Legal Weight Truck Cask Model Impact Limiter Response

N.M. Meinert[1] and L.B. Shappert[2]

[1]*Nuclear Assurance Corporation, Norcross, Georgia*

[2]*Oak Ridge National Laboratory, Oak Ridge, Tennessee, United States of America*

Dynamic and quasi-static quarter-scale model testing was performed to supplement the analytical case presented in the Nuclear Assurance Corporation Legal Weight Truck (NAC LWT) cask transport licensing application. Four successive drop tests from 9.0 meters (30 feet) onto an unyielding surface and one 1.0-meter (40-inch) drop onto a scale mild steel pin 3.8 centimeters (1.5 inches) in diameter, corroborated the impact limiter design and structural analyses presented in the licensing application. Quantitative measurements, made during drop testing, support the impact limiter analyses. High-speed photography of the tests confirm that only a small amount of energy is elastically stored in the aluminum honeycomb and that oblique drop "slapdown" is not significant. The qualitative conclusion is that the limiter protected LWT cask will not sustain permanent structural damage and containment will be maintained, subsequent to a hypothetical accident, as shown by structural analyses. It should be noted that the model cask was fabricated using Type 304 stainless steel, which has a yield strength that is at least 50 percent lower than the Type XM-19 stainless steel the LWT cask is actually fabricated from. Three quasi-static impact limiter tests were performed to clearly demonstrate how the deceleration force develops as the impact limiter crushes. Quasi-static test forces, when corrected for dynamic crush strengthening, were less than or equal to calculated values. Quasi-static tests confirmed a shear force component of the total crush force. The shear force represents a smaller percentage of the total crush force in the full-scale impact limiter response because of the smaller shear area to backed crush area ratio. The quasi-static tests prove that the impact limiter design methodology is applicable and appropriate.

Dynamic and quasi-static testing of the impact limiters are independent confirmation primarily of the impact limiter design and secondarily of the structural design analyses. This confirmation is intended to strengthen the LWT licensing submittal by direct and appropriate example. Design of the LWT cask began in December, 1986, and culminated in March, 1988, with the licensing submittal. A 10 CFR 71 transport license is pending review of the responses made to a series of USNRC questions.

CASK AND MODEL DESCRIPTION

The full-scale LWT cask is designed to safely transport one PWR assembly, two BWR assemblies or up to 15 metallic fuel rods. The cask body structure is fabricated from two concentric, cylindrical Type XM-19 stainless steel shells, welded to thick Type 304 stainless steel forgings at both ends. The outer shell is 1.20 inches thick and has an outer diameter of 28.6 inches. The inner shell is 0.75 inch thick and has an outer diameter of 13.4 inches. Between the outer and inner shells is a 5.75-inch deep annulus filled with solid high purity lead, for gamma shielding the entire active fuel length. Molten lead is poured into the shell annulus under well controlled conditions after the cask is heated, then the cask and lead are cooled carefully to room temperature, to minimize fabrication stresses and lead gaps. Concentric with and welded to the outer shell, is a stiffened neutron shield and expansion tank fabricated from 1/4-inch thick Type 304 stainless steel plate. The passive shield tank system continuously blankets the active fuel length of light water reactor fuels with a borated water/ethylene glycol solution, while providing a chamber for the solution expansion expected during transport. The closure lid is a single 11.25-inch thick forging of Type 304 stainless steel, which is bolted to the upper end forging. A stepped lid design prevents radiation streaming while reducing lateral lid-bolt loading. Two elastomer o-rings provide a testable seal between the lid and the upper end forging. Two isotropic aluminum honeycomb impact limiters, designed using methodology developed by NAC, are bolted to each end of the cask during transport. Both impact limiters are right circular cylinders with a 12-inch deep overlap with the cask body. The impact limiter covering the lid and lifting trunnions, referred to as the top end of the cask, is 65.0 inches in diameter and 27.8 inches deep. The bottom impact limiter is 60.0 inches in diameter and 28.3 inches deep. The scale cask model attempted verisimilitude within practical and economic limits.

The quarter-scale model cask structure was fabricated from Type 304 stainless steel to minimize cost. Type 304 stainless steel (26.7 ksi) has a yield strength which is an average of 54 percent <u>lower</u> than Type XM-19 stainless steel (49.3 ksi) for the entire temperature range of interest. NAC determined that structural analyses and impact limiter design analyses were sufficiently conservative, that the weaker material would perform adequately in the drop test while demonstrating the extent of analytical conservatism. Both the inner and outer structural shells are one-quarter scale without compensating for the weaker material. Like the LWT cask, the annulus between structural shells is filled with lead. The Type 304 stainless steel closure lid is bolted to a thick Type 304 stainless steel shell weldment with a single elastomer gasket between the lid and weldment. The neutron shield and expansion tank are not required to sustain the hypothetical accident scenarios; therefore, they are not tested. The mass of the shielding liquid and tank structure is modeled by 32 appropriately located, Type 304 stainless steel blocks. Four lifting trunnions are welded to the upper weldment. To enable containment to be pressurized for testing, a quick disconnect fitting is tapped into the upper weldment. Inside the cask containment for all drop tests, was a steel cylinder, which represented the mass of the fuel contents and basket. Impact limiters are one-quarter scale facsimiles of the LWT cask impact limiters. The model limiters are fabricated from aluminum honeycomb with aluminum sheet skins attached to the interior and exterior. Dynamic testing of the model cask and impact limiters was performed at Oak Ridge National Laboratories (ORNL), Oak Ridge, Tennessee.

MODEL DYNAMIC TESTING

A procedure, TEST PLAN: LWT QUARTER-SCALE MODEL DROP TESTS, was prepared stating the tests to be performed, data requirements and model cask preparation prior to each dynamic test. ORNL instrumented the cask for the drop tests. Two PCB Model 306106 Triaxial Accelerometers, each having a range of - 500g to + 500g, a nominal sensitivity of 10 mv/g and a frequency range of 1 to 300 Hz (+ 5%), were used. Two axes (radial and longitudinal) of the accelerometers were aligned with the corresponding model cask axes. Signals from the six accelerometers were sent via a data cable to a Model 480D06 signal conditioning amplifiers and recorded on a Honeywell Model 100 multichannel, frequency-modulated (FM) tape recorder. Nine Micro-measurements Model EA-06-125RD-350 (0°, 44°, 90°) Rosette strain gages were bonded to the cask. Signals from the strain gages were transmitted to the Honeywell FM tape recorder. The strain gages will record the instantaneous strain and would reveal any permanent deformation in the outer shell.

Prior to drop testing, accurate measurements were made at the ORNL Metrication Laboratory. Seven positions on the inner diameter, three positions on the outer diameter and four cask length measurements were used as benchmark dimensions. The same measurements were taken after all of the drop tests were completed. Comparison of the initial and final measurements defined any cumulative permanent deformation to the model cask body. Subsequent analysis is used to determine the corresponding damage to the LWT cask.

Proving containment was maintained after each drop and determining cask and impact limiter performance were the primary purposes of the drop test program. Five drop tests were performed. Interest and data focused on the primary impact of each drop. It was known that aluminum honeycomb stored only a small percentage of the energy absorbed, so significant rebounding was not expected. Aluminum honeycomb's response and economic pressures to minimize the cost of the program, determined the order that the drop tests were performed. The drop tests performed were:

Test 1	Vertical (0°) Top End Drop - 30 feet
Test 2	Top Corner (15°) Drop - 30 feet
Test 3	Side (90°) Drop - 30 feet
Test 4	Oblique (30°) Drop - 30 feet
Test 5	Mid-Point Drop Onto a Mild Steel Pin - 40 inches

Test 1 and 2 were performed without an impact limiter on the end of the cask, which is not involved in the event to save the cost of two impact limiters. To protect the free end of the cask from secondary impact damage, it was tethered using steel cable to three 25-foot wooden poles. All other tests were free drop tests on to the unyielding surface without tethers.

The unyielding surface or impact pad was located at the ORNL Drop Test Facility located southeast of the main ORNL area. The pad is constructed from 600 metric tons of reinforced concrete and 70 metric tons of steel armor plate. The impact surface is 6.1 meters (20 feet) long and 2.5 meters (8 feet) wide. A mobile crane was used to lift the model cask to drop height.

Each drop test was performed using similar techniques. A new o-ring seal was installed, the simulated contents load was placed in the cask, lid bolts torqued according to a prescribed pattern. The model cask was pressurized, using a calibrated pressure gage, with nitrogen to verify that the seal was sealing, proving containment prior to the test. Impact limiters were attached and the cask instrumentation and high-speed cameras operational checks performed and the drop test was executed.

DROP TEST RESULTS AND LIMITER DYNAMICS

An exploding bolt simultaneously released the cask and started data recording devices. Test 1, a top end drop, was the proving ground for the procedure and impact limiter testing. An end drop has a distinct advantage over oblique drops and the side drop because one impact limiter is engaged in crushing, and crushing of an isotropic constant crush strength material is easily calculated, allowing easier comparison of calculations and test results.

The 860-pound model cask was positioned on the impact pad equidistant between three wooden poles. The bottom of the end cask was unprotected. Although it was felt that the cask would decelerate and remain upright, prudence demanded that the model cask be tethered using three, approximately 35-foot long, 3/8-inch steel cables to prevent damage to the cask bottom. There was a generous bit of slack in each cable. Each cable weighed approximately 10 pounds. The cask was prepared per the procedure.

Test 1. The impact limiter performed as expected. The area of the cask top of the model cask is 40.9 square inches. The force to crush the 3500-psi crush strength honeycomb immediately next to the cask is 143,200 pounds (166 g). The area of the low crush strength (250 psi) honeycomb layer, is 207.4 square inches and the force to crush the pad supported by the high strength honeycomb is 51,870 pounds. Crushing occurs where a minimum force is required to initiate it. Crushing of the low crush strength layer occurs followed by crushing of the high strength honeycomb trapped between the crushed low strength pad and the cask. The tested limiter revealed this to be true.

Approximately 7.22 square inches of impact limiter crushed uniformly a depth of approximately 0.98 inch. Damage to the limiter cup, in which the top of the cask fitted, indicated the cask drove into the limiter while shearing an area equal to the perimeter of the cask and trunnions. Calculations based on the area of honeycomb crushed and sheared indicated that the cask was decelerated at an average of 270 g. The corresponding volume of honeycomb crushed indicates that 212,300 inch-pounds of energy were absorbed, 70 percent of the total energy to be absorbed. Crushing of the low crush strength honeycomb layer was not visible. The low crush strength layer represents approximately 8 percent of total energy to be absorbed.

Accelerometer data show a peak deceleration of approximately 240 g. The axial strain gage located on the cask outer shell mid-point, returned data indicating there was no permanent set in the cask.

The test valve used to pressurize the cask was sheared off the cask so containment could not be checked. Protective plating was welded around the test valve to prevent a repetition of this failure.

Drop tests 2 through 5 were completed with the results of the drop test shown in Table 1.

Table 1. Dynamic Test Results

Test Orientation	Measured g-load	Calculated g-load	Permanent Set	Containment Maintained
Top End, 0°	240 g	166 g	No	No*
Top Corner, 14°	248 g	208 g	No	Yes
Side, 90°	660 g	181 g	Immeasurable	Yes
Oblique, 60°	250 g	165 g	No	Yes
Mid-Point Pin, 90°			Yes	Yes

* The test valve was sheared off by the impact limiter.

CONCLUSION

The calculated g-load shown in Table 1, is the peak g-load calculated using RBCUBED. There is a strong uncertainty surrounding the measured g-loads, especially after the data cable was cut during the top corner drop test. Further study of the relationship between static and dynamic testing is necessary to a meaningful correlation between the measured and calculated results.

QUARTER-SCALE MODEL IMPACT LIMITER FORCE-DEFLECTION TESTS

NAC performed quasi-static force-deflection tests on the same quarter-scale model impact limiters used during drop testing at ORNL. Using the same scale impact limiters for both the drop testing and the quasi-static testing permitted comparison of the results of both testing programs. Significant portions of the drop tested model limiters appeared undamaged and suitable for quasi-static testing. The drop test impacts could have reduced the adhesive's strength used to assemble the honeycomb and honeycomb blocks. The limiter shell, damaged during drop testing, was hypothesized to be a small part of the total crush dynamics and shell repairs were not made to all limiters tested.

The purpose of the quasi-static tests was to demonstrate how the deceleration forces developed during crushing, which was the basis for design methodology and the limiter design program RBCUBED. RBCUBED has the capability of modeling the energy dissipation material which is being tested. Aluminum honeycomb's dynamic strength would be factored into the quasi-static test results based on testing performed by the honeycomb manufacturer. The aluminum honeycomb manufacturer tested numerous 3-inch cube core samples quasi-statically and at "drop test" strain rates. An average static to dynamic crush strength ratio was determined. The static to dynamic crush ratio was used to scale the quasi-static scale impact limiter test data. Quasi-static testing of each limiter proceeded to "lock-up," the point at which honeycomb's crush strength increases and approaches that of porous solid aluminum. At lock-up, the impact limiter has achieved the maximum stroke for a given impact angle. Impact limiters are useful up to the point where lock-up is achieved.

Three limiter orientations - 0 degrees, 15 degrees and 90 degrees were tested, corresponding to three of the 30-foot drop orientations. For each orientation, a heavy and stiff steel test fixture was fabricated. The test fixture oriented the model limiter relative to the moving head of the Tinius Olsen testing machine, which represented the unyielding surface. Once the limiter was positioned on the test fixture, two calibrated linearly variable differential transformers (LVDT), mechanically attached to the test fixtures, provided signal to an X - Y recorder, which plotted crush force as the impact limiter deformed. Deformation of the limiter proceeded well into honeycomb lock-up. Once lock-up was clearly established, the direction of the mobile head movement of the testing machine was reversed. As the force on the limiter decreased, force and deflection continued to be monitored, revealing the amount of elastically stored energy.

The results of the quasi-static testing program are shown in Figure 1 - End Drop (0° impact, measured from vertical), Figure 2 - Corner Drop (14° impact) and Figure 3 - Side Drop (90° impact). Figure 1 shows the actual limiter forces can be estimated using the RBCUBED computer program. RBCUBED program results do not account for the shearing of honeycomb material during crushing, which underestimates the maximum force by about 10 percent for this size of impact limiter. The shear force is dependant on perimeter of the backed area performing the shearing. The total deceleration force is the sum of the crush force plus the shear force. Crush forces are dependant on crush area where as, the shear force is determined by the linear edge involved in crushing. As the diameter of the impact limiter increases, the shear force is expected to be a smaller portion of the total deceleration force because the perimeter of increases linearly while the crush area increases as the square. Figure 1 and all figures, show that the impact limiter design has energy absorption margin. The point at which the RBCUBED data stops, is the point at which the end of the cask which impacts the unyielding surface stops, and the impact limiter has performed its function. The post lock-up relaxation portion of the static test curve was removed for clarity in each figure. An average of 7 percent of the energy absorbed by the aluminum honeycomb impact limiters is stored elastically for each of the drop test angles tested quasi-statically.

CONCLUSION

The dynamic and quasi-static test program has demonstrated that the impact limiter design program RBCUBED is appropriate for use when designing aluminum honeycomb impact limiters. Forces calculated using RBCUBED tend to overestimate the actual forces, which offers a conservatively design limiter, resulting in lower actual forces being applied to the cask. The RBCUBED program could be modified to include the shear effect. This testing program has enhanced NAC's knowledge of aluminum honeycomb limiter dynamics, LWT cask and limiter actual design margins and ways of improving the impact limiter design methodology.

Figure 1. End Drop (0-Degree Impact)
Force-Deflection Graph

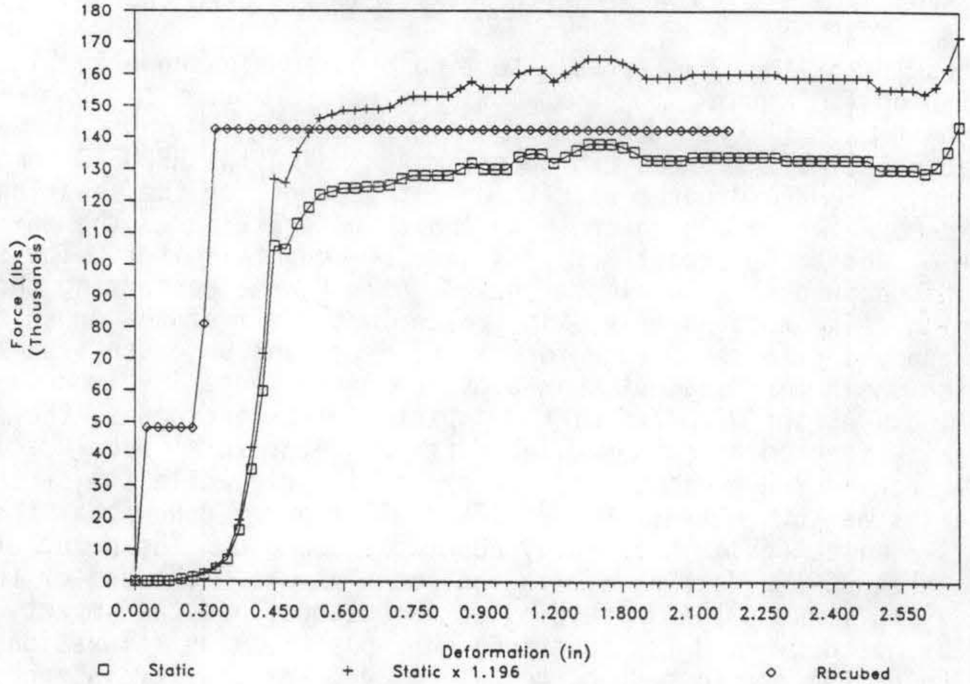

Figure 2. Corner Drop (14-Degree Impact)
Force-Deflection Graph

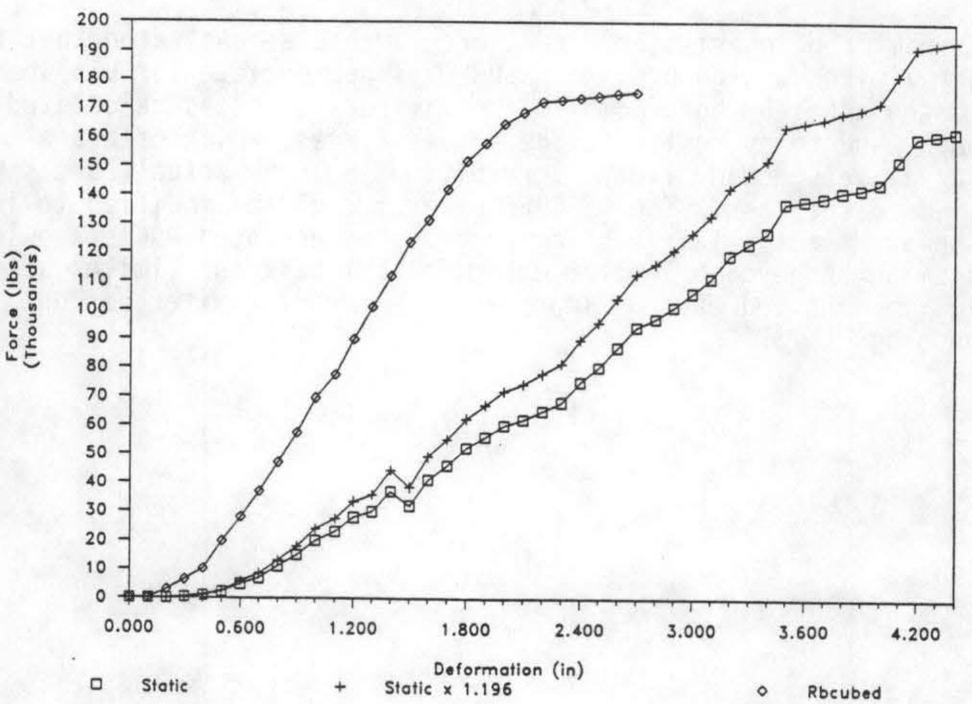

Figure 3. Side Drop (90-Degree Impact) Force-Deflection Graph