CORRELATION OF GA-4 HALF-SCALE MODEL CASK STRUCTURAL VERIFICATION TEST DATA WITH ANALYSIS

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SUMMARY

General Atomics (GA), under contract to the U. S. Department of Energy (DOE), developed the design for a new generation of legal-weight truck-mounted shipping casks to be used to transport spent fuel from commercial nuclear generating stations to an interim storage facility or a permanent repository. Under the DOE program, a one-half scale model was subjected to three drop tests from 9-meters onto an unyielding surface and four 1-meter puncture tests. After the DOE ended its cask program, GA continued private development of the casks and has submitted licensing applications to the U.S. Regulatory Commission for the GA-4 (PWR version) and the GA-9 (BWR version) cask designs.

The structural analyses were verified by the drop and puncture tests and a comparison was made between measured test data and the analyses. Axial and transverse deceleration levels predicted by the computer code GACAP were compared with corresponding levels indicated by the gauges mounted on the cask model. Agreement was very good for maximum decelerations in the directions of most interest, e.g., axial deceleration during the end drop, and transverse deceleration during the side drop and slapdown.

Various crush strength values for the impact limiters were considered in the analysis in order to cover the range of manufacturing tolerances for aluminum honeycomb and to account for temperature effects on crush strength. Analytical predictions for deceleration, strains, stress, and amount of honeycomb crush is presented for maximum and minimum impact limiter crush strengths. These values are compared with the half-scale model test results.

INTRODUCTION

A half-scale model of the GA-4 legal weight truck (LWT) spent fuel shipping cask (Figure 1) was built and tested to verify structural cask design features to supplement NRC certification activities for both the GA-4 and GA-9 casks. Both casks have been designed to maximize capacity. The GA-4 carries up to four PWR spent fuel assemblies. The GA-9 cask carries up to nine BWR spent fuel assemblies. Each cask design represents a significant improvement over current LWT designs that carry either one PWR or two BWR assemblies.

The NRC's transport regulations, specifically 10 CFR 71, require demonstration that a design meets all applicable performance requirements in order to be certified. The GA designs are shown by analysis to meet the requirements of 10 CFR 71. The scale model tests are done to verify specific structural aspects of those analyses, and to augment the NRC reviewers' confidence in the adequacy of the design and analyses.

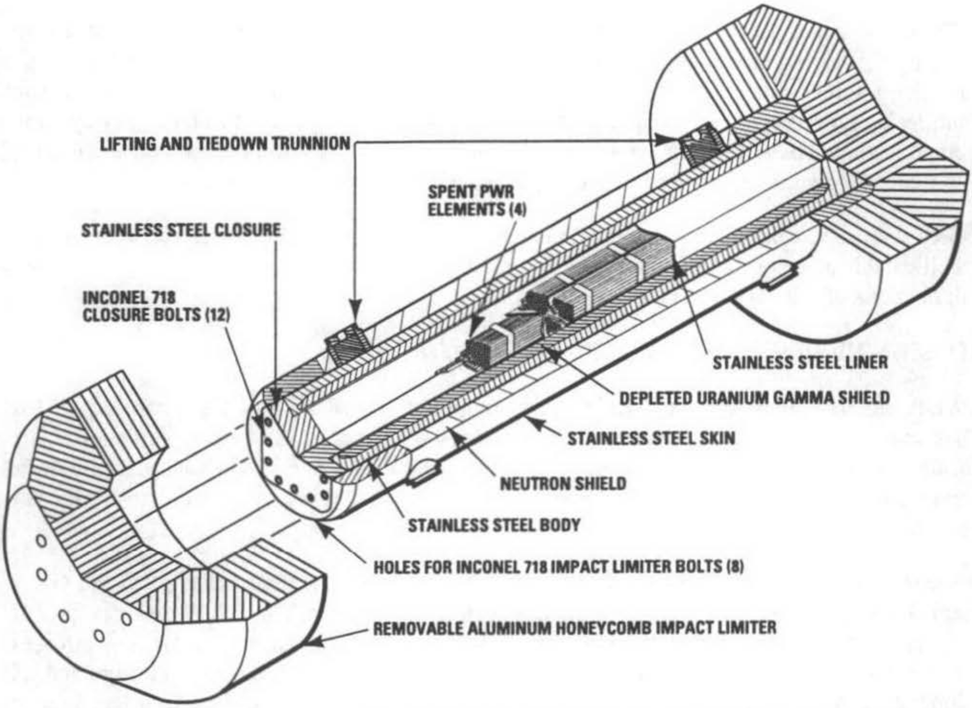

Figure 1. GA-4 Legal Weight Truck Shipping Cask Carries 4 PWR Fuel Assemblies

HIGH CAPACITY CASK DESIGN APPROACH

The high capacities of the GA-4 and GA-9 LWT casks are achieved through optimization of design features, and material selection. They are designed to transport spent fuel that has been out of the reactor for at least five years and therefore do not have to reject large amounts of decay heat. Design features that contribute to capacity improvement are separate cask bodies for PWR and BWR spent fuel, non-circular cross-section, efficient impact limiters, use of depleted uranium for gamma shielding, and the use of XM-19, a high strength austenitic stainless steel, as the primary structural material for the containment boundary. Both casks have aluminum honeycomb impact limiters, liquid neutron shields, and bolted XM-19 closure heads with concentric ethylene propylene elastomer seals. Weight and space efficient criticality control is achieved by an innovative welded fuel support structure (FSS) featuring B_4C inserts located in drilled holes in the FSS weldment.

DESIGN AND COMPLIANCE DEMONSTRATION BY ANALYSIS

Structural design criteria for the casks are established using the normal and hypothetical accident conditions and radiological performance standards of 10 CFR 71. The cask designs are shown to meet these criteria by analysis. Allowable stresses are established for various components of the cask. The containment structure is designed in accordance with NRC Regulatory Guide 7.6, which is based on the ASME B&PV Codes. GA's analyses showed that the GA-4 and GA-9 cask designs have considerable structural safety margins.

The GA-4 and the GA-9 casks both use aluminum honeycomb impact limiters to absorb energy associated with accident events and thereby reducing deceleration levels and the resultant forces transmitted to cask components. During the development of the impact limiter design, samples of the aluminum honeycomb were subjected to static and dynamic crush testing. The test results were used to establish force-deflection curves that are used to analytically predict impact limiter performance under various design conditions.

GA established a number of analytical models representing the cask designs and then utilized well-established computer codes such as GACAP and ANSYS to predict stresses and deflections of critical components.

DESIGN VERIFICATION BY TESTING

While the NRC may grant a Certificate of Compliance based on analysis alone, experience has shown that regulatory review can be expedited by verifying analytical predictions with scale model testing. The non-circular geometry of the GA-4 and GA-9 cask designs make analytical predictions of dynamic behavior difficult so that it was important to verify the results by testing.

A half-scale model of the GA-4 cask was used to verify the structural behavior of the GA-4 and GA-9 casks under selected hypothetical accident conditions. The GA-4 cask design was chosen because analyses showed it to have slightly higher containment boundary stresses than the GA-9 design. The cask model used the same materials as the actual design and all dimensions and tolerances were half size. All features important to the structural behavior of the cask during the regulatory drop and puncture events were included in the model. Half-scale was chosen to allow accurate modeling of the cask internals. The neutron shield and outer stainless steel skin were modeled for mass alone using stainless steel blocks welded to the containment shell. A collection of steel and aluminum rods was used to simulate contents. Loose rods were used to simulate load distributions on the FSS and cavity liner that would be produced by spent fuel assemblies under accident conditions.

TESTING THE GA-4 HALF-SCALE MODEL

GA conducted structural verification testing in late 1995 in San Diego, CA. A target pad, which meets International Atomic Energy Agency guidelines for an unyielding surface, was constructed by GA and consists of a heavy steel plate backed by reinforced concrete. The mass of the target is more than ten times the mass of the cask model. The following three test sequences were performed, each consisting of one drop from nine meters and one or more puncture events from a height of one meter:

First Sequence

A nine-meter drop of the cask model oriented horizontally and striking the impact surface on a longitudinal edge of its cross-section. The nine-meter drop was followed by a one-meter drop of the horizontally oriented cask striking a steel puncture pin adjacent to a corner of the closure side.

Second Sequence

A nine-meter drop of the cask model oriented thirty degrees from horizontal, flat side down and striking the impact surface at the closure end first. A one-meter puncture drop followed the nine-meter drop with the cask horizontal, flat side down striking the pin at the longitudinal center of the cask.

Third Sequence

A nine-meter drop of the cask with its longitudinal axis oriented twelve degrees from vertical with a longitudinal edge striking the impact surface. This drop configuration results in the cask's center of gravity being over the corner that strikes the impact surface. Two one-meter puncture drops followed the nine-meter drop. In the first, the cask's longitudinal axis was oriented seven degrees from vertical and the pin struck the vicinity of the gas sample port and closure bolts. In the second puncture drop the horizontally oriented cask struck the pin at the location of a joint between two depleted uranium rings.

Strain gages and accelerometers were fitted to the cask to measure responses during the drop and puncture events. Strains were measured mid-length on the outer shell where maximum deflections were expected. Accelerometers were mounted at the mid-length of the outer shell, and at each end. The puncture pins were instrumented with strain gages to measure deflection of the pins in order to calculate loads. Instrumentation output signals were recorded on floppy disk and magnetic tape. Photometric data were obtained using two high speed (2000 fps) 16mm movie cameras and one intermediate speed (400 fps) 16mm movie camera. Video camcorders were also used to record test events and to document various pretest ant post-test activities.

All tests were performed at ambient temperatures with the cask cavity initially pressurized to 0.55 mPa (80 psig). The cask was not disassembled nor were any parts replaced during a test sequence. Impact limiters, impact limiter bolts, and closure o-ring seals were replaced after each test sequence. Before and after each sequence, the closure o-ring seals and gas sample ports were leak tested, and the fuel support structure measured to detect any deformation. Impact limiters were examined after test to determine gross deformations. After all testing was completed, dimensional checks and helium leakage tests were performed on the containment boundary and cavity liner.

TEST RESULTS

Performance of the GA-4 half-scale model was consistent with analytical predictions. Measured strains and accelerations were as expected. Accelerometer data confirmed that the decelerations were within the range predicted by analysis. No permanent deformation of the cask body was observed, except at puncture locations where local dents were expected. The cask maintained internal cavity pressures at initial levels for all tests. The model remained leaktight as defined by ANSI N14.5 (1.0×10^{-7} std cm^3/s air). The fact that pressure was maintained means that the closure did not unseat during impact. All closure bolts maintained initial torque values with no measurable deformation. The aluminum honeycomb impact limiters remained attached to the cask body and deformed as predicted, thereby verifying that decelerations (and resulting impact forces) were within the range estimated and used in the analysis. Dimensional checks of the cavity liner and fuel support structure did not indicate any significant permanent deformations.

COMPARISON WITH ANALYSIS

Axial and transverse deceleration levels predicted by the GACAP computer code were compare to the results obtained from the half-scale model tests and are presented in Table 1. Agreement was very good for maximum decelerations in the directions of most interest, e.g., axial deceleration during the end drop and transverse deceleration during the side drop and slapdown.

TABLE 1
COMPARISON BETWEEN HALF-SCALE MODEL
TEST RESULTS AND ANALYSIS

	Analysis		Test[(b),(c)]
	High Str.[(a)]	Low Str.[(a)]	
Seq. 1, Test 1			
30-ft Sidedrop - corner orientation			
g-level at CG	47.7	39.6	40-44
Crush (in.)	11.9	14.2	12
Strain, Z-direction (με)	1854	—	1400
Calculated stress, σ_z (ksi)	52.89		38.77
Seq. 2, Test 1			
30-ft Slapdown - flat orientation			
g-level at CG			
Axial - primary impact	12.3	10.7	7
secondary impact	0	0	16
Transverse - primary impact	21.4	18.6	16
secondary impact	25.9	23.7	24-30
g-level - closure end			
Transverse - primary impact	58	—	30
secondary impact	−28	—	−15
g-level - bottom end			
Transverse - primary impact	−16	—	−10
secondary impact	69	—	51.5
Crush (in.)			
- primary impact	14.7	16.3	15
- secondary impact	14.5	16.9	15.8
Strain, Z-dir., secondary impact (με)	756	—	530
Seq. 3, Test 1			
30-ft CG-over-corner			
g-level, axial	56.5	39.3	46-51.5
Crush (in.)	14.2	16.4	12.6
Strain, Z-direction (με)	−475		−290

(a) High strength and low strength honeycomb used in the analysis.
(b) Deceleration values represent the full cask value (test value x 1/2).
(c) Crush heights represent the full cask value (test value x 2).

GACAP was used to predict decelerations at points along the length of the cask body for various drop orientations, including the three nine-meter orientations (side, end, and slapdown) tested with the GA-4 half-scale model. The computer model used different impact limiter load-deflection curves that bounded the honeycomb crush strength characteristics. Three different load-deflection curves for each drop orientation were used as input for GACAP. The maximum and minimum strength curves considered manufacturing crush strength tolerances and temperature effects including a factor for strain rate effects on the crush strength. The three curves represent:

1. Maximum strength impact limiters,
2. Minimum strength impact limiters, and
3. Actual quarter-scale impact limiters used in early development tests.

The results along with maximum deceleration values taken from the half-scale tests, and are described below:

Nine-meter Side Drop. Figure 2 shows GACAP predicted deceleration levels of about 40g for a cask with low strength impact limiters and 48g if high strength limiters are assumed. Using the load deflection curves from the quarter-scale tests gives 47g. The g-levels are constant along the length of the cask body as expected for a side drop. Maximum decelerations indicated by the accelerometers in the half scale test (divided by 2 for conversion to full scale) fall within the range predicted by GACAP.

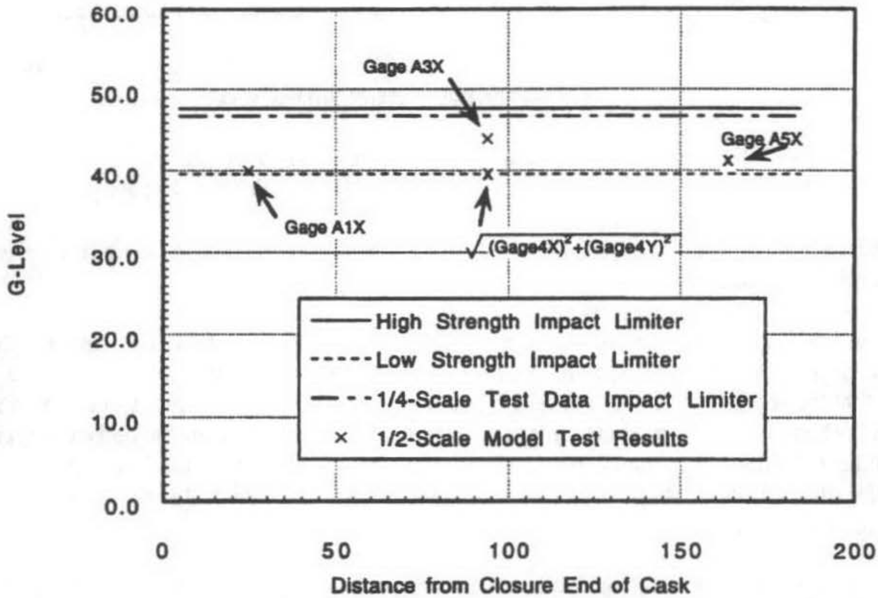

Figure 2. GACP Results Comparison with Half-Scale Test Results for 30-ft Side Drop Transverse g-levels

Nine-meter Slapdown at 30°. Figure 3 shows a plot of transverse g-levels along the length of the cask body resulting from the primary impact on then closure end. GACAP predicts that for any given point along the cask body, the deceleration levels do not vary much with impact limiter strength, at least within the range of honeycomb strength allowed. The maximum deceleration values indicated by the half-scale model tests show good agreement at mid length and near the bottom head (Gages A4Y and A6Y in Figure 3). Gage A2Y located near the closure end showed a maximum deceleration significantly lower than the predictions.

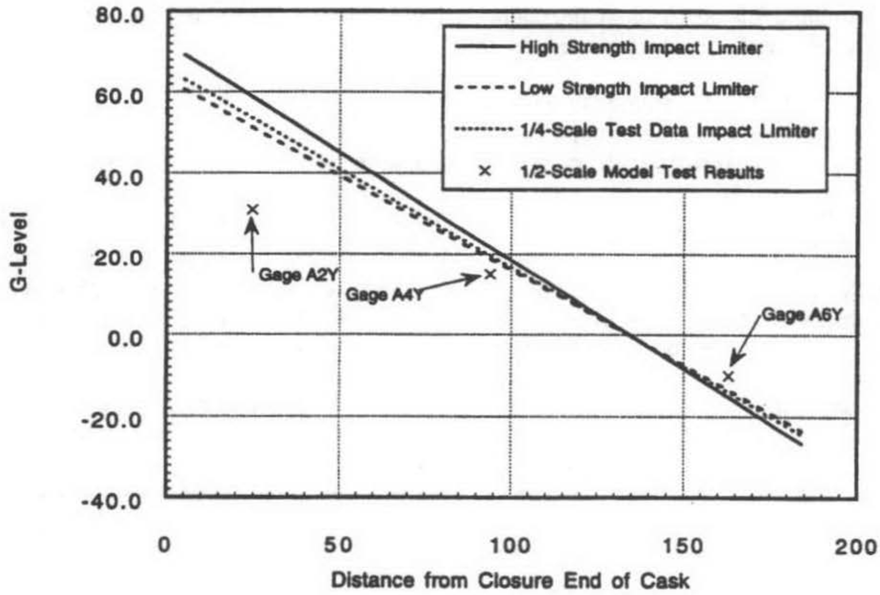

Figure 3. GACP Results Comparison with Half-Scale
Test Results for 30° Slapdown Transverse g-Levels, Primary Impact

This means that the g-levels used in the analysis of the cask body stresses are conservative compared to test measurements.

A similar pattern of agreement between test data and GACAP prediction is evident for the secondary impact where the bottom of the cask slaps down onto the test pad. Figure 4 shows that the accelerometers at mid length and away from the impact area (Gages 2Y, 4Y, and 3X/3Y) agree with the predicted g-levels. Gage 6Y located nearest the secondary impact area, indicated a maximum transverse deceleration of about 10g less than the lowest predicted value for that location. Again the analytical predictions are shown to be conservative compared to test results.

Nine-meter End Drop. Figure 5 gives the results of GACAP predictions for axial g-levels for the 78° cg-over-corner closure end drop. The g-levels range from 39g for the lowest crush strength impact limiter up to 57g if the load deflection curves from the quarter-scale tests are used as input to GACAP. The two accelerometers, A3Z and A4Z, measuring axial deceleration on the half-scale model were located at mid length. The maximum deceleration levels indicated by these gages are within the range of the GACAP predictions.

Puncture Drops. The structural analysis of the cask body predicted that the punch would not produce bending moments across the cask cross section that would result in stresses that would exceed allowable values. The analysis under-predicted the deceleration values actually measured in the tests, but the higher stress levels calculated using measured decelerations are still within allowable values.

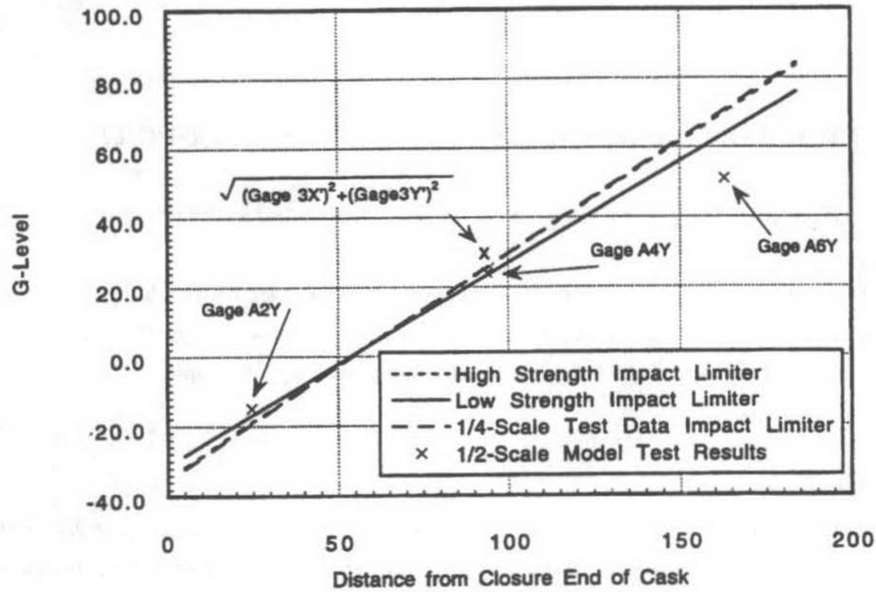

Figure 4. GACP Results Comparison with Half-Scale
Test Results for 30° Slapdown Transverse g-Levels, Secondary Impact

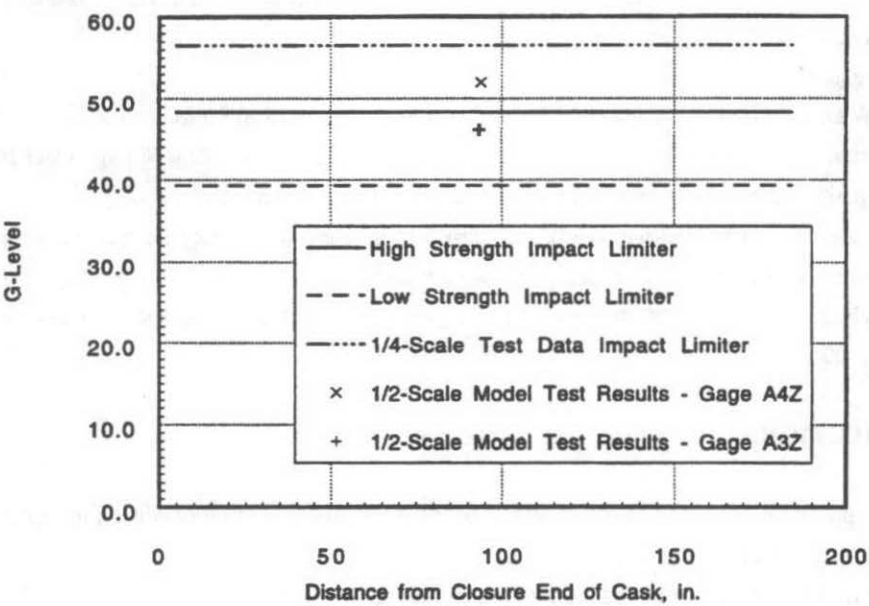

Figure 5. GACP Results Comparison with Half-Scale
Test results for CG-Over-Closure-Comre, Axial g-Levels