Multi-Wall Cask Advantages with Quarter-Scale Model Drop Test Results for the NAC-STC Storable Transport Cask

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Introduction

Engineers are challenged with a multitude of variables influencing their success in achieving optimum disposition of commercially generated spent nuclear fuel. Safety is the most important objective in obtaining universal acceptance. However, following this central theme, design considerations become complicated by a web of interdependent parameters. Design variables are evaluated as functional components of the design process and are assessed with respect to current industry application and regulatory acceptance.

Public safety issues related to the disposition of nuclear waste are the designer's greatest concern. Public acceptance is critical for utilities to assure control of cost and schedule of any activity affected by licensing and public review. In addition, government regulatory organizations are chartered with the responsibility to protect the public and, therefore, only consider fully engineered systems having documented qualification records.

This design process and focus have formed the bases of the dual-purpose NAC-STC (Storable Transport Cask), currently under license review by the USNRC.

Physical drop test results for a quarter-scale model multi-wall cask are presented for the 9 meter end, side and oblique drops with impact limiters, and for the 1 meter side and closure lid pin puncture drops. Lessons learned and final cask test qualification are presented.

Advantages of Multi-Wall Construction

Multi-wall construction adopts the nuclear industry theme of defense-in-depth and provides flexibility to the designer in his selection of materials to achieve optimum performance. Examples of enhanced design through material options are demonstrated in meeting shielding and strength objectives.

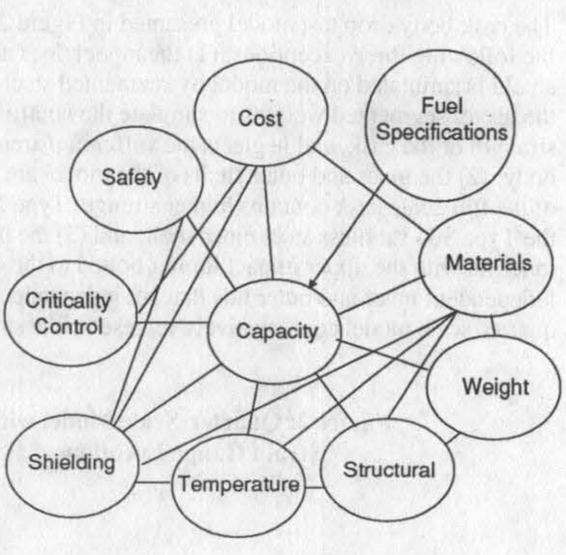
Continuing with safety as the central theme, the designer steps through his task to optimize the disposition of spent fuel and recognizes that increasing capacity and reducing material handling cycles will reduce worker exposure (ALARA) and the possibility of an off-normal or accident event. Incorporating these considerations into the design process leads the designer to maximize capacity in a dual-purpose storable transport cask.

Multi-wall construction offers fabrication advantages over monolithic designs. Process and power system engineers and fabricators have been designing and manufacturing thin-walled vessels for well over a century. Technology and material handling equipment exist throughout the world for the manufacture of thin-walled vessels.

Figure 1 presents a web of parameters that the cask designer must work with to reach the objective. The characteristics of the design basis fuel drive the design process. NAC has addressed these issues in the design of numerous casks over the past few years. Table 1 summarizes the different fuel types and resulting cask capacities developed in response to different project activities and market opportunities. Each design has adopted multi-wall construction, a stacked aluminum disk basket, borated steel or aluminum for criticality control, and a solid neutron shield.

Experience incorporated into this base configuration focusing first on safety followed by the economics of capacity and regulatory issues included: 1) multi-wall construction using an austenitic stainless steel for the inner and outer shell and chemical lead for the enclosed gamma shield addressed the issues of brittle fracture, containment strength, shielding, and weight; 2) use of the stacked aluminum disk basket addressed design efficiencies in temperature, weight, and strength; and 3) use of borated steel or aluminum for criticality control addressed maximizing capacity relative to fuel specification, temperature, and weight.

Figure 1: Cask Design Variables



Regulatory acceptance guidelines provide increased safety margin by requiring criticality control ($k_{eff} \leq 0.95$) based on 75% of the minimum design boron concentration. The use of aluminum for the fuel basket effectively addressed temperature and weight and has led to adopting conservative structural criteria which increased the safety margin (demonstrated in drop test presented below). These issues and the multitude of dependent variables have been incorporated into the designs summarized in Table 1 and have formed the bases for the NAC-STC dual purpose cask presently in licensing review with the USNRC. The adequacy of the NAC-STC cask structural design has been demonstrated through scale model drop testing.

Scale Model Test Program for the NAC-STC

Scale model testing is an accurate means of confirming structural performance of a proposed design and was employed as confirmatory support of the analysis and licensing effort for the design qualification of the NAC-STC cask. Test results confirm analyses and provide additional confidence that the cask design provides for the safe transport of spent nuclear fuel. The scale model test program included quarter-scale model drop tests and eighth-scale model impact limiter quasi-static compression tests to verify: (1) containment function, (2) impact limiter performance, (3) reaction to dynamic impact loadings, and (4) pin puncture resistance.

Table 1: Cask Design Statistics

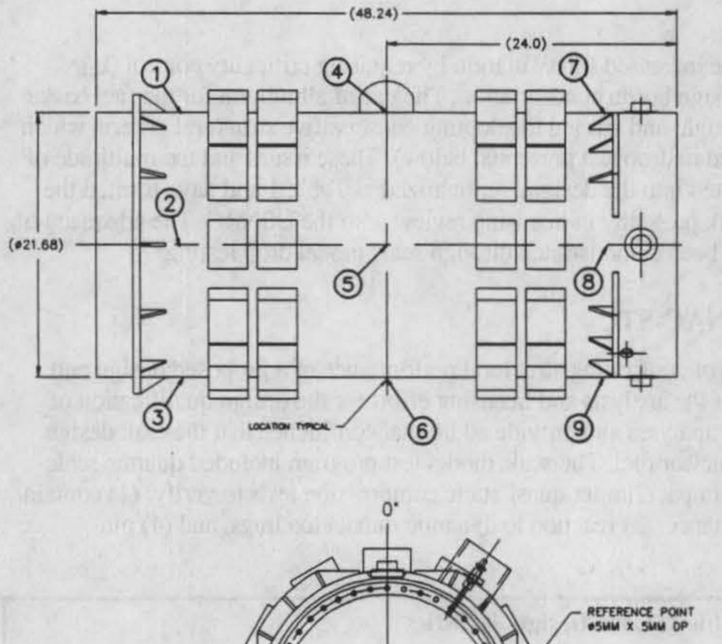
Fuel Type	Enrichment W%	Burnup MWD/MTU	Cooltime Years	Capacity No. of Assys	Cavity Length/Dia. inch/inch
PWR	4.2	40000	5	26	165/71
PWR	4.0	40000	4	21	171/66
PWR	3.5*	40000	10	37	165/71
PWR	3.3	35000	10	24	181/67
BWR	3.4	35000	10	69	181/67
VVER-440	3.6	38000	5	85	128/71
VVER-1000	3.3	27600	5	27	181/67

*Storage with boron credit

Model Component Descriptions

The cask body drop test model presented in Figure 2 is a quarter-scale replica of the NAC-STC cask with the following three exceptions: (1) the model does not include the neutron shield; the weight of the neutron shield is simulated on the model by segmented steel bars welded to the exterior surface of the outer shell; the use of segmented weights to simulate the neutron shield prevents the weights from contributing to the strength of the cask, and neglects the stiffening/strengthening effect of the neutron shield shell on the cask body; (2) the inner and outer shells of the model are entirely Type 304 stainless steel, while the inner shell of the full-scale cask contains higher strength Type XM-19 stainless steel inner shell rings at each end of the Type 304 stainless steel inner shell; and (3) the model includes a recessed outer lid that is bolted to the inner lid with the upper impact limiter bolted to the outer lid. The final design of the NAC-STC includes independent inner and outer lids that are independently bolted to the top forging of the cask body. The quarter-scale model conservatively represents the structural characteristics of the closure region of the full-scale cask and the influence of the neutron shield and inner shell.

Figure 2: Quarter-Scale Model with Strain Gauge Locations



Based on the scale relationship when the dimensions are scaled, the weight of the model cask is the weight of the full-scale cask divided by the "scale" to the third power; material properties and drop heights remain the same as for the full-scale cask. Use of the quarter-scale methodology permits the materials employed in the licensed full-scale cask design to be used in the scale model testing and provides for direct test data representation of the full-scale cask.

The model was fabricated of Type 304 stainless steel inner and outer shells, top and bottom forgings, and inner closure lid; the port covers and the outer closure lid are Type 17-4PH stainless steel; the gamma shield was chemical lead. The impact limiters were modified twice during the test program when test results showed that they were not performing as intended. Specific cask body tests which were influenced by these impact limiter modifications were reperformed.

The model upper impact limiter has four scaled cutouts for the lifting trunnions. The model impact limiters are attached to the end surfaces of the cask model with threaded retaining rods and nuts through the ends of the limiters. The model fuel load consisted of 26 steel bars simulating the scaled size and weight of the tubes and fuel assemblies. These "dummy" fuel assemblies fit within an exact quarter-scale model of the fuel basket.

Scale Model Impact Limiter Compression Tests

In addition to the quarter-scale drop tests, quasi-static compression tests were performed to simulate an end impact, a corner impact, and a side impact using eighth-scale model impact limiters. The eighth-scale models documented in the testing program were also identical to the full-scale design. As mentioned above, the design of the NAC-STC impact limiter was revised twice during the quarter-scale drop test program.

The eighth-scale model impact limiter compression tests demonstrated that:

1) The NAC-STC impact limiter, as designed, limits deceleration loads to those used in the design analyses, and

2) The crush stroke does not exceed the acceptance criteria (the cask body does not come into contact with the impact plane).

Figure 3 presents data typical of the results obtained for the three specific orientations tested. Excellent agreement was obtained between the eighth-scale model quasi-static tests, the analytical evaluation of the limiter response, and the quarter-scale model drop tests. Table 2 presents a comparison of the full scale deceleration values for the 9 meter drop impact.

Figure 3: Quasi-Static Force-Deformation Curve
Eighth-Scale Model Compression Test

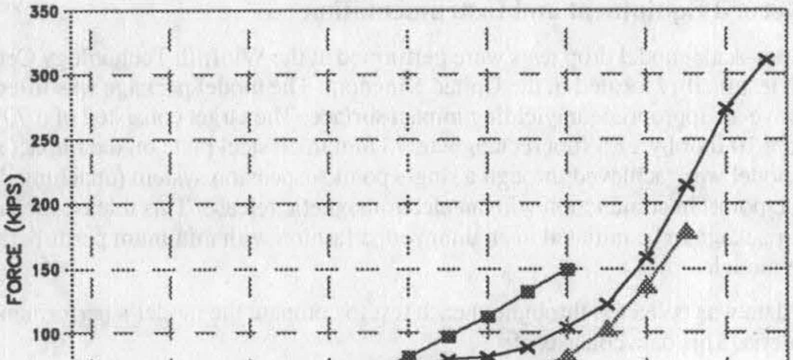


Table 2: Comparison of Full-Scale Deceleration Values for 30-Foot Drop Impacts

	30-Foot Drop Deceleration (g)				
Drop Orientation	RBCUBED[1] (Cold)	RBCUBED[1] (Hot)	Quasi-Static[2] Test	Drop[3] Test	Design[4]
End (0°)	44.6	56.1	54.8	55.6	56.1
Corner (24°)	38.3	44.2	32.6	29.2	55.0
Oblique (75°)	34.0	26.7	-	53.8	55.0
Side (90°)	54.1	49.7	45.6	51.3	55.0

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1. Impact g-loads calculated by RBCUBED (NAC's proprietary Impact Limiter Analysis Program).
2. Extrapolated from eighth-scale model impact limiter quasi-static compression tests.
3. Extrapolated from quarter-scale model 30-foot drop test results.
4. Design g-load values used in the cask and fuel basket analyses.

Acceptance Criteria for Quarter-Scale Model Drop Tests

The acceptance criteria for the quarter-scale model drop test is that the containment boundary be maintained and that the fuel remain in a subcritical configuration. For the cask body this requires that:

1) Permanent deformation must not be observed in the metrology results for the lids and their mating sealing surfaces.
2) Strains in the cask body must not exceed the 0.2 percent offset for determining material yield strength.
3) The pressure test must indicate that there was no loss of cavity pressure during the test.
4) The fuel basket must not exhibit permanent deformation after the tests.
5) The inner and outer lid bolts must not exhibit permanent deformation after the tests.

The function of the impact limiter is to limit the deceleration of the cask body and contents during a cask drop event. Therefore, the impact limiter acceptance criteria require that:

1) The crush stroke be limited to prevent an impact of the cask body on the impact surface.
2) The accelerations be limited to those used in the design analyses (also verified by the static compression tests).
3) The impact limiters remain attached to the cask body and in position after the impact event.

Drop Test Record Equipment and Instrumentation

All of the quarter-scale model drop tests were performed at the Winfrith Technology Centre's IAEA approved drop test facility located in the United Kingdom. The model package was lifted to a drop height of 9 meters above an appropriate unyielding impact surface. The target consisted of a 70 metric ton concrete mass and a 10 foot by 12.5 foot rectangular, 75 mm thick steel plate on the impact surface. Lifting and dropping the model were achieved through a single point suspension system (attaching the cask to the crane hook at a single point) in conjunction with an electromagnetic release. This release mechanism allowed the free fall of the package to be initiated in an unimpeded fashion with minimum perturbation to the angular position of the model.

A set of basic data was collected throughout each test to compare the model's performance to the acceptance criteria. This data consists of:

1) Metrology data - collected to assess permanent deformation of the cask body, including the closure lids and lid seating area. Fuel basket deformation data are used to determine the response of the basket during the drop. Measurements before and after the tests were performed in a metrology lab using instrumentation capable of readings to +/- 0.001 inch.
2) Pressure and temperature data - collected to assess the performance of the cask primary containment boundary and to correlate pressure changes with an increase or decrease in temperature while the test is conducted.

   The cask cavity was pressurized to 30 (+2/-0) psi through a pressure port located near the cask midpoint (for model only; not in full-scale design). 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 thermocouples attached to the cask exterior near the pressure port used to pressurize the cavity.
3) Strain data - collected to determine the maximum amount of strain that occurs in the cask body.

   Strain time - histories were recorded at the locations shown in Figure 2 for each of the 30-foot drops. Ninety-degree tee-rosettes 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, allowing the axial and hoop strains to be monitored. Later in the testing program, the 90-degree tee-rosettes were exchanged at two of the locations for rosettes with three gauges at 45-degree orientations, which 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 were accurately recorded.

Real time recording was accomplished by a system of strain amplifiers, signal conditioners and a magnetic recording unit to store the data. Strain gauge data were taken only for the 30-foot drop tests.

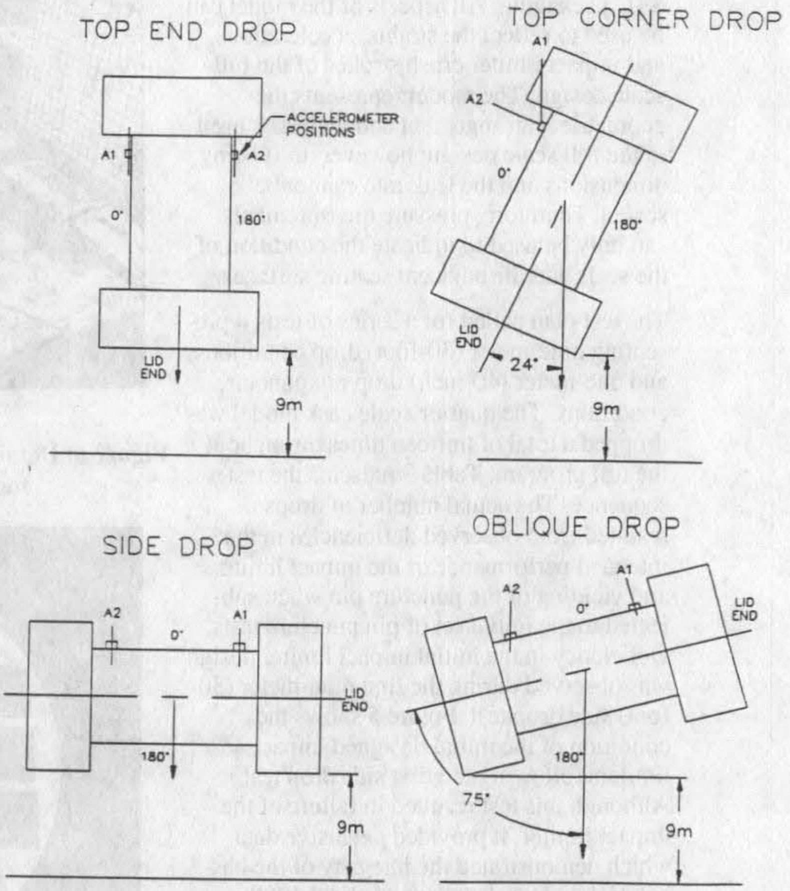
4) Acceleration data - collected to determine the maximum accelerations to which the cask was subjected.

   Two single-axis accelerometers were mounted on the cask body for each of the 30-foot drop tests. The location and orientation of the accelerometers for each test are shown in Figure 4. The accelerometer orientation directions were altered for each individual test to ensure that the vertical deceleration was measured.

   Each accelerometer could measure accelerations up to 20,000 g with an accuracy of 1 percent per 2,000 g. For this application, in which an acceleration level of 300 g was expected, the accuracy was +/- 0.5 g. The frequency response of the accelerometer was from 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 the impact velocities. Acceleration data were taken only for the 30-foot drop tests.

Figure 4: Accelerometer Locations Quarter-Scale Model



5) Impact limiter deformation data - collected 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.

   After each test, the limiters were inspected to determine the amount of deformation that had occurred and to determine the condition of the attachment rods and nuts. Photographs of the deformed limiters were taken to record the post-test condition of the limiters.

6) 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.

   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 slapdown drop, one camera was positioned to capture the overall motion of the cask at 500 frames/sec while the other camera was set to obtain a close-up view of the crushing of the impact limiter at 1000 frames/sec.

Quarter-Scale Model Drop Test Results

The objective of the quarter-scale model drop tests was to confirm the design of the NAC-STC packaging. All aspects of the model can be used to reflect the strains, accelerations, and impact limiter crush strokes of the full-scale design. 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, pressure measurements can only be used to indicate the condition of the seals and the adjacent seating surfaces.

Figure 5: General View After Initial Side Impact

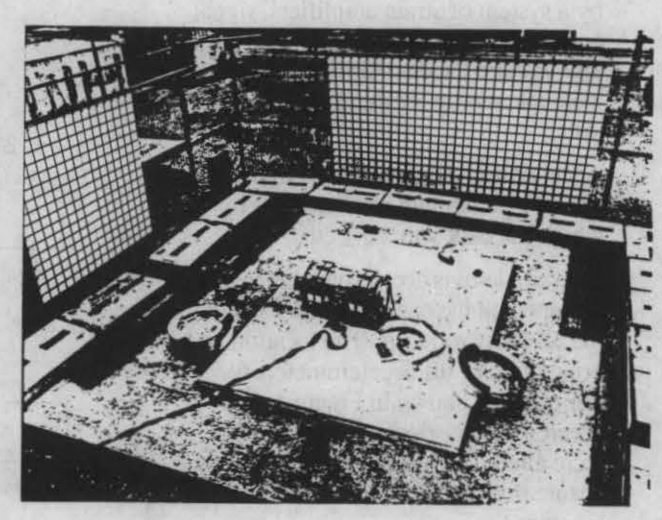
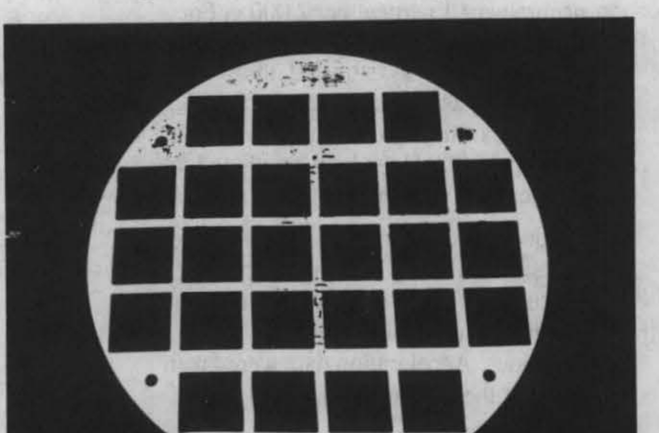


Figure 6: Detail of Distortion to Basket Disc No. 6 Resulting From the Initial Side Impact



The test plan called for a series of tests representing nine-meter (30-foot) drop conditions and one-meter (40-inch) drop pin puncture conditions. The quarter-scale cask model was dropped a total of thirteen times throughout the test program. Table 3 presents the test sequence. The actual number of drops resulted from observed deficiencies in the intended performance of the impact limiters and yielding of the puncture pin when subjected to the initial set of pin puncture tests. Deficiency in the initial impact limiter design was observed during the first nine-meter (30-foot) side drop test. Figure 5 shows the condition of the initial designed impact limiters following the first side drop test. Although this test resulted in failure of the impact limiter, it provided extensive data which demonstrated the integrity of the basket design. Decelerations of about 1200 g were imposed on a basket disk. Outside of the local deformation due to the impact on the steel blocks which represented the radial neutron shield, the basket support disk number 6, which was located opposite the impacted block, was not deformed, (Figure 6). The center basket disk showed no damage. The impact load on disk no. 6 represents a load factor of 5 times the basket design. Moreover, no out-of-plane or in-plane buckling was observed.

Table 3: Drop Test Sequence

Drop Orientation	Phase 1	Phase 2	Phase 3	Phase 4
9 Meter Top End	1			
9 Meter Top Corner	2		8	
9 Meter Side	3		6	13
9 Meter Bottom 75° Oblique			7	12
1 Meter Pin Center of Cask		4	10	
1 Meter Pin Outer Lid		5	11	
9 Meter Top 75° Oblique			9	

In addition to the deficiencies observed in the performance of the impact limiter which led to additional testing, pin deformation was observed in the initial pin puncture tests. During the performance of these tests, the 24-inch long quarter-scale (1.5-inch diameter) 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 reperformed using an 8-inch long pin (Tests 10 and 11 in Table 3).

After reviewing the performance of the upper impact limiter in side and bottom oblique drop orientations, a nine-meter (30-foot), 75° top oblique drop was added to the test plan to assess the performance of the lower impact limiter (without trunnion cutouts) for a slapdown impact. No significant difference in behavior or crush characteristics was noted, supporting the hypothesis that the trunnion cutouts are negligible.

For each of the tests, the pressure and temperature were measured and recorded before and after the test. In all valid tests, closure lid seal integrity was maintained. During the outer lid pin puncture test, the cavity pressure valve was cracked. However, after replacement of the valve and repressurization, prior to lid removal, the cask satisfactorily maintained pressure.

Table 4 presents a summary of selected data recorded during the qualifying test for each drop orientation. The results of the quarter-scale model NAC-STC testing program demonstrate that this cask satisfies the industry and regulatory design requirements for transport packagings.

Table 4: Drop Test Results Summary

	Model Cask Drop Orientation			
	Top End Drop	**Top Corner Drop**	**Bottom Oblique Drop**	**Side Drop**
Cask Body Data				
Maximum Stress (ksi)	8.6	3.8	12.49	29.5
Gage Location	9	9	9	6
Maximum Hoop Strain (μin/in)	80	—	135	135
Gage Location	9	—	9	9
Maximum Acceleration (g) A1	217	127	225	204
Maximum Acceleration (g) A2	247	107	205	108
Pre-Test Cavity Condition				
Pressure (bar)	3.276	3.2114	3.1903	3.154
Temperature (°F)	93.6	46.8	47.8	49.1
Post-Test Cavity Condition				
Pressure (bar)	3.283	3.2045	3.1905	3.1526
Temperature (°F)	94.6	45.3	47.7	49.1
Impact Limiter Data				
Maximum Crush Stroke (in.)				
Top Limiter	2.11	6.4	2.41	2.04
Bottom Limiter	—	—	1.22	2.16