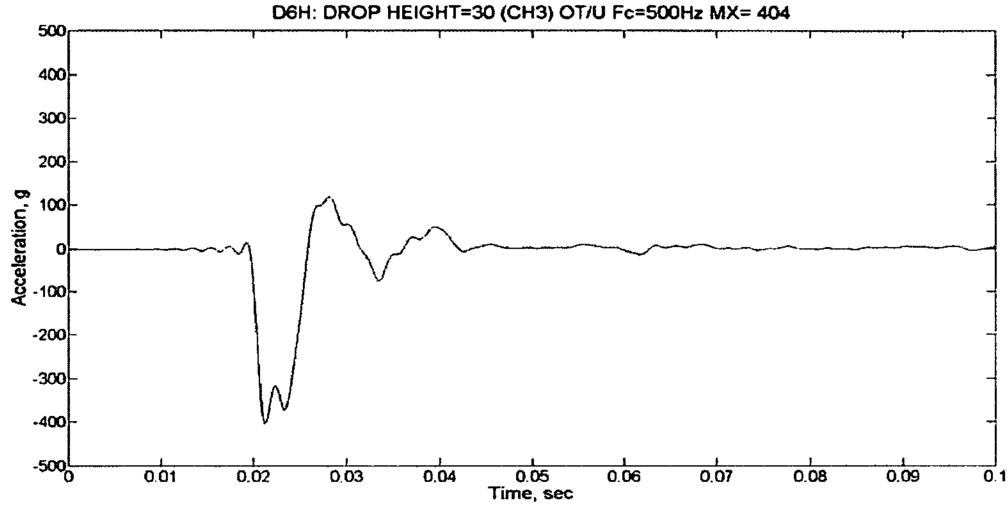

D6N: DROP HEIGHT=4 (CH2) T/L Fc=500Hz MX= 75
Acceleration, g
Time, sec

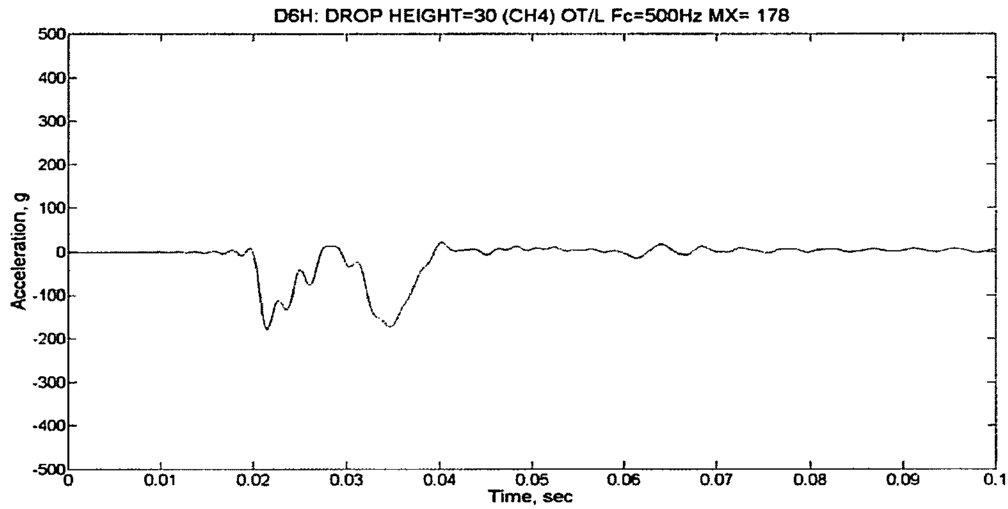

D6N: DROP HEIGHT=4 (CH3) OT/U Fc=500Hz MX= 166
Acceleration, g
Time, sec

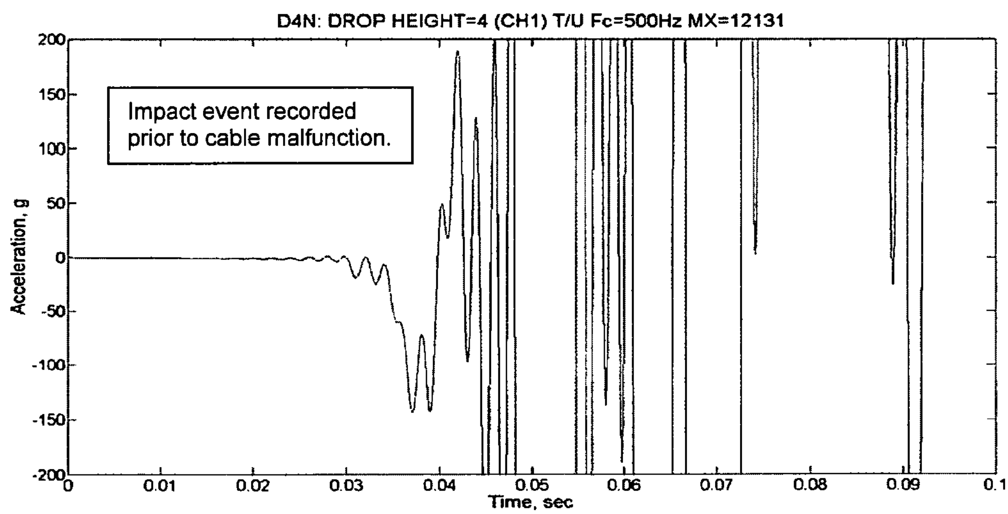

D6N: DROP HEIGHT=4 (CH4) OT/L Fc=500Hz MX= 78
200
150
100
50
0
-50
-100
-150
-200
Acceleration, g
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Time, sec

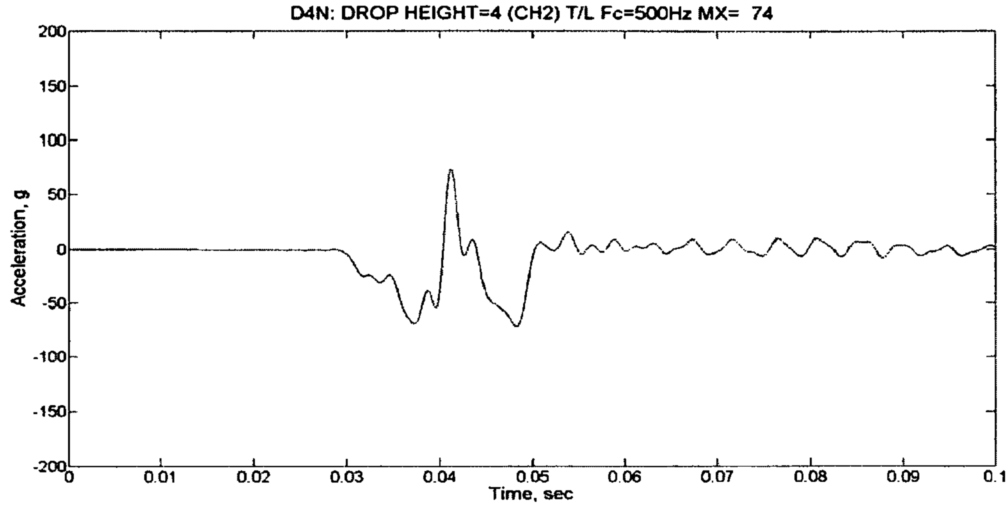

D6H: DROP HEIGHT=30 (CH1) T/U Fc=500Hz MX= 395
500
400
300
200
100
0
-100
-200
-300
-400
-500
Acceleration, g
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Time, sec

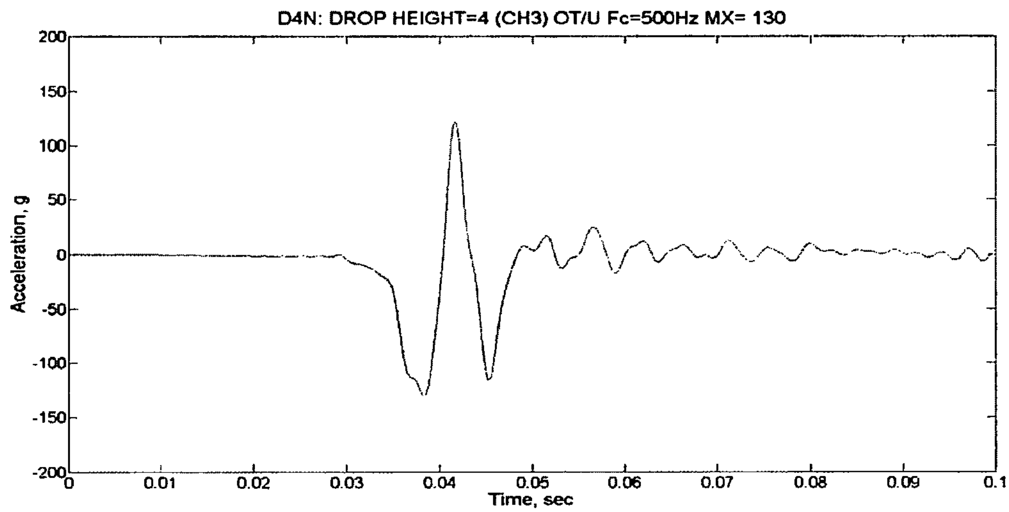

D6H: DROP HEIGHT=30 (CH2) T/L Fc=500Hz MX= 159
500
400
300
200
100
0
-100
-200
-300
-400
-500
Acceleration, g
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Time, sec

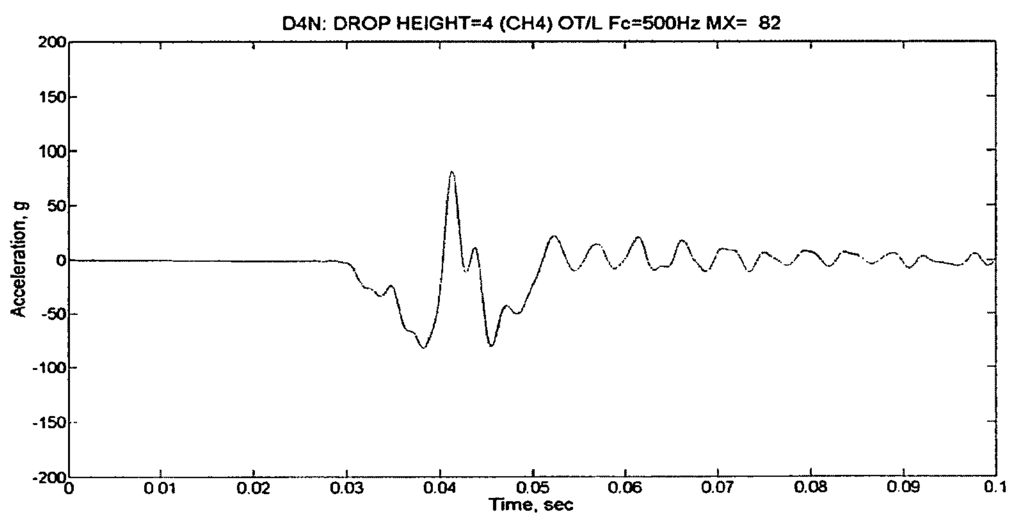

D6H: DROP HEIGHT=30 (CH3) OT/U Fc=500Hz MX= 404
Acceleration, g
Time, sec

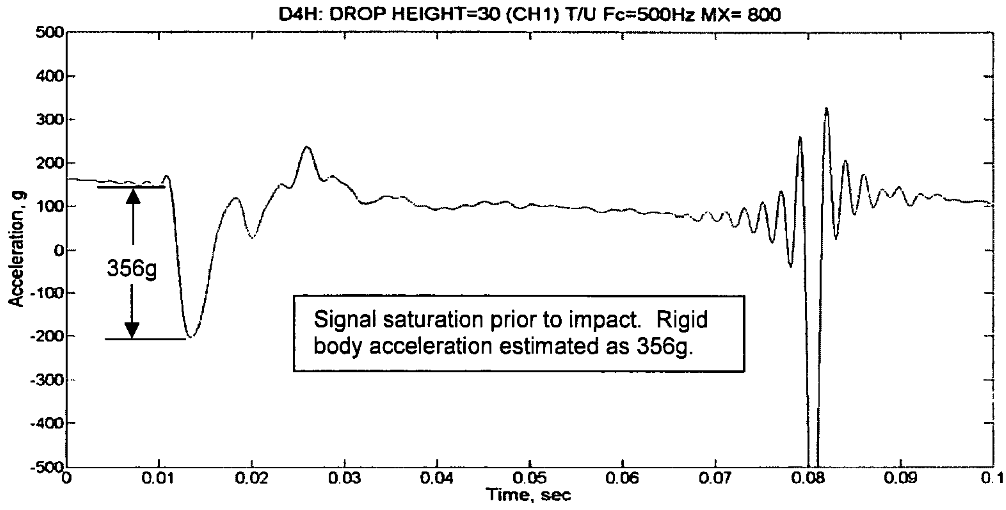

D6H: DROP HEIGHT=30 (CH4) OT/L Fc=500Hz MX= 178
Acceleration, g
Time, sec

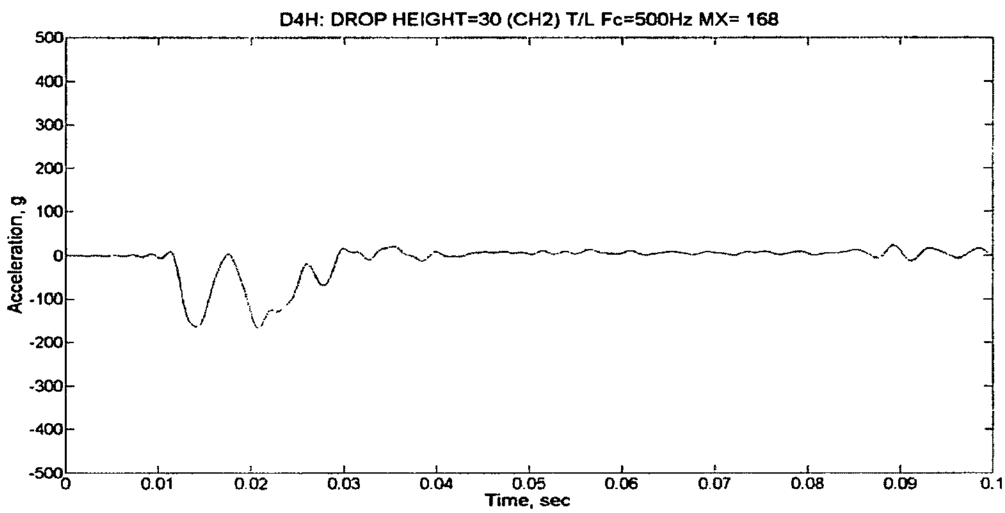

D4N: DROP HEIGHT=4 (CH1) T/U Fc=500Hz MX=12131
Impact event recorded prior to cable malfunction.
Acceleration, g
Time, sec

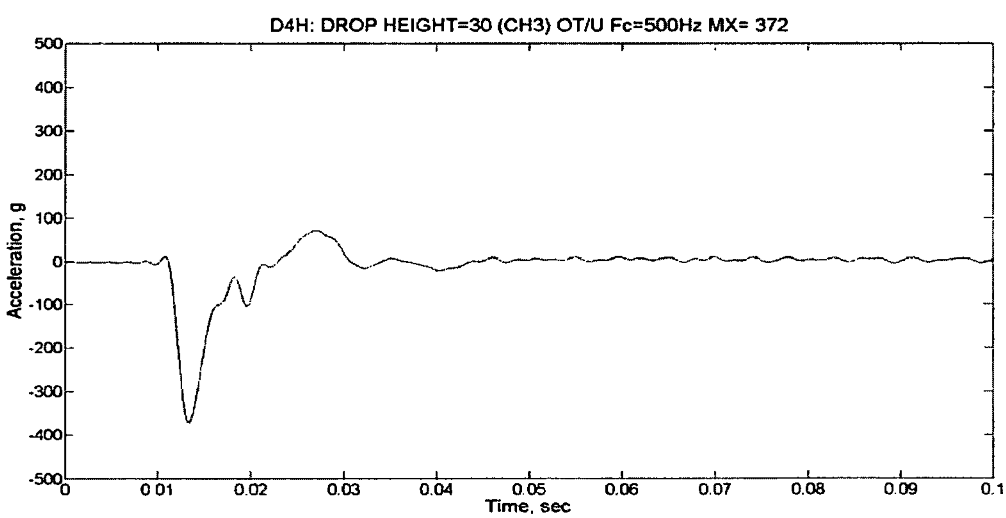

D4N: DROP HEIGHT=4 (CH2) T/L Fc=500Hz MX= 74
Acceleration, g
Time, sec

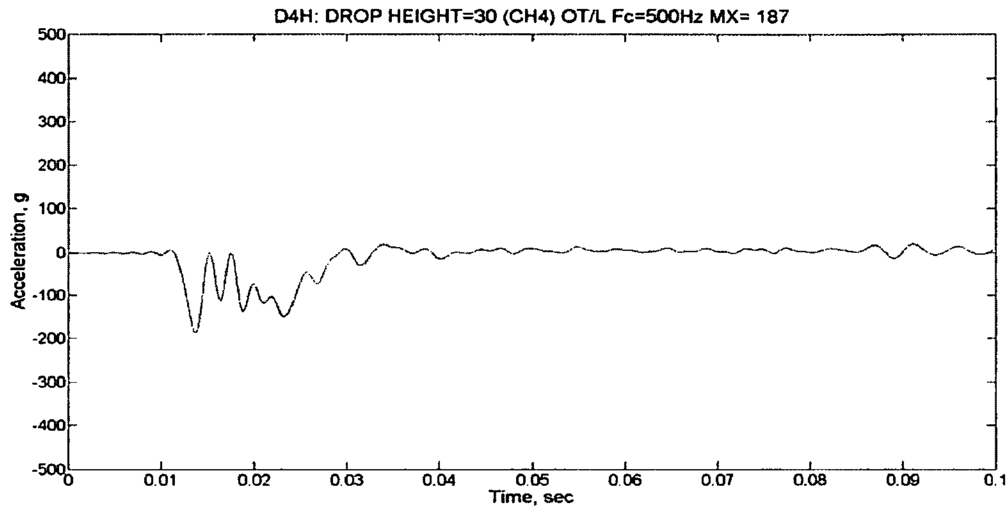

D4N: DROP HEIGHT=4 (CH3) OT/U Fc=500Hz MX= 130
Acceleration, g
Time, sec


D4N: DROP HEIGHT=4 (CH4) OT/L Fc=500Hz MX= 82
Acceleration, g
Time, sec


D4H: DROP HEIGHT=30 (CH1) T/U Fc=500Hz MX= 800
Acceleration, g
Time, sec
356g
Signal saturation prior to impact. Rigid body acceleration estimated as 356g.


D4H: DROP HEIGHT=30 (CH2) T/L Fc=500Hz MX= 168
Acceleration, g
Time, sec


D4H: DROP HEIGHT=30 (CH3) OT/U Fc=500Hz MX= 372
Acceleration, g
Time, sec



2.12.3.7 References

1. Title 10, Code of Federal Regulations, Part 71 (10 CFR Part 71), *Packaging and Transportation of Radioactive Material*, 01-01-11 Edition.
2. 435-B Certification Test Report, PKG-TR-SPC-011, AREVA Federal Services LLC.
3. ANSI N14.5-1997, *American National Standard for Radioactive Materials – Leakage Tests on Packages for Shipment*, American National Standards Institute (ANSI), Inc.
4. International Atomic Energy Agency, *Regulations for the Safe Transport of Radioactive Material*, TS-R-1.