1/3-Scale Model Testing Program*

H.R. Yoshimura[1], S.W. Attaway[1], D.R. Bronowski[1], W.L. Uncapher[1], M. Huerta[2], D.G. Abbott[3]

[1]*Sandia National Laboratories**, Albuquerque, New Mexico*
[2]*Southwest Engineering Associates, El Paso, Texas*
[3]*EG&G Idaho, Inc., Idaho Falls, Idaho, United States of America*

INTRODUCTION

This paper describes the drop testing of a one-third scale model transport cask system. Two casks were supplied by Transnuclear, Inc. (TN) to demonstrate dual purpose shipping/storage casks. These casks will be used to ship spent fuel from DOE's West Valley demonstration project in New York to the Idaho National Engineering Laboratory (INEL) for long term spent fuel dry storage demonstration. As part of the certification process, one-third scale model tests were performed to obtain experimental data. Two 9-m (30-ft) drop tests were conducted on a mass model of the cask body and scaled balsa and redwood filled impact limiters. In the first test, the cask system was tested in an end-on configuration. In the second test, the system was tested in a slap-down configuration where the axis of the cask was oriented at a 10 degree angle with the horizontal. Slap-down occurs for shallow angle drops where the primary impact at one end of the cask is followed by a secondary impact at the other end.

The objectives of the testing program were to 1) obtain deceleration and displacement information for the cask and impact limiter system, 2) obtain dynamic force-displacement data for the impact limiters, 3) verify the integrity of the impact limiter retention system, and 4) examine the crush behavior of the limiters. This paper describes both test results in terms of measured decelerations, post test deformation measurements, and the general structural response of the system. More details on the tests and hardware are provided elsewhere (Yoshimura et al., 1989).

HARDWARE

The cask system was designed for the transport and storage of spent fuel elements (Nolan et al., 1986). The cask body is a thick-walled steel cylinder with an integrally-welded forged bottom end plate. The full-scale system incorporates a bolted closure. For the drop tests, a one-third scale model of the body was fabricated from a cylindrical forging and plates welded at each end (see Figure 1). This model simulated the cask body effects on the impact limiters but was not intended to evaluate the performance of the cask design. The closed end of the cask body was chamfered, as in the full sized unit, to reduce weight. The bolted closure system was not modeled. The model impact limiters were accurately scaled versions of the full sized units which are cylindrical structures with recesses to accept the ends of the cask. They were attached at each end of the cask with four bolts with four shear pins providing additional strength for side loading. The impact limiters were modeled realistically, being fabricated from blocks of balsa and redwood encased in 0.090 in. thick sheet metal. Sixteen radial metal gusset plates (0.060 in. thickness) inside the impact limiter provided confinement for the impact absorbing wood blocks. Wood blocks were cut in the

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** A United States Department of Energy Facility appropriate grain directions to form shaped blocks which geometrically scaled the full size units. Each model impact limiter weighed about 360 lb; the cask body weighed 7850 lb.

TEST PROCEDURE

The 9 m drop tests were conducted at the Sandia Coyote Canyon Test Facility (Uncapher, 1983). The 500,000 lb target at this facility met the IAEA criteria for an unyielding surface. It consisted of a cylindrical plug of concrete covered by a 10 ft by 10 ft by 0.33 ft armor plate.

In the first test, the cask was tested in an end-on orientation, and only one scale model impact limiter was used (see Figure 2). A mock impact limiter made of plywood disks and a steel plate for correct weight was attached to the other end of the cask. This was done to avoid damaging a second impact limiter in case the cask toppled over during the test.

The slap-down test was performed on the same cask after the end-on test, but the mock impact limiter was replaced with a scale model impact limiter. The cask was suspended from the lifting beam so that its axis was positioned at a 10 degree angle with the horizontal. The previously tested impact limiter was subjected to the primary impact; the new limiter was subjected to the secondary impact.

INSTRUMENTATION

The cask body was instrumented with a number of accelerometers to measure decelerations at selected positions during each test. Three Endevco accelerometer models were used in the end-drop test. These included Endevco models 7270A-2K, 2264-5KR, and 2262-1000. The slap-down test used the same models and also included some 7270-6K and soft mounted 7270A-2K units. The soft mounted units included a thin layer of an elastomeric material which was used to filter out very high vibrational frequencies.

A number of sacrificial strain gages were mounted to the impact limiters to signal times of contact with the target. In order to measure the forces tending to dislodge the impact limiters, instrumented bolts were used to retain the rear limiter (which was subjected to the more severe, secondary impact) during the slap-down test. The fasteners were Strainsert internally strain gaged bolts and were sized to exceed the strength of the bolts that would normally be used.

Photometric coverage of the tests was provided by high-speed motion picture cameras. These included Milliken (400 fps), Nova (2,000 fps), and streak cameras.

END DROP TEST RESULTS

In the end drop test, the system impacted the target in a near perfect orientation at a velocity of 44 ft/s. The time of rebound was about 13.6 ms. During the impact, the cask body punched into the impact limiter about 3 in. and remained upright The impact limiter did not crush externally at the limiter/target interface but crushed internally under the projected area of the cask body. Damage to the limiter structure consisted of wood crush, some sheet metal tearing at the interface between the cylinder and external sheathing, and buckling of gusset plates and attachment bolt access tubes.

The vertical motion of the cask and limiter was analyzed by digitizing the position of the cask body and the impact limiter from the streak and framing camera high speed films, differentiating the data, and plotting the results in terms of vertical displacement and velocity as a function of time. These results indicate that the external surface of the limiter stopped abruptly after contacting the target surface. The cask body continued to move into the limiter structure. The differences between the motion of the cask and limiter become clear when examined in terms of velocity-time histories. Figure 3 illustrates the cask and limiter velocity-time histories obtained by differentiating the film displacement data. The abrupt stopping of the impact limiter and the gradual slowdown of the cask can clearly be seen in this figure. These results also indicate that the system had a rebound velocity of about 4 ft/s. It should be noted that fitting a straight line to the velocity-time curve of the cask results in a average deceleration rate of about 100 g's.

The accelerometer results from this test were very disappointing in that most of the traces were not usable due to a very high frequency content indicating that the accelerometers had gone into resonance. The accelerometers were driven to resonance by a force with a very rapid rise time. However, two of the units mounted on the reverse side of instrumentation blocks did produce credible data. Figure 4 is a deceleration trace obtained from one of the units mounted at the approximate midpoint of the cask. This trace, which has been filtered to 1000 Hz, indicates a deceleration pulse of about 170 g's (about 150 g's when filtered to 750 Hz) and a leveling off at about a constant 100 g's. These values will be 1/3 for the full scale cask. It also indicates an event duration of about 14 ms.

SLAP-DOWN TEST RESULTS

Figure 2 shows the slap-down test configuration. The cask system impacted the target at an angle of about 12 degrees (measured). After contacting the target, the system translated vertically and started to rotate as the corner of the impact limiter crushed. At 20.6 ms after start of impact, the cask had rotated sufficiently for the limiter at the chamfered end to strike the target. The limiter then crushed about 6 in. as the cask came to a stop. The total duration of the impact was about 40 ms. Some amount of tearing of the impact limiter skin in the crushed areas was observed. The flattened areas on the limiters were about 22 in. wide.

The film data were digitized to analyze the motion of the cg of the cask and the angular motion as a function of time. These results indicate that the cg displaced about 11 in. downward after the corner of the front impact limiter contacted the target. The cask started to rotate during the first 8 ms of impact, it then rotated rapidly during the next 15 ms, reaching a horizontal attitude at about 23 ms. It then overshot the horizontal attitude by about 1 degree and came back to an almost perfectly horizontal position at about 40 ms. The cask reached a peak angular velocity of about 13 radians per second when the back impact limiter contacted the target. The cg decelerated from the impact velocity of 44 ft/s to rest in about 35 ms.

Because of space limitations, only a sampling of the accelerometer results (front, middle, and rear) will be presented. The traces have been assembled into groups corresponding to the different axial locations on the cask. Figure 5 illustrates results for the front end of the cask; these correspond to the primary impact. The duration of the primary impact was about 15 ms; and the deceleration levels recorded by the front accelerometers were about 110 g's. Figure 6 illustrates results from accelerometers located at the back end of the cask which was subjected to secondary impact. The results from these units indicated peak deceleration levels for the pulse of about 150 g's. Figure 8 illustrates accelerometer results for the approximate center of the cask. These accelerometers measured both the primary and secondary impacts. However, because they were somewhat removed from the ends, the deceleration magnitudes (about 58 to 68 g's) were considerably lower than those measured at the end. Peak deceleration levels recorded by all accelerometers in the axial direction of the cask were about 15 g's.

Since the displacement, velocity, acceleration, and angular velocity and acceleration (Figure 8) of the cg of the body are known from the experimental results, the motion at any point in the body may be determined from the equation for rigid body plane motion (Higdon et al., 1976).

The instrumented impact limiter attachment bolts broke during the secondary impact. The microstrain levels from the instrumented bolts indicated sharp rises in strains but these were greatly below the rated tensile breaking load. Since the bolts were designed to measure tensile strains only, shear and bending strains were not measured. An examination of the upper bolts indicated that the failure mode was purely shear with a failure surface which was almost perpendicular to the bolt axis. The bottom bolts appeared to have failed in a combined tensile and bending mode with an angled fracture surface. This was confirmed with a dynamic structural analysis of loads on the limiters and cask body.

FORCE-DISPLACEMENT CHARACTERISTICS

The force-displacement characteristics of the impact limiter tested in the end-drop orientation was calculated using accelerometer data in conjunction with digitized film data. The results of these calculations are presented in Figure 9. These results indicate a peak force of about 1,750,000 lb. Once buckling was initiated in the metal gusset structure, the force level dropped significantly and remained at a constant level of about 800,000 lb. The area under the force-displacement curve, which represents the crush energy, was calculated as a check on the accuracy of the curve. The agreement between the crush energy and the kinetic energy of the system was within 3 %.

The response of the system to the slap-down test was much more complex. In this case deceleration levels throughout the cask varied significantly with time and space. In order to calculate the forces acting on the cask body, a relatively new technique known as the Sum of Weighted Accelerations (Bateman et al., 1989; Yoshimura et al., 1989) was used to determine the force, moment, and angular motion of the cg of the cask by using a number of accelerometer readings. Displacements were again obtained from the digitized film data. Figure 9 includes the force-displacement results for both the primary and secondary impact. As can be seen here, the secondary impact produced a larger peak force, which was in the vicinity of 500,000 lb. The primary impact produced a peak force with a magnitude of about 400,000 lb. The sum of the crush energy, corresponding to the areas under both curves, came to within 6% of the kinetic energy of the system.

Accuracy of measurements made during the test can be assessed as follows. The expected uncertainties in the accelerometer measurements could be as high as ±15% (Madsen et al., 1987). With regard to photometric data, the principal error is due to poor image quality (inadequate lighting, dust obscuration, forced processing, improper focus, etc.) If the image quality is poor, it is difficult to accurately follow the displacement of the structure. Therefore, judgements regarding the general accuracy of film data can not be made easily and must be done on a case-by-case basis. However, after reviewing the films from these tests, it can be shown that the digitized displacement data are reasonably accurate. This conclusion is based upon comparing results from two different cameras. In terms of impact velocity (44 ft/s), results from the streak and framing cameras agreed within 1 ft/s. These errors would increase as the cask slows because of the smaller displacements measured.

CONCLUSIONS

As designed, the impact limiters greatly mitigated the external forces acting on the cask body. For the end-on impact, the deceleration peaked at about 170 g's due to buckling of the 16 radial gussets. After the initial peak, the deceleration of the cask was constant at about 100 g's. The deformation mode for the impact limiter was one where the cask punched into the limiter.

For the slap-down test, the deceleration level varied through the cask structure as the cask impacted on the front corner, rotated, and impacted on the rear limiter. The primary impact resulted in a deceleration level of about 110 g's at the front end of the cask. The secondary impact was more severe and resulted in a deceleration level of about 150 g's at the back end of the cask. The deceleration level for the full-scale prototype would be one third based on scaling laws. The impact limiter attachment hardware failed during the secondary impact and has been redesigned to withstand higher loading.

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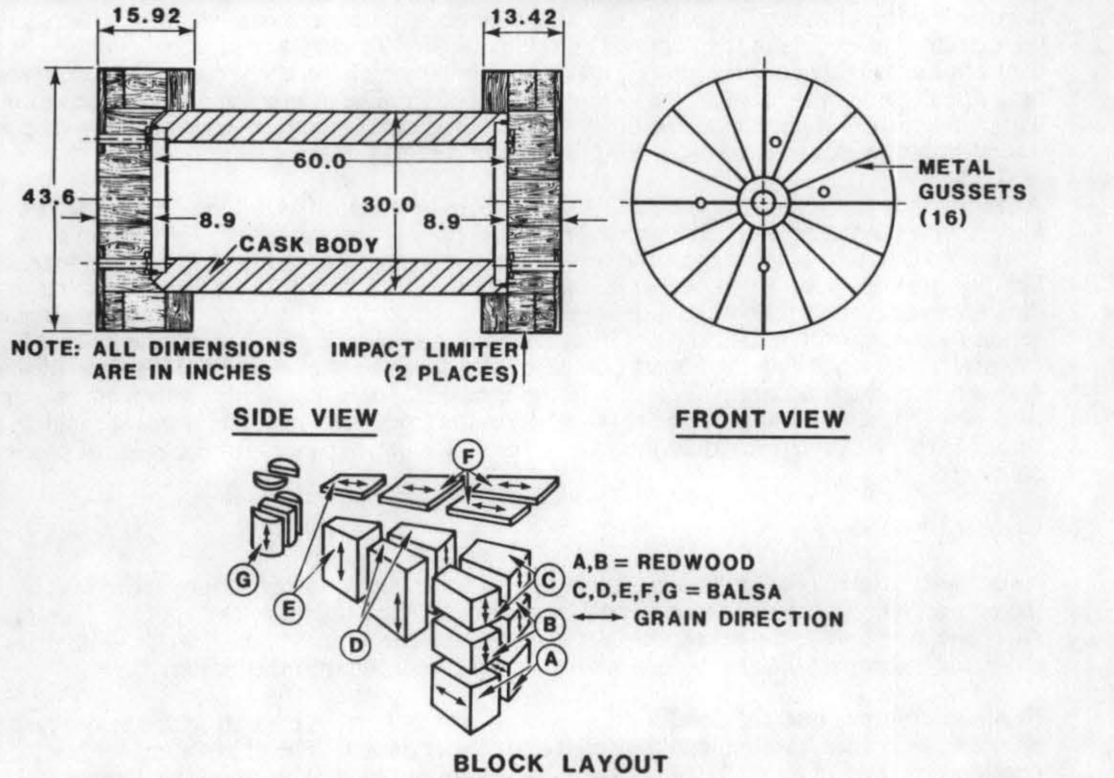


Figure 1. Schematic of 1/3 Scale Model Cask and Impact Limiters

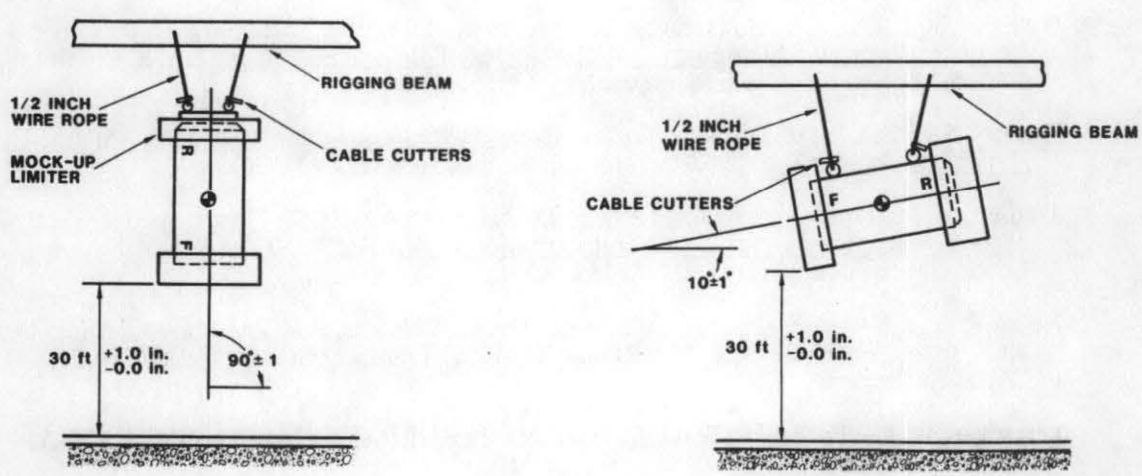


Figure 2. 1/3 Scale Model Cask in End-on and Slap-down Test Configurations

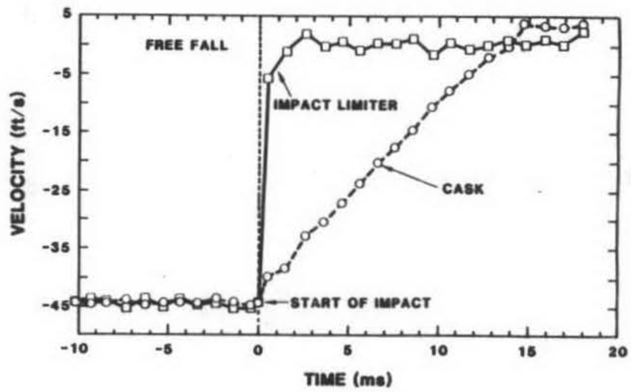


Figure 3. Velocity vs Time Histories for Cask and Impact Limiter in End Drop

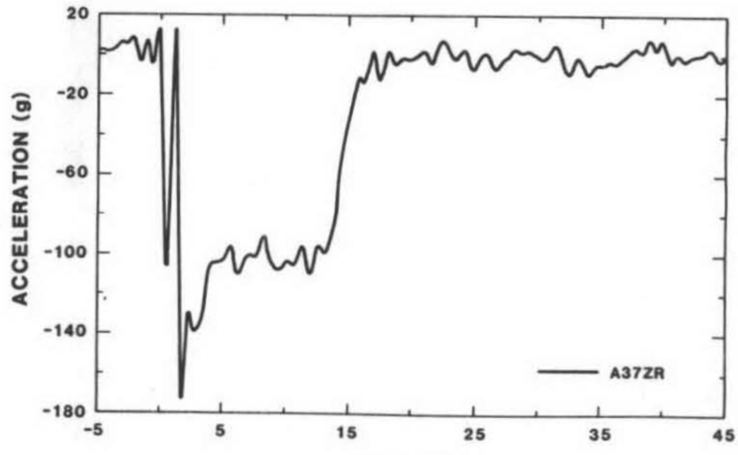


Figure 4. Acceleration vs Time for Cask Body in the End-Drop Test

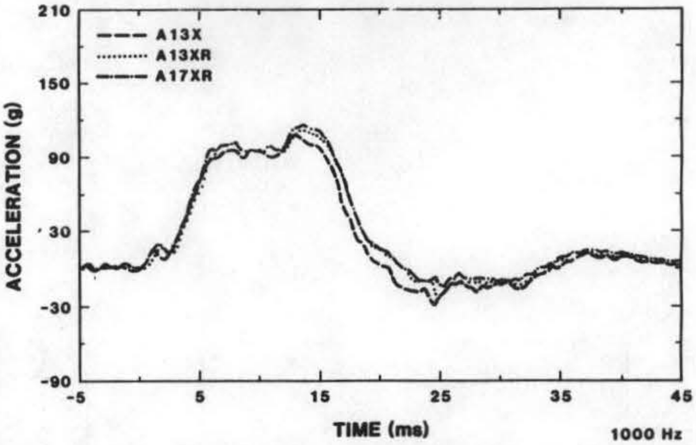


Figure 5. Selected Accelerometer Data for Front End of Cask Measured During the Slap-Down Test (Primary Impact)

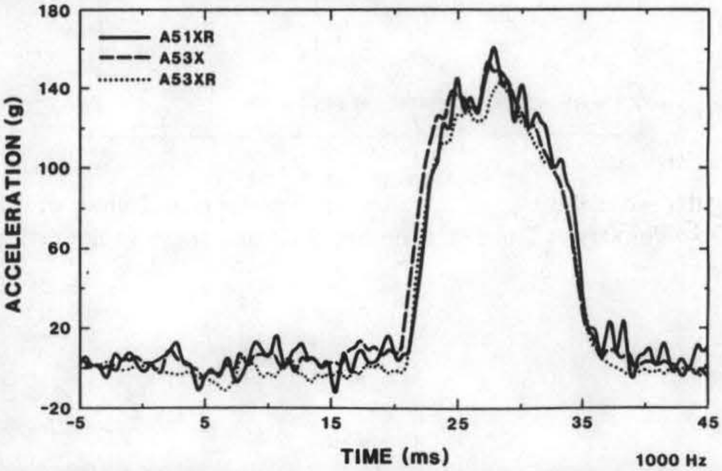


Figure 6. Selected Accelerometer Data for Back End of Cask Measured During the Slap-Down Test (Secondary Impact)

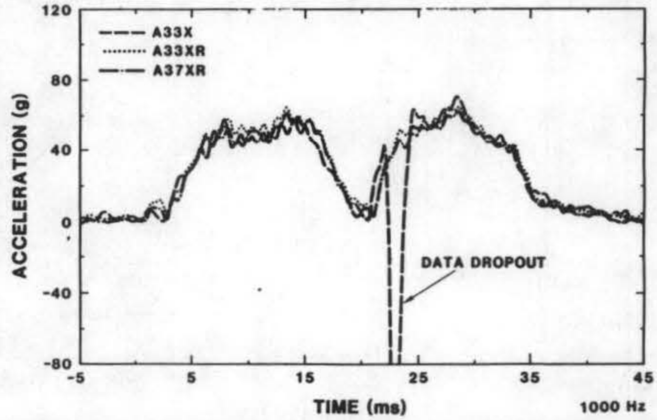


Figure 7. Selected Accelerometer Data for Center of the Cask Measured During the Slap-Down Test (Primary and Secondary Impacts)

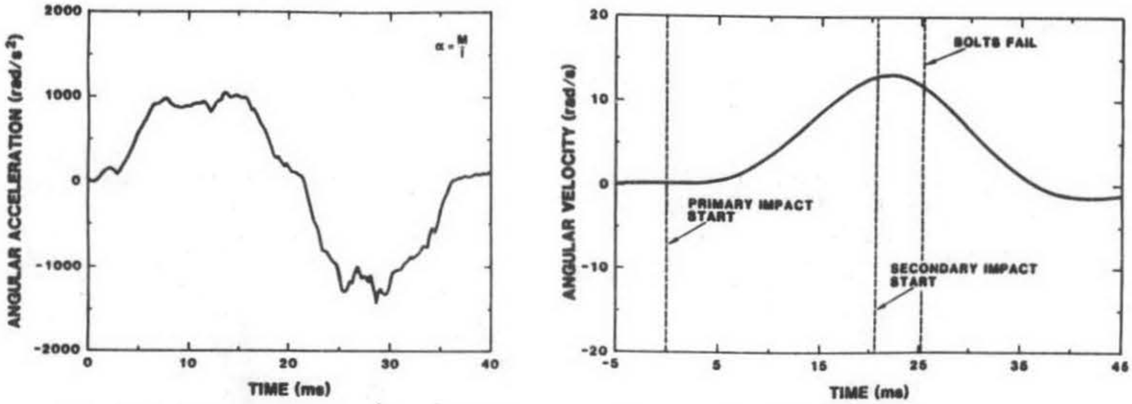
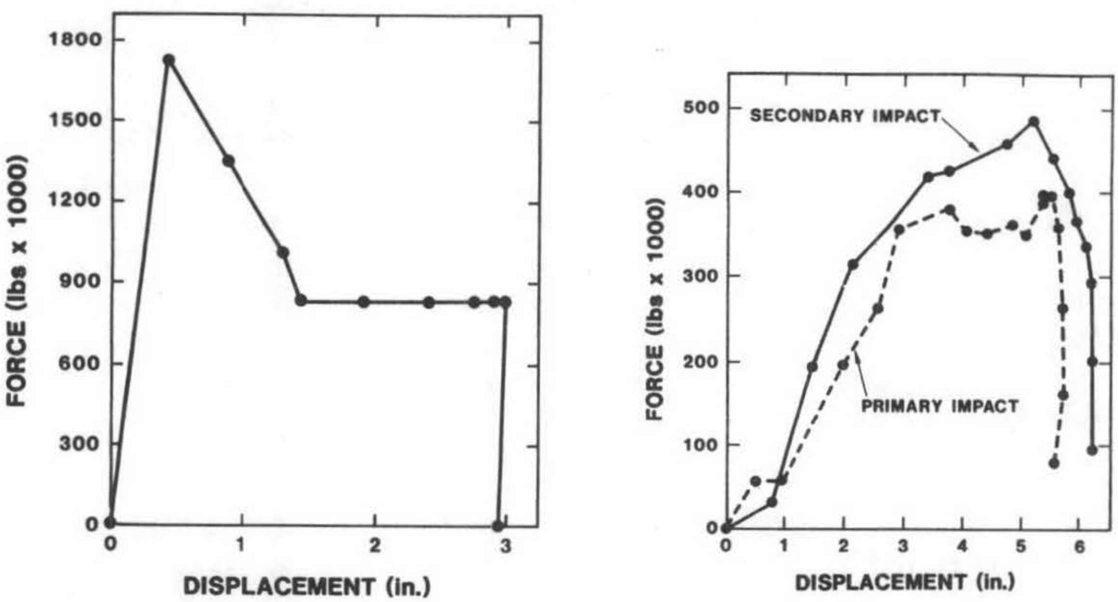


Figure 8. Angular Acceleration and Velocity vs. Time for Cask Center of Gravity in Slap-Down Test



End Drop　　　　Slap-Down

Figure 9. Force vs Displacement for Impact Limiters