Response to Request for Information Items 3, 5, and 6:

Physical Tests Performed on Spent Fuel Packages

Enclosure

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Physical Tests Performed on Spent Fuel Packages

1. Model No. NAC-LWT (Docket No. 71-9225)

The information below was obtained from Section 2.10.8 in NAC International, Inc., consolidated application dated November 30, 2014 (see Agencywide Documents Access and Management System (ADAMS) Accession No. ML15020A548).

A. Tests performed

A series of free drop tests were performed on a quarter-scale model of the NAC-LWT package. Thirty-foot drop test orientations included a vertical top end drop, top corner drop at an angle of 15.7 degrees from vertical (center of gravity over corner), side drop, and a bottom oblique drop at an angle of 60 degrees from vertical. After these tests, the scale model was dropped 40 inches onto a puncture pin at the mid-point side of the package. After the tests, measurements were performed on the package internal pressure to determine whether the containment boundary leaked.

A series of quasi-static crush tests were performed on quarter-scale models of the bottom impact limiter for the NAC-LWT package. These crush tests were performed to document the force-deflection and energy absorption characteristics of the honeycomb material used in the impact limiter. The limiter orientations tested were end (axial), side, and center of gravity over corner (15.7 degrees from axial).

B. Description of the methods or analyses used in tests

The package was instrumented with nine strain gauges to determine maximum bending stresses and maximum plastic strains in the scale model. The strain gauges were attached at three axial locations, 120 degrees apart around the circumference of the outer surface of the scale model.

C. Test Results

Data obtained from the tests consist of both qualitative information with respect to observations about the package and the limiter and quantitative data obtained from the recorders. The data for each test include measured impact limiter deformation, strain gauge data and stress calculations (for the end drop and side drop only), and observations of the package and attachments. The strain gauge data were only presented for the end drop and the side drop since the loads developed in those tests are the most severe from an overall structural consideration. The end drop corresponds to the maximum axial loading condition, while the side drop developed the maximum lateral loading on the overall package body.

a. Top Drop

For the top drop the aluminum honeycomb impact limiter was crushed to an average depth of 1.2 inches out to a diameter of 7.2 inches. The

1.2-inch crush corresponded to an overall crush strain of 33 percent. It was also observed that the attachment lugs for the limiter failed; however, once the limiter is engaged in the crushing action, the lugs do not provide additional functionality in the end drop condition.

The maximum axial strain observed in the test was 560 microstrains. The axial stress is calculated by multiplying the axial strain by the modulus of elasticity. The maximum axial stress in the drop is 15.8 ksi, which is much less than the yield strength of the material.

As the limiter was driven onto the package, the test valve used to pressurize the interior was broken off, which prevented the pressure from being measured after the test. A new valve was installed and the cavity was pressurized to 30 psig and was maintained to determine if the package containment boundary was damaged. There was no measurable pressure loss. The loss of this valve has no implications for the full-scale package, since the full-scale version does not have this valve.

b. Top Corner Drop

For the top corner drop, the maximum amount of crush was 1.38 inches, which corresponds to a strain of 38 percent. Similar to the top drop, the attachment lugs for the limiter failed; however, once the limiter is engaged in the crushing action, the lugs do not provide additional functionality in the corner drop condition.

Based on the pre-test and post-test dimensional measurements, nearly all permanent deformation of the packaging model was limited to the impact limiters, as expected and desired. The only significant deformation of the package body model occurred in the side puncture test, where local deformation of the outer shell and the lead shielding did occur. As designed, the outer shell was not punctured. This local deformation was fully expected and produced a very slight, local dimple in the inner shell wall (0.05 in) of the model. These local puncture deformations are of no consequence since the containment vessel and its contents are protected. Because no deformation to the package was observed, except as previously discussed, and the containment vessel sustained essentially no deformation, leakage was not expected and did not occur.

The coupling connected to the valve used to pressurize the interior was loosened, which prevented the pressure from being measured after the test. The coupling was tightened and the cavity was pressurized to 29.2 psig and was maintained to determine if the package containment boundary was damaged. There was no measurable pressure loss.

c. Side Drop

Limiters in the side drop condition were crushed only in regions that are backed by the package body. The impact limiters were crushed on both the inside next to the scale model and outside where it made contact with the impact surface. The maximum crush on the bottom impact limiter was 2.64 inches near the package and the minimum was 0.2 inches at the bottom. The thickness of the as-built bottom impact limiter is 3.89 inches. The maximum crush on the top impact limiter was 1.52 inches and the minimum was 0.52 inches at the top. The thickness of the as-built top impact limiter is 4.52 inches.

The maximum axial strain observed in the test was 2500 microstrains, which also resulted in a permanent set of 750 microstrains. Due to the manner in which the package is loaded, the maximum strains occurred at the midpoint. The maximum calculated stress for the side drop is 52.2 ksi. The pressure in the package was checked prior to the test and afterwards. It was found to be 30.4 psig. This indicates that pressure containment was maintained during impact.

d. Bottom Oblique Drop

In the 60-degree oblique drop test, the maximum crush on the outside of the bottom impact limiter is 1.25 inches, and the inside which contacts the package is approximately evenly crushed at 1.39 inches. The maximum crush on the outside of the top impact limiter is 0.5 inches, and the minimum is 0.25 inches. The inside of the impact limiter is crushed approximately evenly at 1.5 inches. The pressure measurement indicated that the cavity pressure did not change as a result of the oblique drop test. Cavity pressure was measured to be 30.2 psig before and after the test.

e. One (1) Meter Puncture test

As a result of dropping the package body onto the steel pin, the containment of the package body was not violated. This was confirmed by the pressure measurements before and after the test. All permanent strain was local to the region of impact of the pin. The maximum deformation of the outer shell was 0.5 inch deep and a localized depression of 0.05 inch occurred in the inner shell. Note that the pin puncture impact was directed against the portion of the outer shell that was stressed most severely in the 30-foot drop tests to show that the outer shell retained its puncture capability after the dynamic stress of the 30-foot fall impact.

f. Force-Deflection Tests

Quasi-static force-deflection tests were performed on quarter-scale model impact limiters used in drop testing thee quarter-scale model. Limiter samples were selected for a particular test based on the limiter having no damage for test orientation. Three limiter orientations were tested – 0, 15, and 90 degrees. While each impact limiter tested was being compressed, it was instrumented with two calibrated linear variable differential transformers (LVDT) mechanically attached to test fixtures to obtain crush force as the impact limiter deformed. Deformation of the limiter proceeded well into honeycomb lock-up. As the force on the limiter decreased after the limiter locked up, force and deflection continued to be monitored, revealing the amount of elastically stored energy. The static force for each data point is multiplied by 1.196, a static to dynamic scaling factor, enabling comparison values computed with the RBCUBED computer program.

Forces calculated from the RBCUBED computer program are higher in all cases except the end drop. The end drop forces were higher due to a shearing previously unaccounted for, causing 10 percent higher forces than calculated by RBCUBED. The shearing and shear force generation occurs simultaneously with crushing, and is a small force compared with the crush force. The average maximum/peak forces and g-loads calculated using RBCUBED was compared with corresponding values from each of the quasi-static tests. Structural margins are all positive.

2. Model No. GA-4 (Docket No. 71-9226)

The information below was obtained from the application dated January 31, 1997 (see ADAMS Accession Nos. ML15351A261, ML030860360, ML15351A295, and ML030860386).

A. Tests performed

1. Honeycomb Impact Limiter Force Deflection Tests

Four quarter-scale versions of the impact limiter designs were tested at different crush angles to provide data on the load-versus-deflection curve of the impact limiter. Three impact limiters were tested twice, on opposite sides. The tests performed range from end to side crush. The table below shows the tests performed.

Impact Limiter No.	Test on Impact Limiter	Test Crush Orientation (degrees)	Energy Dissipated During Tests (lb-in)
1	1	60	626,178
	2	15	480,743
2	1	0 (side)	324,570
	2	45	464,708
3	1	75	689,051
	2	35	218,119
4	1	90 (end)	717,358

2. Half-Scale Model Drop Tests

The tests consisted of three regulatory test sequences:

1: Side drop

- 30-foot side drop
- 40-inch puncture test in horizontal orientation.

2: Slapdown

- 30-foot drop with longitudinal axis at 30° from horizontal
- 40-inch puncture test in horizontal orientation.

3: Center-of-gravity (CG) over closure

- 30-foot CG over closure comer drop with the longitudinal axis tilted 12° from the vertical position,
- 40-inch puncture drop with the longitudinal axis oriented 7° from the vertical and the punch striking the closure in the vicinity of the gas sample port and closure bolts, and
- 40-inch puncture drop with the package oriented horizontally with the punch striking a longitudinal edge of the model body near mid-length at the location of a joint between two depleted uranium rings.

3. Full-scale Closure Seal Tests

The primary O-ring seal of the package was tested for leakage using a full-scale mockup of the package closure and flange.

B. Description of the methods or analyses used in tests

1. Honeycomb Impact Limiter Force Deflection Tests

i. Test Methods

The tests were performed on a compression testing machine using a quarter-scale model of the impact limiters. The impact limiters were directly backed by a solid aluminum test fixture. The test set-up was instrumented during the entire event to provide a complete record of the load applied to the specimen as a function of deflection. Graphs of the load-versus-deflection data were produced.

2. Half-Scale Model Drop Tests

i. Tests Conditions

All tests were performed at ambient temperature. The initial pressure in the model's fuel cavity was 80 psig (0.55 mpa). The model was not disassembled or parts replaced during any test sequence. Impact limiters, impact limiter bolts, and closure seals were replaced after each sequence.

ii. Test Methods

GA constructed a concrete and steel drop pad that meets International Atomic Energy Agency's guidelines for an unyielding surface. For puncture events, a 3-inch diameter mild steel puncture pin was bolted to the pad.

Prior to any testing, the model was marked to locate the exact points at which the measurements were to be taken. For each drop, the model was rigged in the proper orientation, lifted to a height of 30 ft (or 40 inches for the puncture tests) by a crane, and released by simultaneously firing multiple explosive cable cutters. Triggering of the high speed cameras and the strain gage and accelerometer data acquisition system was synchronized with the cable cutter firing.

The closure O-ring seals and the gas sample port seals were leak tested before and after each test sequence. The impact limiters were inspected after each test to determine the damage caused by the test. Dimensional checks and helium leakage tests of the containment boundary and cavity liner were performed on the model package after all testing was completed.

The dimensional measurements included are overall length measurements and package body profile. Complete dimensional checks were performed before and after testing was completed. The model was disassembled and all the removable parts inspected. The fuel support structure was not removed from the cavity.

3. Full-scale Closure Seal Tests

i. Test Conditions

Four tests were performed at temperatures of ambient, -42 ºF, 250 ºF, and 380 ºF. Shim plates between the fixture lid and flange, ranging from 0 to 0.038 in., simulated gaps resulting from thermal-induced distortion. The leakage testing was carried out by means of a helium mass spectrometer leak detector, following the guidelines in American National Standards Institute American National Standards Institute (ANSI) N14.5-1987, "Radioactive Materials - Leakage Tests on Packages for Shipment."

ii. Test Set-up

The test fixture consisted of a lid and flange and was a full-scale representation of the cross section of the package closure end. Two dovetail grooves in the lid held the primary and secondary O-ring seals. The grooves and O-ring seals precisely modeled the full-scale package. All fixture materials were fabricated from 304 stainless steel. The fixture lid weighed approximately 170 lb. and the flange 180 lb. The fixture lid was attached to the flange with twenty, 1-inch bolts that thread into nuts tack-welded to the bottom of the flange. The bolts were torqued to 100 ft-lb. Shim plates extending all around the fixture's perimeter maintain uniform specified gaps between the lid and flange.

From operational and handling considerations it was not feasible to fabricate the test lid to the actual closure thickness of 11 inches. Since the test was a verification of the seal performance under the actual temperatures and amounts of compression experienced in the package, seal and groove dimensions were identical to those in the package. The number of bolts was increased from 12 to 20 in the test only to minimize local deflection between bolts of the relatively thin 1-in. lid. This local deflection is absent in the actual package due to the considerably thicker and stiffer lid. The bolt torque in the test was less than actual (100 versus 235 ft-lb) but the seals are fully compressed in both the test and package configurations. Once the seals are fully compressed in their grooves and metal-to-metal contact is established, additional bolt torque produces no further compression of the seals. For the reduced compression predicted by the accident analysis, shims of a known thickness were inserted between the lid and its base to duplicate this effect.

Prior to testing, the small volume between the flange and lid is initially evacuated. When the test begins, this volume is filled with helium to atmospheric pressure. A second port located between the O-rings is continuously evacuated by the helium mass spectrometer leak detector, and the detector measures the helium leakage past the primary (inner) O-ring. The detector output is recorded by a conventional strip chart recorder.

For the tests carried out in the conditioning chamber, the fixture temperatures near the inner seal are measured by two thermocouples (Type T) and recorded.

C. Test Results

1. Honeycomb Impact Limiter Force Deflection Tests - Comparison of Test and Analytical Results.

The largest differences between the test and analytical results occur during the end crush. The test showed a higher initial crush load, dropping to the analytical value later in the crush. The higher load is partly attributable to the buckling of the impact-limiter-bolt guide tubes in the end of the impact limiter. To reduce this tube buckling load, GA changed the tube material from 1/8 hard Type 304 stainless steel with a yield of 90 ksi to 304 Stainless Steel annealed with a minimum yield of

30 ksi. In addition, the tube wall thickness was decreased from .07-inch-thick to .035-inch-thick. This change reduces the guide tube buckling loads to a level that is small compared to the honeycomb crush load, while still maintaining the necessary energy absorption capability during an end crush. The remaining difference between test and analytical results is ignored, since the design margins for the package and neutron shield structure for the 1-ft end drop are high.

The crush forces from the 30º test are lower than the data calculated in ILMOD. (ILMOD is a GA developed computer code to compute the load versus deflection curves for impact limiters with standard unidirectional honeycomb.) This is almost certainly due to the fact that this was the second test of the impact limiter and the first 75º test weakened the impact limiter. After the 75º test, the outer diameter of the impact limiter had grown from 22.48 in. to 23.06 in.

The remaining difference between test and analytical results is ignored since the design margins for the package and neutron shield structure for the 1-ft end drop are high.

2. Structural Tests

The performance of the half-scale model showed the GA-4 package design to be robust. No permanent deformation of the model body occurred except local dents from the puncture attacks. The fuel support structure remained in its keyway attachment to the liner. The cavities formed by the fuel support structure and cavity liner had no permanent deformation except a local indentation of 0.07 in. at the location of the puncture in Sequence 2, Test 2. The model held its full 80 psig (0.55 mPa) internal pressure and remained leaktight (helium leakage less than 1×10^{-7} std cm^3/s) throughout all seven tests.

(Note: The analyses show that the maximum neutron-shield-fluid pressure is 416 psi for a 30-ft end drop at the maximum temperature condition. This pressure includes the increase in pressure due to thermal expansion of the fluid. The analyses show that the ILSS top and bottom end plates can withstand this pressure and meet all design requirements. During a 30-ft drop, the effect of the fluid pressure is to act opposite to the impact limiter loads and thus will reduce the loads on the ILSS outer shell. Because it is less than the impact force, it may be conservatively neglected.)

i. <u>Side Drop</u>

- Sequence 1, Test 1; 30-ft Side Drop

  Using a mobile crane, the model was lifted to a height of 30 ft. above the pad with the package body oriented horizontally and the longitudinal edge of the package marked 225º facing the impact surface. The model released cleanly and did not rotate or yaw significantly during its descent. Time to impact from release for all 30-ft drops is 1.4 seconds.

- Sequence 1, Test 2; Puncture at Side of Closure

  This test was a puncture drop from a height of 40 in. with the model oriented horizontally and the punch striking the model package's structure adjacent to the corner of the closure end. The puncture pin itself was observed to be in good condition after the test. Some of the white paint was scraped off by the honeycomb, but no permanent deformation of the pin was visible.

ii. Slapdown Sequence

- Sequence 2, Test 1; 30-ft Slapdown

  For this test new impact limiters were installed and the model was rigged with its axis tilted 30º from the horizontal position. The model was dropped with the closure end striking first, and the flat side marked 90º facing the impact surface. The closure end impact limiter crushed a maximum of 7.5 in. The model rotated and crushed the bottom end impact limiter 7.9 in. Final orientation of the model on the pad was 3º from horizontal with the closure end sitting slightly higher than the bottom end.

- Sequence 2, Test 2; Puncture at Package Body Flat Side

  Since the puncture pin hit the body directly on the flat side, this event was a severe test of the package body integrity. Both the model and the pin experienced local permanent deformation. The dent on the package body was a maximum of 0.15 inches deep. An examination of the model interior revealed that a small amount of permanent deformation had been transferred to the cavity liner and locally to the edge of one plate of the fuel support structure. The deformation of the cavity was measured as 0.07 inches. No other deformation of the fuel support structure or liner was observed.

  An internal pressure of 80 psig was maintained for sequence 2. The helium leakage test showed that the seals maintained a leaktight condition for the sequence.

iii. CG-over-closure-corner sequence

- Sequence 3, Test 1; 30-ft Drop, CG-over-closure-corner.

This test was a CG-over-closure-corner drop from 30 ft. with the model axis tilted 12º from the vertical position and a longitudinal edge of the model facing the impact surface.

Both impact limiters stayed attached to the model package. The closure end had been fitted with a new impact limiter but the bottom end limiter was reused from a previous test.

- Sequence 3, Test 2; Puncture at Closure Bolt and Gas Sample Port.

  This test was 40-inch puncture drop with the model oriented 7º from the vertical and the puncture pin striking the closure in the vicinity of the gas sample port and closure bolts.

  The objective of this puncture test was to test the integrity of the closure bolts and the gas sample port and cover. The post-sequence examination showed that the puncture pin completely compressed the aluminum honeycomb in its path and dented the impact limiter housing. Some visible local deformation was transferred to the gas sample port cover, damaging the first few threads of the screwed on cover. Due to the damaged threads, the port cover had to be partially drilled out with a hole saw in order to be removed. With the cover removed, it was observed that the quick-connect nipple was undamaged. The post-sequence pressure check of the cavity and helium leakage test of the seals confirmed that this puncture attack did not cause a breach of the containment boundary.

- Sequence 3, Test 3; Puncture at a depleted uranium joint.

  The final test was another puncture drop with the model oriented horizontally, and the punch striking a longitudinal edge of the body near mid-length at the location of a joint between two depleted uranium rings.

  After the completion of the final test, the closure seals were leak tested to assess the condition of the liner and the model package body. Both the liner and the model package body were found to be leaktight.

3. Full-scale Closure Seal Tests

Four tests were carried out with the ethylene propylene seals. One set of seals was used for the test at -40ºF, and another set was used for the other three tests. The first two tests simulated normal conditions of transport, while the last two represented hypothetical accident conditions. For the latter conditions, the thermal and thermal stress analyses predict a maximum lid/flange gap of 0.024 inches, corresponding to a seal temperature of 240 ºF, while 300 ºF is the maximum seal temperature, corresponding to a zero gap. The conditions used in the test are therefore conservative.

GA tested the seal and found it to be leaktight ($<1\times10^{-7}$ ref cc/sec as defined by American National Standards Institute (ANSI) N14.5, "Radioactive Materials - Leakage Tests on Packages for Shipment") at -42 ºF, ambient (-75 °F), and 250 ºF. The maximum calculated temperature of the seals is 135 ºF in the closure and 143 ºF for the drain.

For hypothetical accident conditions the analysis shows that the maximum primary seal temperature is 300 ºF. This includes the closure seal and the seal for the gas sample and drain ports. Manufacturer's data indicate the seal material can withstand a temperature of 350 ºF for 50 hours and 400 ºF for several hours. Using conditions more severe than those predicted by the analysis, the applicant tested the seal at 380 ºF, after heating for 1.5 hours above 350 ºF, and determined it to be leaktight. Therefore, the seal will function during the hypothetical accident thermal event. For the post-accident steady-state condition the maximum temperature of any seal is 175 ºF.

3. Model No. 2000 (Docket No. 71-9228)

The applicant used finite element and other calculation methods as part of the structural evaluation. A thermal test has been conducted on the Model 2000 transport package to verify the thermal analytical model by comparing the analytical results to those of the physical testing.

The information below was obtained from Chapter 4 of the application dated December 2000 (see ADAMS Accession No. ML063650011).

A. Tests performed

A thermal test has been conducted on a GE Model 2000 package. The objective of the test is to verify the thermal analytical model by comparing the analytical results to those of the physical testing. The testing is done at ambient conditions with 600 and 2000 watts heat input in the package cavity to simulate the maximum decay heat. The test also demonstrates the capability of the Model 2000 to safely dissipate 600 and 2000 watts of decay heat.

B. Description of the methods or analyses used in tests

The thermal test was performed by placing an electric heat source concentrically within the cavity. Thirteen temperature sensing devices were placed within the cavity, on the external surfaces of the package, and on the overpack surfaces. In the radial direction, temperatures measured included the package cavity air, internal package wall, external package wall, overpack inside surface, and the overpack external surface. In the axial direction, the temperatures measured included the package cavity floor, the bottom package surface, below the lower honeycomb pad, at the bottom of the overpack, at the top of the package cavity (under the lid), at the gasket lower surface, at the top of the lid, and at the top of the overpack. Three additional transducers recorded the external ambient temperature. The temperature data were recorded at 30 minute intervals during the transient until a steady state condition was reached. Temperatures remain significantly unchanged for a one hour period.

C. Test Results

Differences between the test and the model temperatures were 3% in the package cavity, 1% at the package outer wall, 5% at the overpack inner wall, and 1% at the overpack outer wall. Test data and the LIBRA predictions of cavity wall temperature versus time for the 2000 watt case were plotted in Figure 3.35: excellent correlation between test and analysis results is displayed. The physical test confirmed the adequacy and accuracy of the model used in the LIBRA finite element thermal analysis code for the 2000 package.

4. Model No. NAC-STC (Docket No. 71-9235)

The information below was obtained from Section 2.10.6 in NAC International's consolidated SAR (see ADAMS Accession No. ML112301077) for the impact limiter tests.

A. Tests Performed

The scale model test program for the directly loaded fuel configuration of the NAC-STC included: (1) quarter-scale model drop tests, and (2) eighth-scale model impact limiter quasi-static compression tests.

1. Dynamic Impact Limiter Tests

The objective of the quarter-scale model drop tests was to confirm the design of the NAC-STC packaging through a series of tests conducted at the Winfrith Technology Centre drop test facility located in the United Kingdom. The planned tests included:

- 9-meter (30-foot) top end drop,
- 9-meter (30-foot) top corner drop (24 degrees from the vertical),
- 9-meter (30-foot) side drop,
- 9-meter (30-foot) bottom end oblique drop (75 degrees from the vertical),
- 1-meter (40-inch) pin puncture drop at the cask axial mid-point, and
- 1-meter (40-inch) pin puncture at the center of the outer lid.

When testing commenced, the model employed aluminum shell impact limiters. After completing the first three tests above, testing was suspended to effect repairs to the model. Therefore, these three tests were identified as Phase 1. After repairs were completed, it was decided to perform the fifth and sixth puncture tests above and identify these tests as Phase 2. During the performance of these tests, however, the 24-inch long pin deformed excessively, to the extent that maximum damage was not inflicted on the cask body or the outer lid. Therefore, it was determined that the pin puncture tests would be re-performed using an 8-inch tall pin.

Testing resumed after replacing the aluminum shell impact limiters with stainless steel shell impact limiters. In addition, the planned tests to confirm the cask design was changed to the following:

- 9-meter (30-foot) side drop,
- 9-meter (30-foot) 75 degree oblique bottom end drop,
- 9-meter (30-foot) top corner drop (24 degree),
- 9-meter (30-foot) 75 degree oblique top end drop,
- 1-meter (40-inch) drop cask mid-point pin puncture, and
- 1-meter (40-inch) drop outer lid center pin puncture.

Performance of these six drop tests constituted Phase 3 of the drop test program. As a result of the side and 75 degree oblique bottom end drop tests performed in Phase 3, it was determined that the redwood in the overlap region of the impact limiter was not maintaining its original position and orientation. A design modification was added to the overlap region of the impact limiter to prevent the redwood in that region from changing its orientation during the side impact. After repairing pin puncture damage to the inner shell of the model cask body, both a 9-meter (30-foot) bottom oblique and 9-meter (30-foot) side drop test was performed. These two tests made up Phase 4 of the drop test program.

2. Static Impact Limiter Test Information

A series of quasi-static compression tests were performed to simulate an end impact, a corner impact, and a side impact using eighth-scale model redwood/balsa wood impact limiters. The static compression tests were performed to demonstrate that force-deformation curves are as predicted by analytical methods, energy storage (rebound) in the crushed redwood/balsa wood impact limiters is negligible, and the geometry of both the impact limiter and cask body effectively causes the impact limiter to stay attached to the cask.

Based on the results of the quasi-static tests, the force-deformation curve and the energy absorption capacity (area under the curve) of each model impact limiter was determined. The force-deformation curve is measured by compressing the model impact limiter and recording the deflections and loads applied to the limiter. The energy storage, or rebound, of the model impact limiter is shown by the load-deformation curve as the test machine is unloaded slowly. The model impact limiter presses against the test machine heads and applies a load proportional to the elastically stored energy. This extra energy component can be restored to a cask in a multiple-impact, oblique drop "slap down" scenario.

B. Description of the methods used in tests

1. Dynamic Impact Limiter Tests

The quarter-scale model packaging was an exact replica of the full-scale design with two exceptions: (1) O-rings in the inner and outer lids were not scaled; and (2) the neutron shield was not modeled, but the weight of the neutron shield was modeled by steel blocks welded to the outer shell. All aspects of the model can be used to reflect the strains, accelerations, and impact limiter crush strokes of the full-scale design. With respect to containment, the model represents the geometrical arrangement and materials used in the full scale design. However, the O-ring dimensions and the leak rate cannot be scaled. Therefore, the pressure measurements can only be used to indicate the condition of the seals and the adjacent seating surfaces. The initial scale-model design used impact limiters with aluminum shells. However, due to poor performance, the aluminum shells were replaced with stainless steel shells after the first several drop tests.

Ninety-degree tee-rosette strain gauges were mounted on the cask body for all of the drop tests. One gauge of each tee-rosette was positioned in the axial direction and another in the circumferential direction. These strain gauges allowed the axial and the hoop stresses to be determined. Later in the testing program, the 90-degree tee-rosettes at two locations were replaced with rosettes with three gauges at 45-degree orientations. This allowed the shear stresses to be determined at the surface. All gauges had at least a 50 kHz response time to ensure that the transient strains could be accurately recorded. Real-time recording was accomplished by a system of strain amplifiers, signal conditioners and a magnetic recording unit to store the data.

Accelerometers which could measure accelerations up to 20,000 g with an accuracy of 1 percent per 2,000 g were employed for the drop tests. Since an acceleration level of only 300 g was expected, the test accuracy was $\pm$ 0.5 g. The frequency response of the accelerometer was between 2 Hz to 15,000 Hz. which enveloped the frequency of the system. All accelerometer data were conditioned and stored on magnetic media for later processing, which included filtering and integrating to obtain impact velocities.

Two high-speed cameras were used to record the behavior of the quarter-scale model as it impacted the target surface. For the top end drop, both cameras were operated at 500 frames/sec. and the cameras were positioned 90 degrees apart (side and end views). For the final top corner drop, side drop, and oblique slap down drop, one camera was positioned to capture the overall motion of the cask at 500 frames/sec. and the other camera was set to obtain a close-up view of the crushing of the impact limiter at 1000 frames/sec.

2. Static Impact Limiter Test Information

Eighth-scale tests were performed with lower impact limiters primarily because the trunnion cutouts in an eighth-scale model upper impact limiter are extremely difficult to fabricate using the scaled shell thickness. This was determined to be acceptable because previous analyses, scale model compression tests, and scale model drop tests demonstrated that the trunnion cutout regions of the upper impact limiter do not significantly affect the energy absorption capability of the impact limiter. Initially, the model impact limiters were fabricated from aluminum alloy. However, during the quarter-scale drop test program, the model design was revised to use 0.031-inch stainless steel to fabricate the impact limiter shells. The impact limiter models used in the static tests represented the revised configuration. Like the full-scale design, the eighth-scale models used redwood/balsa wood as the energy absorbing materials.

The eighth-scale model impact limiters were crushed quasi-statically in a tensile test machine capable of also applying compressive loads. The tensile test machine capacity limited the maximum size of the test impact limiter to one-eighth scale. The eighth-scale model impact limiters were not attached mechanically to the cask-shaped test fixtures. Duct tape was used to hold the model impact limiter in place while the compressive test load was applied. The tape relaxed as successively higher loads were applied, demonstrating that the impact limiter geometry produces net crush forces that press the impact limiter against the cask body, regardless of the impact angle.

While each model impact limiter tested was being compressed, two calibrated linear variable differential transformers (LVDT) mechanically attached to test fixtures provided data to an X - Y recorder, which plotted crush force versus deformation. Deformation of the model impact limiter proceeded well into the compression lock-up range of the redwood. As the compression load on the model impact limiter was decreased after the test was stopped, force and deflection continued to be monitored, revealing the amount of elastically stored energy. The static force for each data point is multiplied by 1.06, a static to dynamic scaling factor, enabling a direct comparison with the analytically computed values. The dynamic scaling factor was determined from Figure 9 of NUREG/CR-0322, “The Effects of Temperature on the Energy-Absorbing Characteristics of Redwood,” which is based on Sandia National Laboratories tests.

C. Test Results

1. Dynamic Impact Limiter Tests

The acceptance criteria for the cask body performance is that cavity pressure be maintained and that the fuel remain in a subcritical configuration. For the cask body, this requires that permanent deformation must not occur to the lids, the lid mating sealing surfaces, the fuel basket and the lid bolts (both inner and outer) after completion of the drop tests.

The impact limiters must limit the deceleration of the cask body and components during a cask drop event. Therefore, the impact limiter acceptance criteria requires that the crush stroke be limited to prevent the cask body from contacting the impact surface, the accelerations be limited to those used in the design analyses, and the impact limiters remain attached to the cask body and in position after the impact event.

To assess the model performance against the acceptance criteria, the following data was collected for each test:

- Metrology data - to assess the permanent deformation of the cask body, fuel basket, lid seating areas, or in the lids themselves. Measurements for all dimensions except the inner diameters in the lower portion of the model cask cavity were obtained in a lab before and after the tests. The tolerance for all measurements was $\pm$ 0.001 inch.

- Pressure and temperature data - to assess the retention of pressure by the cask primary containment boundary, the cask cavity was pressurized to 30 (+2,-0) psi using a pressure port located near the model cask midpoint. The pressure in the cask cavity was measured before and after each test. To assist in correlating the pressure change with a change in the cask temperature, the temperature of the cask body was also obtained by Chromel/Constantan thermocouples attached to the cask exterior near the pressure port used to pressurize the cavity.

- Strain data - strain time-histories were recorded for each of the 30-foot drops to determine the maximum amount of strain experienced by the cask body. Stress data were mathematically derived from the strain gauge data. Strain gauge data were only taken for the 30-foot drop tests. It was concluded that the strain gauge data were not needed for the pin puncture drops.

- Acceleration data - to determine the maximum accelerations to which the cask was subjected, two single-axis accelerometers were mounted on the cask body for each of the 30-foot drop tests. The directions were altered for each individual test to ensure that the vertical deceleration was measured. Acceleration data were only taken for the 30-foot drop tests. It was concluded that the accelerometer data were not needed for the pin puncture drop tests.

- Impact limiter deformation data - to evaluate the behavior of the impact limiters, the crush stroke for each orientation, and the condition of the limiter attachment to the cask body after each test, the limiters were inspected to determine the amount of deformation that had occurred after each test. In addition, the condition of the attachment rods and nuts was also determined. Photographs of the deformed limiters were taken to record the post-test condition of the limiters.

- High speed photography - to review and assess the actual angle of impact and the behavior of the cask body and impact limiters during the impact.

i. Thirty-Foot Top End Drop Using Impact Limiters with Aluminum Shells - Test No. 1 of Phase 1

This was the first drop test to be performed of the four phases of tests using the quarter-scale cask model. The impact limiters used the aluminum shell design, which weighs less than the stainless steel shell design used in later tests. The cask model at the time of the top end drop was within 0.5 percent of the design weight of 3906 pounds ($250{,}000/4^3$ pounds).

Essentially all of the crushing occurred within the backed region of the impact limiter. The crush deformation was 2.11 inches, corresponding to a crush strain of 23 percent. The maximum stress was 8.6 ksi. The hoop strain component was extremely small. All three gauge locations near the top showed similar behavior in the axial and the hoop direction. One of the strain gauges showed a maximum permanent strain of 0.0015 percent. Since the normal stresses are so low, this offset is not attributed to any yielding of the material. Two accelerometers were mounted 180 degrees apart at the top end of the cask model. The maximum acceleration obtained from a 1000 Hz filtering of the accelerometer trace was 247 g. This value corresponds to a full-scale acceleration of 62 g. The filter frequency was computed by considering the first longitudinal vibrational mode, f_l, of the model as determined using an expression from Blevins for a lump mass attached to a cantilevered beam. The pressure measured after the test showed a slight increase, which corresponds to the small increase in the cask body temperature. Since the temperature data cannot be expanded to determine the temperature of the cavity gas, an accurate calculation of the corresponding increase in the pressure cannot be made. The pressure measurements indicate that there was no loss of pressure. After the top end drop test, the basket was removed from the cask body to inspect for deformations. The fuel basket was removed without any interference and neither the fuel basket nor the dummy fuel assemblies had deformed. This indicates that out of plane buckling due to the vertical deceleration loads did not occur, and that buckling of the inner shell due to lead slump did not occur. As evidenced by the nearly uniform crush of the impact limiter and the data from the two axial accelerometers, the load on the lead was essentially uniform around the model circumference. Thus, yielding of the inner shell at one location on the circumference would have precipitated yielding of the larger shell around the entire circumference. However, there was no evidence of yielding in the lead, basket, lids, or bolts used in the model. This test satisfactorily verified the packaging design for the nine-meter (30-foot) end drop.

ii. Thirty-Foot Side Drop Using Impact Limiters with Aluminum Shells - Test 3 of Phase 1

The high speed film showed that the welds along the edges of the aluminum limiters failed immediately upon impact, which allowed the four steel blocks at the lower edge of the cask to strike the impact surface. The force to decelerate the cask model was concentrated at the four steel blocks. The energy was absorbed by the local deformation of the model cask body shells and the model fuel basket. Based on the high-speed film, the rebound of the cask body was small, indicating that essentially all of the energy was absorbed in the initial impact. As a result of the localized loading on the cask body shells, the top forging, which serves as the seat for the lids, was deformed and the internal cavity pressure was not maintained. However, the lids remained firmly attached to the cask body during and after the impact. This test served to describe the behavior of the cask body in a guillotine-type impact without a neutron shield.

Strain gauge data were recorded at nine locations. A permanent strain in both the hoop and axial directions was identified. Therefore, an equivalent plastic strain (e_{eq}) was computed based on the Von Mises and Prandtl-Ruess Flow Rule material representation for material yielding to assess the amount of work-hardening undergone by the material. The maximum value found was 1811 microstrains, or 0.18 percent, at the midpoint of the cask at the point nearest the impact plane. Two strain gauges were approximately 0.25 inches from the edge of the blocks, which were displaced into the outer shell. This implies that the strain gauges were able to reflect the maximum strains generated by the impact.

The maximum accelerations recorded were 996 g and 1190 g. The first six or seven milliseconds correspond to the crushing of the redwood, after which the large increase in the deceleration is due to the steel blocks striking the impact surface.

The radial deflection was greatest at the lid end of the cask. The inner radius was decreased by 0.126 inches at the point of impact (the 0-180 degree diameter). The impact also caused out-of-round deformation of the cask at other measured locations by approximately 0.06 inches to 0.09 inches on a radius.

The inner and outer lids were inspected for out-of-plane deformation, and the measurement of the out-of-plane dimensions showed that no deformation had occurred during the Phase 1 tests.

The deformation of the model cask body required that the fuel basket be partially disassembled in the cask cavity in order to remove the basket after the side drop test. Two support disks were damaged in the drop test. One support disk had been loaded by the steel blocks, and the other support disk was located at the axial center of the basket. The out-of-plane measurement for the support disk located at the axial center of the basket was 0.001 inch, which is the sensitivity limit of the equipment. In addition, the support disk at the axial center of the cask did not experience plastic deformation. For the support disk loaded by the steel blocks, the maximum variation in the direction perpendicular to the plane of the disk was 0.004 inch. The impact also caused deformation to the bottom of the support disk. The impact of the steel blocks into the cask body and basket resulted in the lateral movement of the lower four fuel assembly positions by 0.19 inches. In addition, none of the support disks exhibited any out-of-plane buckling.

The deformation of the fuel basket near the steel block is not classified as buckling deformation, but rather deformation imposed by the impact of the steel blocks. Before proceeding with further testing, damaged components were repaired to meet the model drawing specifications and a new basket was installed. Since the inner shell was subjected to a small degree of work-hardening, the yield strength changed slightly.

The change in the yield strength is estimated by the product of the tangent modulus (Et) and the e_{eq} strain determined from the drop test. From NUREG/CR-0481, “An Assessment of Stress-Strain Data Suitable for Finite-Element Elastic-Plastic Analysis of Shipping Containers,” for Type 304 stainless steel, Et is 370,000 psi. Multiplying 370,000 by 0.18 percent, the yield strength increased by approximately 700 psi. The 700 psi change corresponds to a change of about 2 percent for Type 304 stainless steel at 70 °F. This change is considered to be insignificant. Although this test demonstrated that aluminum welds are inadequate to maintain the integrity of the impact limiter, this test clearly demonstrated the strength of the fuel basket design.

iii. Thirty-Foot Top Corner Drop Using Impact Limiter with Stainless Steel Shells - Test 3 of Phase 3

For the top corner drop test, the cask axial centerline was oriented 24 degrees from the vertical. This corresponded to the center of gravity of the cask being over the edge of the impact limiter.

The high speed film and the shape of the crushed impact limiter indicated that a small amount of impact limiter rotation occurred during the top corner drop. As the crushing was initiated, a force couple was applied to the impact limiter by the crushing force at the edge of the impact limiter and by a force due to the edge of the cask bottom moving into the impact limiter. This force couple resulted in rotation of the impact limiter away from the cask bottom, which produced the appearance of two crush faces on the bottom of the impact limiter. Initially, the crushed surface of the bottom of the impact limiter was at a 24-degree angle with respect to the uncrushed portion of the limiter (corresponding to the corner drop angle).

During the impact, the impact limiter shifted slightly and the angle became smaller. The maximum permissible deformation was assumed to be the distance from the edge of the redwood at the corner of the limiter to the edge of the limiter nearest the edge of the cask bottom. This was to ensure that the cask corner did not impact the unyielding surface.

The crush stroke for the corner drop was significantly larger than that for the end drop, since the crush area for the corner drop initially started out as a point and increased to the maximum area of 350 square inches. For the end drop, the crush area remained constant at 477 square inches. The decreased crush area and crush force in the corner drop resulted in a much larger crush stroke.

Although strain data were recorded for all locations, the data for some locations was inadvertently destroyed during post-processing. The maximum axial strain for the top end drop was 90 inch/inch, and maximum axial strain for the top corner drop was 63 inch/inch. With the exception of one axial strain measurement taken near the bottom of the cask, which was away from the point of impact, all axial strain measurements for the top end drop exceeded the axial strain measurements for the top corner end drop. Thus, the data confirm that the top end drop axial load envelopes the top corner drop axial loads. Therefore, the maximum stress computed for the data obtained in the top end drop, 8.6 ksi, envelopes the maximum stress that occurs in the top corner drop. The maximum acceleration was 127 g.

The trace reflects the gradual increase of the impact limiter crushing area. As the impact limiter crush area increases, the deceleration force also increases. Since the dynamic modes of deformation are similar to those for the end drop, the cut-off frequency used for the top end drop is applicable for the top corner drop. The data for this test were also filtered at 4000 Hz to demonstrate the effects of using higher filter frequencies. In comparing the top corner drop to the top end drop, the top corner drop produces significantly lower accelerations.

There are two reasons for this. First, the total crush area for the top end drop was 477 square inches while the top corner drop utilized 350 square inches. Additionally, the top corner drop does not subject the redwood to a uniform strain, but rather the top corner drop crush strain varies from a maximum value to zero. The cavity pressure measured after the top corner drop test showed a decrease of 0.2 percent due to a 1.5°F decrease in the cask body temperature. The pressure measurements indicate that the cavity pressure was maintained during the test. The lids, lid bolts, basket and fuel assemblies were removed and no damage to any component was observed. This test satisfactorily verified the packaging design for the nine-meter (30-foot) top comer drop.

iv. One-Meter Pin Puncture Drops - Tests 5 and 6 of Phase 3

In preparation for the pin puncture tests, the fuel basket was removed to prevent it from supporting the cask shells during the pin puncture tests. Bags of lead weights were placed in the model cask cavity to simulate the weight of the components that were removed.

A pin puncture test was performed at the axial midpoint of the cask, and a second pin puncture test was performed at the center of the outer lid. For the cask mid-point pin puncture test, the pre-test pressure was 3.007 bar and the post-test pressure was 3.002 bar. This pressure drop was attributed to the 7.2 degree drop between the pre-test and post-test cask temperature measurements.

In the cask outer lid pin puncture event, the cavity pressure valve cracked allowing the cavity pressure to decrease. (The cavity pressure valve in the model serves only as a convenient fixture to pressurize the model cavity, and is not a part of the full-scale NAC-STC design.) The cask was refitted with another valve and the cask was re-pressurized to 3.1997 bar. At the end of 10 minutes the pressure was still at 3.1995 bar, indicating that the closure lid system had performed satisfactorily.

The cask mid-point pin puncture resulted in an indentation of 0.33 inch in the outer shell. This did not result in penetration of the outer shell. The test, however, did result in deformation of the pin itself, but the effect of the deformation of the 8-inch long pin is considered to be negligible.

For the outer lid pin puncture test, the pin was found to have impacted at a location 2.53 inches away from the true center. This corresponds to approximately 10 percent of the diameter, and would produce essentially the same result as if it were at the exact center. The metrology data indicate no permanent deformation of the outer lid for the pin puncture condition at the off-center location. A pin puncture at the center would not be expected to result in permanent deformation of the closure lids either. Some minor scraping of the outer surface of the outer lid was also noted. Performance of these tests satisfactorily verified the packaging design for the pin puncture events.

v. Thirty-Foot Bottom Oblique Drop (Top End Slapdown) using Modified Impact Limiters with Stainless Steel Shells - Test No. 1 of Phase 4

In this test, the bottom of the cask impacts first causing the top end of the cask to rotate (and slap down). For a shallow angle oblique impact (near side impact), the slap down impact usually will result in a higher acceleration than for a side drop due to the angular momentum of the rotating cask. The high-speed film verified that the model orientation angle was 75 degrees from the vertical. It is required for the quarter-scale model that the maximum crush stroke be less than 3.22 inches to prevent the neutron shield from contacting the impact surface.

In the top end slap down, the maximum crush stroke occurred in the top limiter, which was subjected to the slap down effect and was determined to be 2.41 inches. The maximum stress occurred at the top end impact limiter at the 180 degree location. While some permanent strain was recorded, the level was significantly less than 0.2 percent. The maximum acceleration occurred at the top end of the cask and was approximately 10 percent greater than that at the lower end. The peak acceleration value, 225 g, was measured using a filter frequency of 750 Hz to avoid artificially inflating the acceleration levels because of higher frequency signals associated with the instrumentation.

The pressure measured before and after the test remained constant to within the accuracy of the instrumentation indicating that no loss of pressure occurred during the test. The metrology data indicate that, for a measurement tolerance of 0.01 inch, none of the diametral dimensions changed. No resistance was encountered when removing the basket. Performance of this test and Test No. 2 of Phase 4 described below, demonstrated that the modified impact limiter design prevents the neutron shield from contacting the impact surface.

vi. Thirty-Foot Side Drop - Test No. 2 of Phase 4

After rotating the limiter from the oblique drop test 180 degrees, the side drop was performed for Phase 4. In the slap down test, the loading is not uniform and tends to be concentrated towards the slap down end. In the side drop the loading tended to be uniformly distributed over the length of the cask and equally applied to each impact limiter.

The high-speed film verified that the cask was horizontal as it approached the impact surface. For the side drop test, the crush stroke was 2.16 inches for the bottom impact limiter and 2.04

inches for the top impact limiter. The crush data does reflect that a clearance will exist between the neutron shield and the impact plane after the side drop condition.

The maximum strain (135 in/in) and the maximum stresses (29.5 ksi axial and 17.5 ksi hoop) occurred at the 180 degree location of the cask midpoint for the side drop. The side drop stresses were larger than those for the oblique drop even though the oblique drop deceleration was 10 percent larger. The accelerometers measured accelerations of 208 g on one end of the cask and 204 g on the other end of the cask. This concurs with the crush stroke data.

The pressure measured before and after the test remained constant to within the accuracy of the instrumentation, indicating that no loss of pressure occurred during the test. The metrology data indicate that, for a measurement tolerance of 0.01 inch, none of the diametral dimensions changed. During basket removal, the basket was removed without resistance and no deformations was identified. Performance of this test and Test No. 1 of Phase 4 described above, demonstrated that the modified impact limiter design prevents the neutron shield from contacting the impact surface.

2. Static Impact Limiter Test Information

For the end impact case, the impact limiter compression forces from the quasi-static test are higher than the analytical values using the maximum tolerance cold temperature crush strength and the minimum tolerance hot temperature crush strength properties of redwood. This difference in compression forces can be attributed to the additional forces on the cask due to the redwood material's resistance to shearing along the periphery of the "backed" area of the cask. The calculated equivalent deceleration force of the full-scale cask, based on the quasi-static eighth-scale model impact limiter test, is 54.8 g for the end impact case. This force is greater than the analytically determined 44.6 g end drop deceleration force using the maximum tolerance cold temperature crush strength of redwood, but less than the analytically determined 56.1 g deceleration force obtained using the minimum tolerance hot temperature crush strength of redwood. The higher deceleration force obtained using the minimum tolerance hot temperature crush strength of redwood is a result of the larger deformation and the partial lock-up of the redwood that occurs before the cask is stopped. Based on the area under the dynamically scaled force-deformation curve for the end impact case, all of the energy of a one-eighth scale model of the NAC-STC for a 30-foot drop is absorbed when the impact limiter deformation reaches 1.58 inches (1.63 inches from the static force-deformation curve), which extrapolates to a 12.6-inch deformation for the full-scale NAC-STC impact limiter, or 42 percent of the depth of the impact limiter.

For the corner impact case, the calculated equivalent deceleration force of the full-scale cask, based on the quasi-static eighth-scale model impact limiter test, is 32.6 g. This compares with the analytically determined 44.0 g deceleration force using the maximum tolerance cold temperature crush strength of redwood, and with the analytically determined 49.3 g deceleration force calculated using the minimum tolerance hot temperature crush strength of redwood. Based on the area under the dynamically-scaled force-deformation curve presented for the corner impact case, all of the energy of a one-eighth scale model of the NAC-STC for a 30-foot drop is absorbed when the impact limiter deformation reaches 3.22 inches (3.30 inches for the static force-deformation curve), which extrapolates to a 25.76-inch deformation for the full-scale NAC-STC impact limiter, or 70 percent of the depth of the impact limiter.

For the side impact case, the calculated equivalent deceleration force for the full-scale cask, based on the quasi-static eighth-scale model impact limiter test, is 45.6 g. This force compares with the analytically determined 51.7 g deceleration force using the maximum tolerance cold temperature crush strength of redwood and with the analytically determined 51.3 g deceleration force using the minimum tolerance hot temperature crush strength of redwood. Based on the area under the dynamically-scaled force-deformation curve presented for the side impact case, all of the energy of a one-eighth scale model of the NAC-STC for a 30-foot drop is absorbed when the impact limiter deformation reaches 1.64 inches (1.70 inches for the static force-deformation curve), which extrapolates to a 13.12-inch deformation for the full-scale NAC-STC impact limiter, or 71 percent of the depth of the impact limiter.

The aluminum alloy shells split along the weld seams and came apart as compressive load was applied. The Type 304 stainless steel shells remained ductile and did not split along the weld seams. The eighth-scale model impact limiter compression tests showed that a maximum of 8.2 percent of the absorbed energy may be stored during crushing and later released. The results of the eighth-scale model NAC-STC impact limiter quasi-static compression tests clearly demonstrate that the NAC-STC impact limiter design provides the energy absorption capacity to decelerate the cask to a stop for a 30-foot drop accident for the various impact orientations while maintaining maximum compression forces that are less than the cask design values.

5. Model No. TN-FSV (Docket No. 71-9253)

The information below was obtained from Section 2.10.3 in Public Service Company of Colorado's SAR pages submitted with their response to a request for additional information by NRC staff (see ADAMS Accession No. ML063530662) for the impact limiter tests.

A. Tests performed

A series of static and dynamic tests was performed on three half-scale models of the TN-FSV impact limiters. The following two static crush tests were performed on a single half scale TN-FSV impact limiter at room temperature:

- Load applied radially on the side (0 degree) of the impact limiter, and
- Load applied on the corner at an angle of 10 degree to simulate the 80 degree corner drop.

The 0 degree orientation was selected because it has the highest transverse g loading at the center of gravity. The 80 degree corner crush test was selected because it has high axial g loadings, and higher expected impact limiter deformations than the end drop.

Two 30-foot drop tests were performed at low temperature to evaluate the adequacy of the impact limiter enclosure and attachments. The orientations were a 15 degree slap down (shallow angle side drop) and an 80 degree corner drop. The 15 degree slap down orientation was selected because it puts the highest stresses on the attachment bolts, and it is the orientation for which the highest impact force is expected for a side drop orientation. The 80 degree corner drop was selected to compare with the static test and because it is the orientation for which the largest limiter deformation is expected and for which significant decelerations are expected.

All the kinetic energy of the model package must be absorbed by a single limiter for the 80 degree corner test which is very nearly a center of gravity over corner test. In a 0 degree side impact, 50% of the total energy must be absorbed by each of the two limiters. However, analyses indicated roughly 68% of the energy is absorbed by the secondary impact limiter (i.e., the impact limiter hitting second) for a shallow angle (slap down) side drop. Therefore, since the impact of the second impact limiter is nearly the same as a 0 degree side drop, the 0 degree static crush test was continued to an energy level beyond 50% to approximate the second hit of the 15 degree side drop.

B. Description of the methods or analyses used in tests

For the static crush tests, the stainless steel impact limiter structure is steel shells closed off by flat plates and reinforced by six (6) radial gussets. The model and full-scale configurations are identical, but all linear dimensions in the model are half-scale. Although the balsa and redwood densities used in the model are consistent with that specified for fabrication of the full-scale impact limiters, the wood used in the models had densities on the high end of the specified range. The model contains the same number of wood blocks as the full-size impact limiters. The wood blocks are made up of a number of smaller pieces of wood glued together with phenol resorcinol adhesive, using the same procedure to be used on the full-size impact limiters. The attachment bolts are made from the material specified for the full-size limiters. Bolts (5/8-11-2A) with an undercut shank diameter of 0.511 in. were used on the models.

The testing was performed using a 1.2 x 10^6 lb. compression testing machine. The loading surface was maintained perpendicular to the direction of crushing and the massive impact limiter support fixture was restrained from shifting during loading. The deflection of the impact limiter was measured continuously during testing using a linear potentiometer mounted to the testing machine crosshead. The crush force versus vertical movement of the test plate was recorded continuously on an x-y plotter.

For the dynamic tests, the test model is a solid carbon steel test body with a front impact limiter on each end. The test body is 103.5 inches long with an outside diameter of 15.5 inches. The total length of the dynamic test model, including impact limiters, is 123.5 inches. The dynamic tests were performed in accordance with approved written procedures. The impact surface was an unyielding concrete pad weighing more than 250,000 lbs. resting on bedrock. A mild steel plate, 2 inches thick, was secured to the surface of the concrete pad. The test drop height was 30 feet + 1.0 in./-0.0 in. Each drop was photographed and videotaped.

For the slap down test, the impact limiter that impacts second was cooled more than 18 hours to a temperature of -20 °F prior to attachment to the test body. The ambient temperature was 9 °F during the drop test. Following the slap down test, the test model was rotated 180 degrees to allow the uncrushed side of the impact limiter used for the primary hit in the slap down case to be used for the 80 degree corner drop. As before, the ambient temperature was around 9 °F.

C. Test Results

The side crush static test was terminated when the deflection reached approximately 5 inches and 81% of the kinetic energy associated with a 30-foot package drop was absorbed (5 of the 6 attachment bolts were simultaneously broken at this point). Significant deformation of the impact limiter was evident after the test. The bolt tunnels above the heads of the attachment bolts collapsed so that the heads of the bolts were inaccessible. The weld seams between the outer cylindrical shell and the flat plates on the front edge of the impact limiter tore approximately 3-4 inches in length in two places directly below the impact surface. Similarly a 3-inch tear on the back edge of the impact limiter was evident. After the impact limiter was removed from the fixture, evidence of inside crushing of the impact limiter was noticed. The seam between the inner cylindrical shell and circular plate had split in the region closest to the impact.

After the slap down test, the impact limiter attachment bolts that hit first lost their torque due to deformation of the washers beneath the bolt heads as well as tightening of the impact limiter against the test body because of the drop. None of the bolts were broken. Two weld seams between the gussets and flat segments opened slightly. The primary impact limiter pushed inward toward the test body indicating inside crushing, and also crushed on the outside at a 15 degree angle. The crushing on the secondary impact limiter was similar to a 0 degree angle (perpendicular to the package axis) side drop crush. Therefore, dynamic test data from the secondary impact limiter is compared to load-versus-displacement curves generated from the side crush static test data. Analyses indicated, for a 15 degree side drop, that roughly 68% of the total kinetic energy associated with a 30-foot package drop is absorbed by the secondary impact limiter (rather than 50% for a true side drop). The permanent crush depth associated with the secondary impact limiter after the dynamic test was about 3.57 inches not including elastic springback and about 3.82 inches assuming an estimated 0.25 inches of springback from static crush test data. The corresponding deflection from the associated load-versus-displacement curve is 4.4 inches. The crush deformations, therefore, agree within about 14%.

The corner crush static test was terminated after the deflection reached 7 inches and a total of 113% of the required energy was absorbed. The bolt tunnels above where the bolts are installed had buckled and folded closing the bolt holes. Although the outer cylinder bulged near the top seam, no exterior seams opened as a result of the corner crush test. After the 80 degree corner crush test, one segment of the impact limiter was cut open. The wood was removed and examined. It was noted that glue joints between the individual pieces of wood in the blocks did not fail as the wood crushed. For the corner crush static test, with 100% of the kinetic energy associated with a 30-foot drop absorbed by the impact limiter, the measured deflection was 6.5 inches.

After the corner crush dynamic test, the attachment bolts also lost their torque. There was evidence of both inside and outside crushing. The side of the impact limiter closest to the edge hitting first pushed around the test body due to inside crushing of the limiter on one side. Total deflection for the 80 degree corner drop, without accounting for springback, was calculated to be 6.3 inches and 6.5 inches assuming an estimated 0.2 inches of springback from the static test data.

6. Model No. NUHOMS® MP187 Multi-Purpose Cask (Docket No. 71-9255)

The information below was obtained from Sections 2.10.11 and 2.10.12 in Transnuclear's NUHOMS®-MP187 Multi-Purpose Cask SAR (see ADAMS Accession No. ML063520505) for the dynamic and static impact limiter tests, respectively.

A. Tests performed

1. Pre-operational Tests

Prior to performing the certification test program a series of five pre-operational drop tests were performed, using two quarter-scale models. The pre-operational drops conducted with these limiters were:

- Test 1: 30 ft.-0 in. drop with package axis at 30 degrees to horizontal, impact onto small diagonal facet with slap down onto opposite limiter;
- Test 2: 30 ft.-0 in. drop with package axis at 30 degrees to horizontal, impact onto large flat facet with slap down onto opposite limiter;
- Test 3: 30 ft.-0 in. flat side drop with impact on large flat sides;
- Test 4: 30 ft.-0 in. vertical drop; and

- Test 5: 30 ft.-0 in. flat side drop with impact onto diagonal corners of the limiters to impart the maximum rotational energy to the test article.

2. Dynamic Impact Limiter Tests

   The dynamic tests were performed using two quarter-scale prototypical impact limiters, in multiple uses, in different drop orientations. The test sequence was as follows:

   - A 30-foot drop with the package longitudinal axis inclined at 30 degrees to the horizontal and the 90 degrees azimuth at the top. Primary impact was on the large flat facet at 270 degrees azimuth on impact limiter "a" with a secondary impact (slap down) onto impact limiter "b".

   - A 30-foot drop with the package's center of gravity over a corner and the package's axis inclined at 72 degrees to the horizontal and rotated so that impact will occur on a diagonal corner of impact limiter "a."

   - A 40-inch drop onto a mild steel quarter-scale, cylindrical puncture spike. The spike had a diameter of 1.50 inches, a top edge radius of 0.06 inches, and a projected length of 16.0 inches, or 28.0 inches above the surface of the drop pad. The package was oriented at 45 degrees to the vertical on limiter "b." The 40 inch distance was measured from the point of impact on the package to the top of the puncture spike.

   - The end puncture event was performed on impact limiter "a" using a quarter-scale, cylindrical puncture spike similar to that described for the immediately above.

3. Static Impact Limiter Test Information

   The static test program was developed using two quarter-scale model impact limiters for multiple tests in different loading orientations. The total crush deflections imposed for each test were larger than the maximum predicted deflection expected to occur under the bounding loading conditions. The static tests are numbered sequentially from test 5 to 9. Details of the test program, starting at Test Number 5 are:

   5. A static test with the load applied to the 45 degrees azimuth flat surface of the honeycomb portion of the limiter.

   6. A static test, on the same impact limiter, with the load applied to the 180 degrees azimuth large flat honeycomb facet.

   7. With a new impact limiter, the static load was applied at 30 degrees to the package longitudinal axis to the 180 degrees azimuth large flat side of the limiter.

8. A static load was applied at 30 degrees to the package longitudinal axis through the 40 degrees azimuth small corner facet.

9. A third static test was performed on the second impact limiter. For this test the load was applied at 60 degrees to the package longitudinal axis to the 325 degrees azimuth diagonal corner of the impact limiter.

B. Description of the methods or analyses used in tests

1. Pre-operational Tests

The pre-operational drop tests were performed to demonstrate that the equipment and digital acquisition system were working correctly. The pre-operational test models were identical to the certification limiters with the exception of the honeycomb material. For the pre-operational tests the honeycomb was replaced with foam of similar density and crush strength; all other details were identical.

2. Dynamic Impact Limiter Tests

The primary method of determining package deformations was high speed film. High-speed cameras provided 400 and 2,000 frames per second coverage during all four dynamic tests. The cameras were placed parallel and perpendicular to the package impact zone to provide optimum viewing for measurement of the dynamic deformation in the impact limiters. Photometric coverage also included real-time color video and still shots. Painted backboards 12 ft. wide by 8 ft high, with a 12-inch lined grid, were placed behind the drop pad to provide a contrasting background to assist in measurement of the dynamic deformation of the limiters from the film. Following film processing the total impact limiter deformations were determined using a film comparitor with the capability of resolving displacements to 1/10th of an inch.

As a backup to the film, eight accelerometers were mounted to the package to measure rigid body accelerations. The accelerometers were installed at the package center of gravity and at each end adjacent to the impact limiters, close to the location of the "critical" spacer discs for the full scale package.

3. Static Impact Limiter Test Information

The instrumentation used for these tests consisted of displacement and load transducers. The deflection of the specimen was measured with two wire potentiometers (wirepots), one on each side of the special loading plates installed under the universal testing machine head. The average of these two measurements was used to characterize the deflection corresponding to the applied load. Another displacement transducer was used to measure the deflection of the lower part of the impact limiter. In addition, the displacement of the universal testing machine head (stroke), measured via an internal transducer, was also recorded for data verification purposes. The applied load was measured by a pressure transducer installed inside the control panel of the universal testing machine. All instruments were calibrated prior to the testing program.

C. Test Results

1. Pre-operational Tests

Test 1: For the first test, the two impact limiters impacted at different times. The impact forces calculated for the first impact limiter were 57 g in the longitudinal direction and 187 g in the transverse direction. The impact forces measured for the first impact limiter were 66 g and 63 g in the longitudinal direction and 185 g and 90 g in the transverse direction. The impact forces calculated for the second impact limiter were 18 g in the longitudinal direction and 203 g in the transverse direction. The longitudinal direction impact forces measured for the second impact limiter were 29 g and 23 g. The transverse direction impact forces measured for the second impact limiter were 335 g and 225 g. These transverse direction impact forces, when adjusted by the dynamic load factor associated with the rigid body effect of the dummy package, which is discussed below, equal 210 g and 141 g.

Test 2: For the CG-over-corner drop test, the calculated longitudinal and transverse forces were 110 g and 40 g respectively. The measured longitudinal forces were 110 g. while the measured transverse forces were 52 g and 30 g.

Test 3: The 45 degrees drop puncture spike cleanly punched through the stainless steel impact limiter shell and foam until it impacted the reinforcing ring at the inner shell. The internal reinforcing ring deflected the pin to follow the inner cylindrical shell; no puncture of the inner shell occurred and the pin was stopped 1.5 inches short of the package attachment ring by a highly compacted wedge of honeycomb. The total penetration into the limiter was approximately 11.5 inches. With the vertical motion of the test article stopped by the limiter, the package toppled, and bent the pin through a 45 degrees angle without tearing any of the material from the limiter. After the opposite limiter contacted the ground, the test article rolled sideways and the pin was then bent approximately 90 degrees to the initial bend without any evidence of any material tearing from the limiter. Internal damage to the limiter was restricted to broken foam and crushed honeycomb material at the entry point. The maximum gap was 3 inches at the foam/honeycomb interface where the initial 45 degrees rotation of the pin occurred; there were no other damaged areas that have any impact on the integrity of the limiter.

Test 4: The puncture pin penetrated 13.0 inches to the inner steel shell while being deflected sideways approximately 4 inches to impact on the reinforcing ring at the outer edge of the inner shell. The slow-motion film showed that the test article stopped with the pin completely embedded in the limiter and then slowly toppled, bending the puncture pin at approximately 60 degrees. After the test article rotated about 60 degrees, the bottom edge of the impaled limiter contacted the test stand, the impact point on the bottom of the limiter was raised vertically, and the pin pulled up and out of the stand. Damage to the limiter was confined to the puncture entry point and the slightly curved path taken to the impact point on the inner shell. The stainless steel outer shell and foam had sufficient strength to totally restrain the pin and bend it through 60 degrees, plus extract it from the test stand.

Dummy Package Tests: Examination of both the pre-operational and certification acceleration test data showed a ringing signature at approximately 350 Hz for the flat side slap down drop. This response indicated that the test results included a significant non-rigid body response. Two additional drops of the dummy package without impact limiters were conducted to determine the natural response of the bare package. The package was instrumented the same as the certification tests and dropped from heights of 12 and 40 inches. These drops both measured a natural frequency at the same frequency as the ringing tone (approximately 350 Hz). Additional analyses were conducted to include the response of the dummy package and define the rigid body response.

A dynamic load factor was determined for a range of frequencies for a damping ratio of 6%. The damping ratio was calculated as the logarithmic decrement from the filtered drop acceleration time histories. The predicted rigid body response for the flat side slap down drop was used as the forcing function for the dynamic load factor calculation. This analysis produced a predicted dynamic load factor of 1.6. Applying the calculated dynamic load factor of 1.6 to the measured peak accelerations produced the rigid body response.

The pre-operational tests clearly demonstrated that the impact limiter attachment bolts, and package attachments, were robust and capable of sustaining the design basis drop loads and keep the limiters securely attached to the package for multiple design basis drops.

2. Dynamic Impact Limiter Tests

Test 5: The limit event for this test was a deflection of 5.5 inches. The specimen was loaded to a peak load of 287 kips, which produced a deflection of 5.61 inches. The deflection after removing the load was 4.69 inches.

Test 6: Test 6 occurred immediately following test 5. The limit event was defined to be a deflection of 5 inches. Loading was interrupted when the deflection was 3.86 inches (386 kips of load) because the loading fixture was too close to the test fixture. The displacement instrumentation was disconnected, and the position of the loading fixture under the universal testing machine head was moved to apply further deformation to the specimen. The displacement transducers were reconnected to the specimen, and the load reapplied.

Testing was stopped when the load was 603 kips and the displacement 4.81 inches because the loading fixture was again close to the test fixture. Local buckling and yielding were also observed in the test fixture beams supporting the triangular component of the test fixture. The localized failure of the test fixture permitted a small rotation of the test fixture and imparted a small deflection component to the measured results. As the honeycomb material had been crushed to a solid matrix, this deflection is not considered to be important. The local buckling failure of the test fixture is not loaded in subsequent tests and did not require repair before continuing the loading sequence. After removing the load, the permanent deflection of the specimen was (60% crush) 3.81 inches.

Test 7: The defined limit displacement was 4 inches. Loading was stopped when the deflection was 3.85 inches because the loading plate was too close to the test fixture. The maximum load applied to the specimen of 484 kips occurred at a displacement of 3.52 inches. A permanent deflection of 2.79 inches was measured after unloading the specimen. The wire of the potentiometer used to measure bottom displacement snapped at a displacement of 1 inch and 322 kips of load.

Test 8: The specimen was loaded to 339 kips, with a corresponding displacement of 5.67 inches. Following a visual examination of the impact limiter, it was decided to apply further loading. The peak load measured during the test was 373 kips with a corresponding deflection of 6.25 inches. The peak displacement measured was 6.44 inches, after the load had dropped to 353 kips. The permanent deflection after unloading was 5.15 inches.

Test 9: The limit event was a displacement of 9.6 inches. This displacement was achieved with a load of 484 kips. It was then decided to load the specimen further. The peak load achieved was 700 kips at a deflection of 10.74 inches. The peak deflection was 10.90 inches, measured after the test was paused, and the load had dropped to 648 kips. The permanent deflection after unloading was 9.06 inches.

7. Model No. HI-STAR 100 System (Docket No. 71-9261)

The information below was obtained from Appendix 2.A of the SAR for the HI-STAR 100 Cask System, Revision 15, dated October 11, 2010 (see ADAMS Accession No. ML102871079).

A. Tests performed

A series of static compression tests were performed on eighth-scale models of the impact limiter for the HI-STAR 100 package. These crush tests were performed to document the force-deflection and energy absorption characteristics of the honeycomb material used in the impact limiter. The tests were conducted at temperatures ranging from -30 °F to 120 °F with impact limiter orientations of 0 degrees (side), 30 and 60 degrees (oblique) and 90 degrees (end). The purpose of this test was to confirm the static force-crush prediction model, determine the effect of temperature on the impact limiter and access and confirm the performance of the impact limiter backbone.

A series of free drop tests were performed on quarter-scale models of the HI-STAR 100 package instrumented with five accelerometers. Thirty-foot drop test orientations included a vertical top end drop, top corner drop at an angle of 67.5 degrees from horizontal (center of gravity over corner), side drop, and a slap-down drop at an angle of 15 degrees from horizontal so that the top impact limiter hits the surface first followed by a higher velocity impact of the bottom impact limiter.

The purpose of these tests were to confirm the predictions of the finite element software LS-DYNA used to create a full scale model of the HI-STAR 100 package and the AL-STAR impact limiter, specifically, the deceleration of the package, impact duration, maximum crush depth of the impact limiter and performance of the attachment system. Following the confirmation of the model, three more drop tests were performed at 30, 45 and 60 degrees with content weight varying from 270,000 lbs. to 280,000 lbs. (range of weight allowed in the package) to confirm the impact orientation of maximum damage.

B. Description of the methods or analyses used in the drop tests

The package was instrumented with five accelerometers to determine maximum deceleration of the package and record the duration of the impact for the scale model. Three accelerometers were attached at three axial locations. The other two accelerometers were attached 120 degrees from the first three, and aligned with the top and bottom accelerometer.

C. Test Results

Data obtained from the tests consists of both qualitative information with respect to observations about the package and the limiter and quantitative data obtained from the recorders. The data for each test include measured impact limiter deformation, deceleration time history, and observations of the package and attachments.

1. Impact Limiter Force-Deflection Tests

The static compressions tests were performed on eighth-scale model impact limiters used in drop testing the quarter-scale model. Of the four compression testes performed, two (0 and 30 degrees) were unsatisfactory, because the backbone did not remain elastic. The other two orientations (60 and 90 degrees) showed close agreement of the numerical model. As a result, the backbone was redesigned, and three additional eighth-scale model tests were performed at 0 degrees (side), 67.5 degrees (center of gravity over corner) and 90 degrees (top end). The backbone remained elastic and the force-deflection results showed close agreement with those predicted by the numerical model. Additionally, the tests indicated that temperature (within the range tested and the regulatory requirements) has no effect on the performance of the impact limiter.

Following the quarter-scale model testing, three additional compression tests were performed on three eighth-scale models of the impact limiter. The orientations were 0 degrees (side) 67.5 degrees (center of gravity over corner) and 90 degrees (top end). Good agreement was observed between the theory and the test for the side and center of gravity over corner crush orientations. For the end drop, the test results suggested that there may be elastic behavior at the interface of the package and the impact limiter that the model was not capturing. The dynamic test results (described below) demonstrated that the predication of the peak deceleration, extent of crush and impact duration were not affected by these elastic behavior effects.

2. First Series of Drop Tests

The orientations used for the first series of drop tests included the top end, center of gravity over corner and the side drop. The peak deceleration of the top end drop was well above the design basis of 60g. The reasons for the discrepancy between the test and the model were determined to be the use of a low value for a dynamic multiplier assumed in the impact limiter design and the lack of pre-crush of the honeycomb material in the impact limiter. As a result, the impact limiter was revised with new crush strengths and redesigned and a new set of quarter-scale model impact limiters was manufactured.

3. Second Series of Drop Tests

The same orientations were used in the first phase of the second series of drop tests. In all cases, the deceleration values were within the design limit of 60g; however, the attachment system did not survive the side impact drop test. The attachment system was redesigned prior to the slap-down test, which is considered to be the most definitive test of the package/impact limiter attachment integrity. The bottom impact limiter remained in place following the slap-down test and the deceleration was within the design basis.

Table 2.A.3 and 2.A.4 of the SAR shows the comparison of the test date for the seven drop tests with the prediction of the LS-DYNA software model. The predicted deceleration values, impact duration and total crush depth compared well with the test data. In three cases, the test data exceeded the predicted value of the model. In these cases, the measured total crush depth was greater than the predicted crush depth, but in all cases, the actual total crush depth was less than 80% of the available depth. This means there was several inches of impact limiter available to crush before package would impact the surface.

The results of the compression tests and the drop tests confirmed the accuracy of the numerical model, which was used to simulate the one-foot drop required for the assessment of normal conditions of transport.

The simulation produced maximum decelerations less than the design basis.

8. Model No. UMS Universal Transport Cask Package (Docket No. 71-9270)

The information below was obtained from Section 2.10.3 of the SAR on the Model No. UMS Universal Transport Package (UMS), Revision 99A, dated June 1999 (see ADAMS Accession No. ML063480388).

A. Tests performed

A series of free drop tests were performed on a quarter-scale model of the UMS package. Thirty-foot drop test orientations included a vertical top end drop, center of gravity over top corner drop, and a side drop. The test data consisted of measurements of the deformations of the impact limiter, the package accelerations, and inspection of the retaining rods.

Two static crush tests were performed on quarter-scale models of the impact limiter for the UMS package. These crush tests were performed to confirm the design of the UMS impact limiters, specifically to identify any potential initial stiffness in the impact limiter and to indicate any effect of the thick walled screw tubes on the impact limiter crush force in the top end drop orientation. Additionally, the crush data were used to confirm the validity of the RBCUBED computer program analysis of the UMS impact limiter.

B. Description of the methods or analyses used in tests

The package was instrumented with 3 accelerometers for the top end drop and the top corner drop and 4 accelerometers for the side drop to determine the maximum deceleration and impact duration of each drop. Additionally, two high-speed cameras were used to record the behavior of the model as it impacted the target surface.

C. Test Results

Data obtained from the tests consist of both qualitative information with respect to observations about the package and the limiter and quantitative data obtained from the recorders. The data for each test include measured impact limiter deformation, acceleration time history and assessment of the angle of drop based on the high-speed camera.

1. Top End Drop

For the top end drop the impact limiter was sawn into quarters and the average crush was measured at 2.04 inches, which scaled up to 8.16 inches for a full scale package. During the removal of the impact limiter, which required two hydraulic jacks, it was observed that several of the retaining fords had broken due to plastic buckling. Based on the accelerometer time history, the maximum deceleration was measured at 51.8g and the impact duration was 12 milliseconds. The measured acceleration was bounded by the design basis value of 60g and the crush depth was less than that required for the package to impact the impact surface.

2. Static Crush Test for the End Drop Orientation

   To further confirm the design of the UMS impact Limiters, two static crush tests in a top end drop orientation were conducted to identify any potential initial stiffness in the impact limiter and to indicate any effect of the thick walled screw tubes on the impact limiter crush force. The results of the static crush test confirmed the response of the impact limiter in the top end drop impact, and confirmed the validity of the RBCUBED program analysis

3. Side Drop

   Following the side drop, it was observed that the three retaining rods nearest the impact had broken, but that the remaining 13 of 16 retaining rods were intact and still threaded into the model body. The scaled-up crush depth was 11.8 inches and 11.4 inches for the top and bottom impact limiters respectively, which compared well with and were bounded by the RBCUBED predicted values of 13.0 and 13.7 inches.

   The peak accelerations for the top and bottom impact limiters were 51.1g and 37.9g respectively, which were also bounded by the RBCUBED predicted values of 52.1g and 48.6g. The measured accelerations were all bounded by the design basis value of 60g and the crush depth was less than that required for the package to impact the impact surface.

4. Center of Gravity over Top Corner Drop

   Like the side drop test, following the center of gravity over top corner drop, it was also observed that the three retaining rods nearest the impact had broken, but that the remaining 13 of 16 retaining rods were intact and still threaded into the model body. The scaled-up crush depth, 12.8 inches, was significantly less than the RBCUBED predicted value of 27.7 inches. The RBCUBED value bounded the actual crush depth. The acceleration time history from the accelerometers produced a maximum deceleration of 30g that was also significantly less than the RBCUBED predicted value of 47.8g, both of which are less than the design basis of 60g.

   The test confirmed that the UMS impact limiters are able to provide an adequate design margin to limit the deceleration and the crush depth of the transport package for drop test.

9. Model No. FuelSolutions™ TS125 Transportation Package (Docket No. 71-9276)

The information below was obtained from revision 6 of the FuelSolutions™ SAR dated September 2006 (see ADAMS Accession No. ML070230678).

A. Tests performed

1. Development Testing

A series of specimen bench tests and sub-model tests was performed to support the development of the impact limiter design. Specimen bench tests were performed to determine the characteristic behavior of the individual energy absorbing aluminum honeycomb materials used to fabricate the impact limiter. The aluminum honeycomb specimen tests examined the effects of crush rate, temperature, and impact orientation on the crush properties of the aluminum honeycomb materials. In addition, sub-model specimen bench tests were performed to address specific impact limiter design and loading issues.

Quasi-static crush tests of aluminum honeycomb material having nominal crush strengths of 1,200 psi and 2,500 psi were performed for a range of crush orientations and temperatures. Quasi-static crush tests were conducted along each of the principal axes for both 1,200 psi and 2,500 psi material at room temperature. Additional quasi-static crush tests were performed at temperatures of –20 °F and 220 °F. Three separate specimens were tested for each condition.

2. Confirmatory Static Crush Testing

Quasi-static crush tests, using scaled impact limiter test articles, were performed to confirm the adequacy of the inputs used in the analytical tools and methodology used to calculate the impact limiter force-deflection relationships. These tests address the effects of impact limiter geometry and construction and the effects of backing on the force-displacement relationship for various impact orientations. In addition, the quasi-static crush tests confirm the adequacy of the attachments used to secure the impact limiters to the transportation package. The orientations for the quasi-static crush tests include the end, center of gravity over corner, and side crush orientations. All static crush tests were performed using either an eight-scale or quarter-scale replicas of the full-scale impact limiter design.

3. Confirmatory Drop Testing

The 9-meter (30-foot) free drop tests were performed using quarter-scale impact limiter test articles to confirm the adequacy of the analytical tools and methodology used to calculate the rigid-body response of the transportation package for the free drop conditions specified in Title 10 of the *Code of Federal Regulations* (10 CFR) Part 71. The dynamic drop tests address the dynamic response of the impact limiter energy-absorbing materials for various impact orientations. In addition, the dynamic drop tests confirm the structural adequacy of the impact limiter shell assembly and the hardware used to attach the impact limiter to the ends of the transportation package. Four free drop orientations have been tested, including:

- **End Drop** – A free drop with the package longitudinal axis orientated perpendicular to the target (i.e., vertical).

- **Corner Drop** – A free drop with the package longitudinal axis oriented at an angle of 21 degrees with respect to vertical. This orientation places the package center of gravity directly over the center of the crush force.

- **Side Drop** – A free drop with the package longitudinal axis oriented parallel to the target (i.e., horizontal).

- **Slapdown** – A free drop with the package longitudinal axis initially oriented at an angle of 75 degrees from vertical (i.e., 15 degrees from horizontal). This free drop condition results in a primary impact and as subsequent secondary impact (i.e., slapdown).

B. Description of the methods or analyses used in tests

1. Development Testing

The tests were performed using blocks having a 4.00-inch by 4.00-inch cross-section and a thickness of 2.00 inches in the direction of crushing. Pre-crushed test specimens were used for the static crush tests. The pre-crushed specimens were created by cutting the blocks 2.25 inches thick, and crushing one side 0.25 inch to attain the final 2.00-inch thickness. Each specimen had 0.020-inch thick 5052 aluminum alloy sheets bonded to each of the 4.00-inch x 4.00-inch faces to help reduce the possibility of sample splitting during the test. This resulted in a nominal specimen thickness of 2.04 inches. All quasi-static crush tests were conducted using a head speed of 0.2 inch per minute.

2. Confirmatory Static Crush Testing

The eighth-scale end crush test was performed on a 300-ton capacity manual static testing machine at an approximate head speed of 0.2 inch per minute unless noted otherwise. The force measurements were manually recorded from the dial gauge on the Tinius-Olsen machine, and the displacements were manually recorded from a patriot gauge with a digital displacement indicator.

3. Confirmatory Dynamic Drop Testing

Data collection and reduction was performed by Sandia National Laboratories using the Mobile Instrumentation Data Acquisition System. The 44-foot long MIDAS trailer, which was developed by Sandia National Laboratories using the Mobile Instrumentation Data Acquisition System for the U.S. Department of Energy to provide efficient and accurate test data acquisition and analysis for radioactive material packages, was located at the drop test site.

The test assembly was instrumented with a total of 18 accelerometers attached at various locations on the outer surface of the test fixture, providing sufficient redundancy. The accelerometers used provide accurate measurement of response frequencies up to 20 kHz and accelerations exceeding 1,000g.

C. Test results

1. Development Testing

The results of the quasi-static crush tests are summarized in the table below. The average crush strengths shown represent an average over the flat response section of the stress-strain curves (i.e., neglecting initial rise and densification). The test results show that the average crush strength for 1,200 psi and 2,500 psi material at –20 °F is approximately 7.5% higher than the average crush strength at room temperature. The test results also show that the average crush strength for 1,200 psi and 2,500 psi material at 220 °F is approximately 11% lower than the average crush strength at room temperature. As discussed in the Hexcel CROSS-CORE® product literature, the crush strength is generally 7% to 10% higher at –20 °F and 9% to 11% lower at 220 °F than the crush strength at room temperature. Therefore, the results of the static specimen crush tests confirm the information contained in the product literature.

Core Type (Designation Number)	Nominal Crush Strength (psi)	Test Temp (°F)	Test Direction	Average Crush Strength (psi)	Average Densification Strain (%)	Average Densification Modulus (ksi)
AL-CC-3/16-052-18.0 (A8A00)	1200	-20	T1	1324	65.9	23.6
		70	T1	1239	65.8	26.1
		70	T2	1180	66.4	21.9
		70	W	179	NA	NA
		220	T1	1106	67.8	25.6
AL-CC-1/8-5052-27.0 (A8A06)	2500	-20	T1	2677	59.1	31.6
		70	T1	2417	60.6	20.5
		70	T2	2297	60.0	25.3
		70	W	814	NA	NA
		220	T1	2169	61.8	28.1

2. Confirmatory Static Crush Testing

i. Quasi-Static End Crush Test Results

The maximum crush depth (crosshead displacement) achieved in the eighth-scale quasi-static end crush test was over 5 inches, which is equivalent to a full-scale displacement exceeding 40 inches. This crush depth conservatively exceeds the 14 to 15 inches of crush (approximately 1.8 inches for eighth-scale) required to absorb all of the kinetic energy for the worst-case hot end drop condition. Thus, the available stroke exceeds that needed to assure that bottoming out under the worst-case conditions does not occur.

The resulting end crush force-deflection curve shows excellent agreement with the calculated static end crush force deflection curve. The general magnitude and slope of the test curve and calculated curve for the end crush test are within the expected experimental accuracy over the full range of interest. The only difference observed between the test results and the calculation is the initial response of the impact limiter. The test results show a gradual ramp-up over the first 0.2 inch of crush, whereas the calculated response shows an instantaneous rise. The difference results from the calculation assumption of fully effective backing through the entire crush range, which neglects initial shifting of the honeycomb segments within the impact limiter shell assembly. However, the ramped-up response for the end drop orientation is accounted for by adding a take-up deflection to the calculated acceleration time-history curves for the quarter-scale confirmatory end drop test and the full-scale drop load analysis, although this effect is not significant on the resulting loads. Therefore, it is concluded that the analytical tools, assumptions, and inputs used to develop the static force-deflection curve for the end crush are adequate. The resulting end crush force-deflection curve shows excellent agreement with the calculated static end crush force deflection curve.

ii. Quasi-Static Corner Crush Test Results

The crush depth achieved in the corner crush test was approximately 6 inches, which bounds the anticipated stroke required of the design. The calculated corner crush force-deflection curve was determined using the dimensions and crush strengths of the eighth-scale impact limiter, with the same analytical tools and assumptions applied to the full-scale impact limiter corner drop loads evaluation. The calculated force-deflection curve neglects the contribution of the impact limiter shell assembly, and assumes that all material is effectively backed and contributes to the crush force. The resulting corner crush force-deflection curve shows excellent agreement with the calculated static corner crush force deflection curve. The general magnitude and slope of the test curve and calculated curve for the corner crush test are within the expected experimental accuracy over the full range of interest. Therefore, it is concluded that the analytical tools, assumptions, and inputs used to develop the static force-deflection curve for the corner crush are adequate. The resulting corner crush force-deflection curve shows excellent agreement with the calculated static corner crush force deflection curve.

iii. Quasi-Static Side Crush Test Results

A 600-kip capacity Tinius Olson hydraulic quasi-static testing machine with a 12-inch stroke and 1.2-inch per second maximum displacement rate was used for the test. The static side crush results show that the measured force-deflection curve exceeds the pre-test prediction force-deflection curve for deflections of approximately 2.2 inches and higher. Based on the results of the post-test evaluation using the modified input parameters, it is concluded that the analytical tools, inputs, and modified input parameters accurately predict the static force-deflection response for the static side crush condition.

3. Confirmatory Dynamic Drop Testing

i. 30-Foot End Drop Testing and Results

The post-test measurements of the impact limiter show that the average crush distance resulting from the end drop is 3.5 inches, compared with the pre-test prediction of 3.2 inches. Upon post-test inspection following the end drop test, there was no noticeable failure of the impact limiter shell or the impact limiter attachment hardware. Therefore, the results of the 30-foot end drop test confirm the analytical tools, inputs, and assumptions used to determine the rigid-body response of the transportation package for the HAC end drop.

ii. 30-Foot Side Drop Testing and Results

The post-test measurements of the impact limiters showed that the maximum crush depth resulting from the confirmatory side drop test was 3.3 inches, compared to a pre-test prediction of 3.2 inches. In general, the test results show excellent agreement with the pre-test prediction.

Iii 30-Foot Corner Drop Testing and Results

In general, the test results show excellent agreement with the pre-test predictions. The measured test result exhibits the same general shape, pulse duration, and peak acceleration magnitude as the pre-test prediction. The post-test measurements of the impact limiter show that the crush distance resulting from the corner drop was approximately 6.4 to 6.8 inches, compared with the pre-test prediction range of 6.8 to 7.3 inches. Upon post-test inspection following the corner drop test, there was no noticeable failure of the impact limiter shell or the impact limiter attachment hardware. Therefore, the results of the 30-foot corner drop test confirm the analytical tools, inputs, and assumptions used to determine the rigid-body response of the transportation package for the hypothetical accident conditions corner drop.

iv. 30-Foot Slapdown Drop Testing and Results

In general, the test results show excellent agreement with the pre-test prediction for the primary impact and are slightly higher than the test prediction for the slapdown impact. The post-test measurements of the impact limiter show that the crush distance resulting from the slapdown drop primary impact is 2.9 inches, compared with the pre-test prediction of 4.6 inches. Similarly, the measured crush depth in the secondary impact limiter is approximately 3.0 inches, compared with the pre-test prediction of 3.6 inches. Upon post-test inspection following the slapdown drop test, there was no noticeable failure of the impact limiter shell. During the test, two of the twelve attachment studs located on the crushed side of the impact limiter on the secondary impact end failed. However, the impact limiter remained attached to the test fixture throughout the duration of the test and all other attachment studs remained intact. Thus, the impact limiter attachment studs performed their intended function during the quarter-scale slapdown drop test.

10. Model No. TN-68 Transport Package (Docket No. 71-9293)

The information below was obtained from Section 2.10.9 in Transnuclear Inc.'s application, dated May 19, 1999 (see ADAMS Accession Nos. ML063340727 and ML063340703).

A. Tests performed

A series of dynamic tests were performed on one-third scale models of the TN-68 impact limiters. The tests were performed to evaluate the effect of the 30-foot free drop hypothetical accident defined 10 CFR 71.73(c)(1). The objectives of the test program were to:

- Demonstrate that the inertia G values and forces calculated for the TN-68 package and basket are acceptable.
- Verify the adequacy of the impact limiter tie rods and bolts.
- Demonstrate the adequacy of the impact limiter enclosure.

The drop configurations examined are the 15^o slap down, 90^o end drop, 0^o side drop, and 90^o end drop for puncture.

B. Description of the methods or analyses used in tests

Accelerometers (12 possible in total) were mounted to brackets around the exterior of the test body at 0^o, 90^o, 180^o, and 270^o orientations at the approximate center of gravity location and adjacent to each impact limiter. An inclinometer will be placed on the test body to measure the initial angle (± 1) of its longitudinal axis with respect to the target (i.e., impact surface). Data were collected by accelerometers capable of measuring data at a minimum frequency response of 6,000 Hz per channel.

C. Results

The results of the 15º slap down showed that the adequacy of the attachment design of the impact limiters, and that the impact limiters did not bottom out and the trunnions would not impact the target. The 90º end drop resulted in both impact limiters remaining intact and crush values comparing well to predicted values. The 0º side drop indicated good correlation between measured and predicted crush depths for the side drop event. 90º end drop for puncture resulted in impact limiters staying attached to the package. In all, measured and predicted performance agreed very well.

11. Model No. NUHOMS®-MP197, NUHOMS®-MP197HB (Docket No. 71-9302)

The information below was obtained from Section 2.10.9, in Transnuclear Inc.'s application, dated May 2, 2001, pre-application meeting slides, and Appendix A.2.13.8.1 (see ADAMS Accession Nos. ML063190444, ML090420165, and ML112640444).

A. Tests performed

One-third-scale tests were performed for the MP197 package to evaluate the effect of the 9 m free drop hypothetical accident defined in 10 CFR 71.73(c)(1). The unyielding drop surface consisted of a 2-inch thick steel plate secured to the surface of a concrete pad. The test model was a solid steel third-scale mockup of the package body with impact limiter. The steel body was designed to scale the weight and the center of gravity of the package.

For the MP197 package, the objectives of the package impact limiter tests were to:

- demonstrate that the inertia g values and forces used in the analyses are conservative,
- demonstrate that the extent of the crush depths are acceptable (i.e., the neutron shield does not impact the target), and
- demonstrate the adequacy of the impact limiter enclosures.

The tests performed consisted of the following:

- A 0° side drop because this orientation generates the highest transverse acceleration as well as significant deformation. The 0° side drop also provides a reasonable estimate of the likelihood of the neutron shield impacting the target.
- A 20° slap down drop because the 20° orientation puts the highest load on the impact limiter attachment bolts, and stainless steel shell.
- The 90° end drop orientation was chosen because it causes the highest axial deceleration.
- The 40-inch drop onto a 1/3 scale 6-inch diameter puncture bar was performed in accordance with 10 CFR 71.73(c)(3).

Test Number	Drop Orientation	Drop Height	Impact Limiter Number	Location of impact limiter
1	0° side drop	30 ft	1 2	Top Bottom
2	20° slap down	30 ft	3 2	Top, 2nd impact Bottom, 1st impact
3	90° end drop	30 ft	3 4	Top Bottom-impact end
4	90° end drop	40 in	3 4	Top Bottom- puncture end

B. Description of the methods or analyses used in tests

An inclinometer was placed on the test body to measure the initial angle (±1°) of its axis with respect to the drop pad (impact surface). The impact surface was an unyielding horizontal surface, weighing more than 250,000 lb. versus 9,750 lb. for the weight of the 1/3 scale dummy.

Accelerometers were used to measure the inertial g load during impact for the three 30-foot drops performed. At least 10 accelerometers were used during each 30-foot drop.

Four, third-scale impact limiters were constructed for the drop testing.

The following data were measured and recorded before, during and after each drop test:

1. Prior to each drop test

   - Torque of the impact limiter bolts,
   - Impact limiter dimensions,
   - Height from test article to drop pad,
   - Angular orientation of the test article to the impact surface, and
   - Atmospheric condition data (i.e., ambient temperature, wind speed, immediately and prior to the release of the test article).

2. During each drop test

   - Test article behavior on videotape,
   - Date and time of test,
   - Observations of damage or unexpected behavior of the test article, and
   - Impact acceleration time histories and frequency responses (excluding the puncture drop test).

3. Following each drop test:

- Observations of the damage to the test article on features other than the limiters (i.e., attachment bolts).
- Measurements of deformation to each impact limiter to fully describe the extent of the damage, including:
    - Depth of internal and external crush of the impact limiter
    - Overall thickness of each impact limiter after each test.
    - Dimensions of impact footprint

C. Test Results

The four drop tests were performed without any unusual observations. The impact limiters contained the wood during the drop tests, and none of the attachment bolts failed.

No openings in the stainless steel impact limiter shell were evident and no welds in the shell failed.

The puncture bar sheared a circular section of the outer shell of the bottom impact limiter. No other sections of the impact limiter were damaged and no welds on the impact limiter shell were broken. The puncture bar did not penetrate the inner stainless steel shell of the impact limiter or the aluminum thermal shield. Both impact limiters remained attached to the package during the puncture drop event and no additional impact limiter attachment bolts were damaged.

The predicted performance of the impact limiters in terms of decelerations and crush depths agrees well with the measured data.

Results of the Third-scale benchmark LS-DYNA drop test vs. analysis

Test Conditions	Parameter	Drop Test Results	LS-DYNA Analysis Results
90º End Drop (-20 ºF)	Acceleration	65g	65.1g
	Impact Duration	0.010 sec.	0.012 sec.
	Wood Crush Depth	2.5”	2.8”
0° Side Drop (Room Temperature)	Acceleration	61g	65.6g
	Impact Duration	0.012 sec.	0.013 sec.
	Wood Crush Depth	2.69”-2.75”	2.7”-2.9”
20° Slap Down 1st Impact (Room Temperature)	Acceleration at Center of Package	17g	20.8g
	Acceleration at Bottom of Package	36g	40.1g
	Impact Duration	0.016 sec.	0.018 sec.
	Wood Crush Depth Bottom Limiter	4.92”	4.9”
20° Slap Down 2nd Impact (Room Temperature)	Acceleration at Center of Package	32g	36.3g
	Acceleration at Top of Package	73g	72.2g
	Impact Duration	0.009 sec.	0.010 sec.
	Wood Crush Depth Upper Limiter	4.72”	2.8”

Calculated decelerations (maximum value and time duration) are close to or bound the measured drop test decelerations. It is therefore concluded that the methodology, material models, and material properties are properly benchmarked.

The results of the tests demonstrate that:

- The crush depths do not result in lockup of the wood in the impact limiters,
- The crush depths for the 0° side drop case would not result in the neutron shield impacting the target,
- The predicted performance of the impact limiters in terms of decelerations and crush depths agrees well with the measured data,
- The impact limiter enclosure is structurally adequate in that it successfully confines the wood inside the steel shell,

- The impact limiter attachment design is structurally adequate in that the attachment bolts hold the impact limiters on the ends of the package during all drop orientations, and
- The effects of low temperature (-20 °F) on the crush strength of the impact limiters is minor, and is bounded by the conservative accelerations and forces used in the analysis.

A 40-inch drop onto a scaled 6-inch diameter puncture bar, as per 10 CFR 71.73(c)(3), does not significantly destroy the impact limiter. The impact limiter and attachment remain firmly secured to the package and the impact limiter wood is confined.

12. Model No. TN-40 (Docket No. 71-9313)

The information below was obtained from Section 2.10.9 in AREVA's application dated August 31, 2006 (see ADAMS Accession No. ML070750136).

A. Tests performed

Tests performed on a third-scale impact limiters and a dummy package included three 30' drops (side drop, slapdown and end drop) and one 40" drop onto a puncture pin. Accelerometers were placed on the dummy package.

B. Description of the methods or analyses used in tests

The test goals were:

1. validation of calculated acceleration values,

2. demonstration that the crush depths are acceptable,

3. demonstration of the adequacy of the impact limiter enclosure and attachment design,

4. evaluation of the effects of low temperature (-20 °F) on dynamic performance of the impact limiters, and

5. evaluation of the effects (puncture depth and shell damage) of a 40-inch drop onto a scaled 6-inch diameter puncture bar on a previously crushed impact limiter.

The side drop orientation was chosen to generate the highest transverse acceleration as well as a significant deformation.

The slap down orientation puts the highest load on the impact limiter attachment bolts, tie rods, and stainless steel shell.

The end drop orientation causes the highest axial acceleration, while the pin drop orientation was chosen because it assures that the puncture impact absorbs 100% of the drop energy.

The test package consisted of a third-scale model of the TN-40 transport package with impact limiters on each end. The impact limiters are attached to each other by thirteen, 0.5-inch-diameter tie rods, snug tight, and to the package with four, 0.5-inch bolts. The test package weighs approximately 10,100 lb. and has maximum dimensions of approximately 87.0 inches long by 48.0 inches in diameter.

Lifting and dropping the test article was accomplished using a mobile crane. A quick release mechanism was used to initiate the drop. It consisted of a hydraulic piston that loaded a bolt to failure releasing a shackle supporting the test article via a rigging system.

An inclinometer was used to measure the initial angle (± 1°) of the test body longitudinal axis with respect to the drop pad (i.e., impact surface). A measured line, 30 feet long (+ 3.0, -0.0 inches), was attached to the lowest point on the test package in order to assure the proper drop height.

The impact surface was a 2-inch thick steel plate attached to a concrete block weighing approximately 250,000 lb. resting on bedrock. This configuration can be considered as an essentially unyielding surface.

A puncture bar made of cold-rolled steel was welded to the impact surface for the 40 inch puncture drop. The pin was scaled to match the test article resulting in a 2-inch-diameter pin with the upper end edges rounded to a radius of approximately 0.083 inches.

Accelerometers were used to measure the impact *g* load for all drops performed.

Twelve PCB Piezotronics 353B18 accelerometers were attached to aluminum blocks that were bolted to the test body at 0°, 90°, 180°, and 270° orientations at three elevations.

Drop Test Sequence

Test Number	Drop Orientation	Drop Height	Impact Limiter Number	Impact Sequence	Comments
1	0° Side Drop	30 feet	1	-	Limiters 1 and 2 installed.
			2	-	
2	64° CG Over Corner drop	30 feet	1	1st	The 1 and 2 impact limiters were rotated 180° so the undamaged portion of the impact limiters face the pad.
			2	2nd	
3	0° Side Drop (2nd test)	30 feet	1	-	The test body and limiters were rotated 90° so that an undamaged portion of the impact limiters faced the pad.
			2	-	
4	20° Slap Down	30 feet	3	1st	Limiters 1 and 2 were removed and replaced with limiters 3 and 4.
			4	2nd	
5	90° End Drop	30 feet	3	1st	Limiter 3 was removed and chilled at –20 °F for 48 hours before being re-installed on the test body.
			4	-	
6	90° End Drop (Puncture Test)	40 inches	3	1st	Drop onto 2 inch diameter puncture bar.
			4	-	
7	90° End Drop (2nd test)	30 feet	2	1st	Limiters 2 and 4 were used. The center portion of limiter 2 was relatively undamaged by previous drops and thus provided a useable crush volume.
			4	-	

The following data were measured and recorded before, during and after each drop test listed in the table above.

1. Prior to each drop test

   - Torque of the impact limiter bolts.
   - Impact limiter dimensions.
   - Height from test article to drop pad.
   - Angular orientation of the test article to the impact surface.
   - Atmospheric condition data (i.e., ambient temperature, wind speed, immediately and prior to the release of the test article).

2. During each drop test

- Test article behavior on videotape.
- Date and time of test.
- Observations of damage or unexpected behavior of the test article.
- Impact acceleration time histories (excluding the puncture drop test).

3. Following each drop test

- Observations of the damage to the test article on features other than the limiters (i.e., attachment bolts).
- Measurements of deformation to each impact limiter to fully describe the extent of the damage include depth of internal and external crush of the impact limiter, overall thickness of each impact limiter after each test, and dimensions of impact footprint.

C. Test Results

The performance of the test program allowed to:

- Verify the impact limiters are not dislodged from the package as a result of the drop.
- Demonstrate the effectiveness of the impact limiter tie rods, attachment bolts, and stainless steel covers.
- Provide data on the deformation of the impact limiters due to the drop.
- Provide data on the acceleration experienced by the test package during impact.
- Provide data on the impact limiter damage caused by a 40-inch drop on a 2 in. diameter puncture bar.

As an example, the following table shows the maximum transverse accelerations measured by the accelerometers during the second 0° side drop (converted to full scale), as well as the maximum acceleration predicted by a computer program.

Accelerometer Location	Measured Transverse Acceleration (*g*s) (converted to full scale)	Average Measured Transverse Acceleration (*g*s)	Predicted Maximum Transverse Acceleration (gs) (Appendix 2.10.8 in SAR)
Top (2)	68	57	51
Center of Gravity	50		
Bottom (10)	55		

The following table summarizes the measured and predicted crush depths for the bottom impact limiter. A spring back of 0.50 inches is assumed (based on previous crush tests).

	Impact Limiter Number 1	Impact Limiter Number 2
Maximum Inside Crush Depth (in.)	1.44	1.50
Maximum Outside Crush Depth (in.)	0.75	0.75
Spring Back (in.)	0.50	0.50
Total Crush Depth (in.)	2.69	2.75
Predicted Crush Depth x 1/3 (in.)	4.52	

From the above table it can be seen that the measured crush depths are slightly less that those predicted by the computer program. It should also be noted that neither the neutron shield nor the trunnions would contact the impact surface during the impact. The distance between the outer diameter of the neutron shield and the outside diameter of the impact limiter is 7.16 in. Therefore, a clearance of 7.16 - 2.75 = 4.41 in. would remain between the impact surface and the neutron shield, based on the measured crush depth. Similarly, a distance of 3.84 in. would remain between a trunnion and the impact surface.

Both impact limiters remained attached to the package during and after the side drop impact. All of the tie rods and tie rod brackets remained intact, thus preventing separation of the impact limiters from the package. In addition, the impact limiter attachment bolts remained in place, in spite of damage to two of the eight bolting brackets. Only a single small opening in the stainless steel shell of each of the impact limiters was evident. Both openings consisted of a tear along the weld between two of the outer flat plates of the impact limiter. The tears were roughly 4 inches long. Despite these tears, all impact limiter wood remained completely confined within the shell.

The results of the tests demonstrate that:

- The loadings used in the basket and fuel rod cladding structural analyses bound the dynamic measured data.
- Based on the applied loading and factor of safety, the package can withstand much higher loads than those resulting from the dynamic measured data.
- The crush depths do not result in lockup of the wood in the limiters.
- The crush depths for all the drop cases would not result in the neutron shield or trunnions impacting the target.
- The impact limiter enclosure is structurally adequate in that it successfully confines the wood inside the steel shell.
- The impact limiter attachment design is structurally adequate in that the impact limiters remain on the ends of the test dummy during and after all drop orientations.
- The effect of low temperature (-20 °F) on the impact limiter wood is not available due to lost test data. However, based on a similar design (TN-

68) chilling the impact limiter wood (-20 °F) will increase the g load roughly by 15% to 20%.

- An increase of 20% in the accelerations for both axial and transverse directions is acceptable based on applied loading and resulting factors of safety shown in the analyses.
- A 40-inch drop onto a scaled 6-inch-diameter puncture bar, as required by 10 CFR 71.73(c)(3), does not significantly damage the impact limiter, nor are there any indications of damage to the test dummy.
- The impact limiters remain firmly secured to the test dummy, and the impact limiter wood is confined.

13. Model No. HI-STAR 180 (Docket No. 71-9325)

The information below was obtained from Section 2.7 in the Holtec International consolidated application dated May 29, 2009 (see ADAMS Accession No. ML14114A178).

A. Tests performed

No tests were specifically performed for the HI-STAR 180. For casks in this list that note "no tests," 10 CFR 71.41 permits the use of analyses to demonstrate compliance with 10 CFR 71.73 test requirements.

B. Description of the methods or analyses used in tests

The applicant derived an LS-DYNA model of the HI-STAR 180 impact limiters consistent with the previously HI-STAR 100 benchmarked model. The HI-STAR 100 benchmarked analysis was revised only to properly account for the compressive and shear strength properties of the honeycomb material in three directions.

The structural qualification of the HI-STAR 180 package relies only on transient LS-DYNA analyses and static ANSYS analyses. LS-DYNA is used to predict peak rigid body decelerations and impact limiter crush behavior. ANSYS is used to determine stress/strain levels in the package components by applying peak decelerations from LS-DYNA. Conservative upper and lower bound strength properties were analyzed where physical test data was not available for a particular crush/shear direction.

C. Test Results

No tests were performed for the HI-STAR 180.

14. Model No. HI-STAR 60 (Docket No. 71-9336)

The information below was obtained from Section 2.7 in the Holtec International consolidated application dated May 29, 2009 (see ADAMS Accession No. ML091540454).

A. Tests performed

No tests were performed specifically for the HI-STAR 60.

B. Description of the methods or analyses used in tests

The certification basis for the HI-STAR 60 was predicated on analysis only and relied on HI-STAR 100 test data solely to the analytical modeling capabilities with respect to rigid body dynamics. This preliminary analysis was designated as a benchmark study and consisted of simulation of HI-STAR 100 quarter-scale drop tests conducted by the applicant on the HI-STAR 100. The benchmarking of the HI-STAR 100 drop test provides additional assurance that the deceleration and gross deformation results obtained from the HI-STAR 60 evaluation are reasonably accurate and conservative.

C. Test Results

No tests were performed specifically for the HI-STAR 60.

15. Model No. BEA Research Reactor (BRR) Package (Docket No. 71-9341)

The information below was obtained from Section 2.12.2 and 2.1 in AREVA Federal Services, LLC, consolidated application dated May 29, 2009 (see ADAMS Accession No. ML112640462).

A. Tests performed

A series of free drop tests were performed on a half-scale model of the BRR package. The SAR presents test results, including time-history deceleration package body response traces and photograph records of deformations and damaged attachments of the impact limiters, for the initial series of three, 30-ft free drop tests and five puncture drop tests. The specific drop tests were:

- 30-foot end drop
- 40-inch puncture test oblique drop onto thicker end plate
- 30-foot slapdown drop, with the longitudinal axis 15 degrees from vertical
- 30-foot drop with CG-over-corner
- 40-inch puncture where the puncture bar strikes the inside edge of the slapdown primary-end damage from 2nd drop test, above,
- 40-inch puncture where the puncture bar impacts the end of the damage impact limiter from 2nd drop test, above,
- 40-inch puncture test with CG-over-corner drop, with impact on the thinner conical shell material, and
- 40-inch puncture test with the puncture bar striking the center of the slapdown secondary damage.

B. Description of the methods or analyses used in tests

The test articles were chilled generally between -10 °F and -20 °F. The impact limiter performance is demonstrated by tests of the half-scale, prototypical units and a dummy package body.

The primary means of recording the results of the tests was physical measurements and observations of the test packages (including impact limiters) before and after testing. Each free drop impact was recorded using accelerometers.

C. Test Results

Data obtained from the tests consist of both qualitative information with respect to observations about the package and the limiter and quantitative data obtained from the recorders. The data for each test include measured impact limiter deformation, strain gauge data and stress calculations (for the end drop and side drop only), and observations of the package and attachments. The strain gauge data were only presented for the end drop and the side drop since the loads developed in those tests are the most severe from an overall structural consideration. The end drop corresponds to the maximum axial loading condition, while the side drop developed the maximum lateral loading on the overall package body.

Five puncture drops were performed on the half-scale certification test unit to demonstrate structural adequacy of the package. The tests showed that the puncture bar would neither penetrate beyond the impact limiter shell located on the flat bottom nor create a significant exposure of foam adjacent to the package to the containment seal. The impact limiters would remain attached to the package ends. Also shown in one of the tests was that the puncture bar would not enter the impact limiter through a side impact on the limiter shell and rip open a large area. For the package thermal evaluation, the tests provided bounding impact limiter damaged configurations for fire event modeling consideration.

The tests demonstrated that the impact limiters were capable of limiting the package body deceleration to the design basis of 120 g applicable to all package drop orientations. The application notes that, although the impact limiters were damaged with some exposure of the foam, they remained attached to the package body. Also noted is that the damaged configuration is included in the thermal model for the HAC fire event analysis.

Therefore, the value of 120 g was utilized as the bounding value to calculate and evaluate package body structural performance for all drop orientations for all the tests.

16. Model No. TN-LC, (Docket No. 71-9358)

The information below was obtained from Sections 2.6 and 2.7 in AREVA Inc., consolidated application dated November 30, 2012 (see ADAMS Accession Nos. ML12340A309 and ML12340A310).

A. Tests performed

No tests were performed specifically for the TN-LC.

B. Description of the methods or analyses used in tests

The applicant demonstrates the structural capabilities of the package by analyses using ANSYS code. A third-scale model drop testing of a structurally similar packaging is used (Model No. NUHOMS MP197 transportation package), to benchmark the impact limiter finite element analysis model, which was subsequently adapted, for determining bounding deceleration g-loads for the package structural evaluation by analysis.

C. Test Results

No tests were performed specifically for the TN-LC.

17. HI-STAR 180D (Docket No. 71-9367)

The information below was obtained from the NRC staff's safety evaluation report dated August 5, 2015 (see ADAMS Package Accession No. ML14211A015), that used Holtec International's SAR dated July 16, 2014 (see ADAMS Package Accession No. ML14203A285), as its basis.

A. Tests performed

There were no tests performed specifically for the HI-STAR 180D.

B. Description of the methods or analyses used in tests

The licensing basis for the Model No. HI-STAR 180D package structural performance is predicated on analytical modeling rather than experimental testing. The LS-DYNA modeling approach had been determined to be adequately benchmarked for certifying the Model No. HI-STAR 100 package in computing cask rigid body decelerations for the free-drop accident conditions.

C. Test Results

There were no tests performed specifically for the HI-STAR 180D.