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EVALUATION OF IMPACT
LIMITER PERFORMANCE DURING
END-ON AND SLAPDOWN DROP TESTS OF
A ONE-THIRD SCALE MODEL STORAGE/TRANSPORT
CASK SYSTEM*

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ABSTRACT

This report describes drop testing of a one-third scale model shipping cask system. Two casks were designed and fabricated by Transnuclear, Inc., to ship spent fuel from the former Nuclear Fuel Services West Valley reprocessing facility in New York to the Idaho National Engineering Laboratory for a long-term spent fuel dry storage demonstration project. As part of the NRC's regulatory certification process, one-third scale model tests were performed to obtain experimental data on impact limiter performance during impact testing. 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. Two 30-ft (9-m) 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 slapdown configuration where the axis of the cask was oriented at a 12.4-degree angle with the horizontal. Slapdown occurs when one end of the cask impacts the target at an angle, resulting in a primary and secondary impact. This report describes the results of both tests in terms of measured decelerations, posttest deformation measurements, and the general structural response of the system.

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1.0 INTRODUCTION

This report describes drop tests of a one-third scale model storage/transport cask system. Two casks were designed and fabricated by Transnuclear, Inc., to transport spent fuel from the former Nuclear Fuel Services West Valley reprocessing facility to the Idaho National Engineering Laboratory for a long-term dry storage project. As part of the NRC's regulatory certification process, scale model tests were performed to obtain experimental data on impact limiter performance during impact tests. Two 30-ft (9-m) drop tests were conducted in accordance with regulatory requirements. In the first series, the system was tested in an end-on drop orientation; the second series of tests involved a slapdown orientation with the cask axis at a nominal angle of 10 degrees to the horizontal. Slapdown occurs when one end of the cask impacts the target at an angle, resulting in a primary and a secondary impact.

These test series were designed to obtain deceleration and displacement information for the system as well as dynamic force-displacement data for the impact limiters. The tests also allow evaluation of the crush behavior of the impact limiters and the performance of the limiter retention system.

In both test series, the cask was instrumented with numerous accelerometers and the tests were photographed with high-speed cameras. Instrumented bolts attached an impact limiter to the cask body.

Test results are described in terms of measured decelerations and the observed structural response of the system. Also included are estimates of the dynamic force-displacement characteristics of the impact limiters. All accelerometer traces are provided on microfiche inside the back report cover.

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2.0 SCALE MODEL 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 closure. The full-scale system incorporates a flanged and bolted forged top lid. The one-third scale model that was tested had welded plates at each end of the cylindrical body and did not simulate the bolted closure of the prototype. The scaled cask body acted only as an equivalent mass and was not intended to model the full-scale cask in detail. Each end of the cask had four attachment bolts as well as four unthreaded holes to accept shear pins on the limiters. The model cask weighed 7850 lb. Figure 1 is a schematic of the fabrication features of the model cask.

Figure 2 illustrates the construction of the 360-lb impact limiters. The impact limiters used redwood and balsa encased in sheet metal plating. The steel plating on the outer surface of the model limiter was 0.090 in. thick. Internally, the limiters featured 0.060-in. gusset plates running radially. Figure 3 illustrates how the wood was placed in the steel shell. Each wood piece in the model was scaled down from the prototype. All cut lines of the prototype limiters were reflected in the model. Fabrication drawings for the cask and limiters are included in Appendix A.

Figure 1. Schematic of the Model Cask

Figure 2. Schematic of the Impact Limiters

Figure 3. Impact Limiter With the End Cover Plates Removed

3.0 TEST PROCEDURE/INSTRUMENTATION

The tests described in this report were conducted at the Coyote Test Facility of Sandia National Laboratories. The target at the facility meets International Atomic Energy Agency criteria for being essentially unyielding. It consisted of a block of reinforced concrete weighing about 225 metric tons (500,000 lb) covered with a 10-cm- (4-in.-) thick armor plating.

In each test the system was suspended from a beam using wire rope. Explosive cutters were fitted to each supporting rope to allow the cask to drop onto the target.

In the first test, the cask was tested in an end-on orientation, impacting the top or square end. Figure 4 shows the cask before the first test and a close-up view of an accelerometer block mounted on the cask body at mid-plane. Only one impact limiter (top end) was used in this test; an impact limiter mock-up was fabricated and fitted to the bottom (tapered) end of the cask. The mock-up was used to prevent damage to the costly scaled impact limiter should the cask topple over during the test. The 360-lb mock-up impact limiter consisted of a steel plate and several circular layers of plywood. Like the actual impact limiter which is secured by four retaining bolts the mock-up was bolted to the tapered end of the cask.

For the slapdown drop test, the mock-up impact limiter was replaced with an actual limiter. The impact limiter used in the end-on drop was left on the cask for the slapdown drop test. This impact limiter was crushed in the area adjacent to the end of the cask. The annular portion of the limiter was not crushed. Thus the limiter was judged to be adequate for use in the slapdown test. The cask was suspended from the rigging beam at a 10-degree angle to the horizontal. The top (square) end of the cask impacted the target first. The tapered end which had the undamaged limiter was subjected to the secondary impact.

Figure 4. The Test System Before the End-On Drop Test

Numerous accelerometers were used to monitor the response of the cask during each test. Figure 5 is a schematic of the accelerometer layout for the end-on drop test. Three Endevco models (Appendix A) were installed in three planes at different axial positions on the cask. Each unit was given a designation beginning with the letter "A" followed by two numbers and a letter indicating the direction of alignment. Designations ending with 'R' represent a redundant transducer at that location. Figure 5 shows the superimposed coordinate system. The first number of the designation indicates the plane in which the unit was located, and the second number indicates the circumferential location on the cask body. For the end-on drop tests, most of the units were aligned

Figure 5. Schematic of the Instrumentation for the End-On Drop Test

in the Z direction, which was the direction of impact. The model was dropped on the top end.

Figure 6 illustrates the accelerometer locations for the slapdown drop test. In this test, accelerometers were installed at four different planes located at different axial positions on the cask. Four different Endevco models were used (Appendix B). A number of them were soft mounted using a thin layer of an elastomeric material, as described in Appendix B. The soft mounting was used to dampen frequencies above 3000 Hz, which were observed in the end drop test. For this test the significant acceleration readings were predominantly in the X direction. Accelerometer results were digitized and filtered to levels of 500, 750, 1000, 1500, and 2000 Hz.

Figure 7 illustrates the instrumented bolt channels and their fit in the system. The bolts were 0.5 inch diameter Straininsert™ internally gauged bolts selected to exceed the strength of the bolts that would normally be used (Appendix A). The instrumentation wires were run through the bolt installation tubes and attached to connection strips on the cask body. Instrumented bolts were used only on the bottom end of the cask. These channels were designated SB5-SB8. Regular bolts retained the top impact limiter. The shear pins indicated in Figure 7 were 0.5 inch in diameter and were fabricated from high-strength steel (ASME SA-540). Sacrificial strain gages were installed near the corners of the impact limiters to signal the times of contact.

The tests were recorded by high-speed motion-picture cameras, including Milliken cameras (400 frames/sec), Nova cameras (2000 frames/sec), and a streak camera. The films were digitized to obtain displacement and velocity data.

Figure 6. Schematic of the Instrumentation for the Slapdown Drop Test

BOLT AND SHEAR PIN PATTERN

INSTRUMENTED BOLT DETAIL

Figure 7. Schematic of the Impact Limiter Bolt Instrumentation

4.0 RESULTS

4.1 End-On Drop Test

The system was dropped from 30 ft and impacted the target in an almost perfect orientation at 44 ft/sec. Figure 8 shows the cask system, just before the test, suspended on the cross beam above the target. Figure 9 is a sequence of photographs taken from a high-speed film recording of the event focusing on the impact end of the cask. The duration of the impact was about 13.4 ms. During the impact, the cask body punched into the impact limiter about 3 in. The limiter did not crush at the limiter/target interface. (A more detailed description of damage sustained by the system can be found in Appendix C.) The motion of the cask moving into the limiter can be observed in Figure 9 by noting the displacement of the stripes on the cask relative to the impact limiter. Figure 10 is a photograph taken at the end of the impact just as the cask had come to rest. The system remained in an upright position and the damage sustained was not readily apparent.

Disassembly of the system was complicated by the collapse of the tubes which allow access to the bolts. The damage sustained by the limiter was observed by cutting away a portion of the limiter end plate to allow access to the wood. A portion of the wood was then removed to observe the damage. Damage to the structure consisted of some tearing of sheet metal and buckling of gusset plates and tubes. Figure 11 includes a photograph showing a buckled tube and gusset plate and a sketch of the approximate deformation pattern of the gusset plate. Note that the gusset plates were severely buckled under the cask body whereas portions of the gusset plates extending along the sides of the cask body did not undergo significant buckling.

The vertical motion of the cask and limiter was observed by digitizing high-speed film recording and plotting the vertical displacement and velocity results as a function of time. Figure 12 is a plot of the cask and impact limiter displacement. These displacement results indicate that the external surface of the limiter stopped almost

Figure 8. The Test System in Position for the End-On Drop Test

**TIME
(SEC)**

$t=0.0$

$t=0.002$

$t=0.004$

Figure 9. Sequence From High-Speed Film of the End-On Drop Test

**TIME
(SEC)**

$t=0.006$

$t=0.008$

$t=0.010$

Figure 9. Sequence From High-Speed Film of the End-On Drop Test
(continued)

**TIME
(SEC)**

$t=0.012$

$t=0.014$

Figure 9. Sequence From High-Speed Film of the End-On Drop Test
(concluded)

Figure 10. The Test System After the End-On Drop Test

instantly after contacting the target surface. The cask body kept moving and punched into the limiter, causing the damage described above. The velocity differences between the dynamics of the cask and limiter are more dramatic. Figure 13 illustrates the velocity-time histories of the cask and impact limiter. The gradual slowdown of the cask and the abrupt stopping of the impact limiter can be seen clearly in this figure. These results indicate that the system had a rebound velocity of approximately 4 ft/sec. Fitting a straight line to the velocity-time history of the cask results in an average deceleration of about 100 g.

The accelerometer results from this test were disappointing in that most traces were not usable; a very high frequency content caused the units to "ring," thus rendering the data unusable. However, two units mounted on the reverse side of the instrumentation blocks did yield credible results. Figure 14 is a deceleration trace from a unit mounted at the approximate midpoint of the cask. (A complete data set on microfiche is included inside the back cover of this report.) This

Figure 11. Deformation Pattern in the Impact Limiter Gusset Plates After the End-On Drop Test

Figure 12. Vertical Displacement vs. Time for a Point on the Cask and on the Impact Limiter During the End-On Drop Test

Figure 13. Vertical Velocity vs. Time for a Point on the Cask and on the Impact Limiter During the End-On Drop Test

Figure 14. Acceleration vs. Time for the End-On Drop Test

trace, filtered to 1000 Hz, indicates a deceleration spike to approximately 180 g and a leveling-off at about 100 g. It also indicates a pulse duration of about 13 ms.

4.2 Slapdown Drop Test

The cask system was successfully dropped and impacted the target at an angle of 12.4 degrees. Figure 15 shows the cask system just before contacting the target. Figure 16 is a sequence of photographs taken during the impact. The duration of this impact was approximately 40 ms. After impacting at 44 ft/sec, the system translated vertically, without rotating, for about 8 ms, crushing the corner of the impact limiter on the top end. The system then began rotating while continuing to crush the impact limiter. At 20.6 ms into the impact, the cask had rotated sufficiently for the bottom impact limiter to contact the target. The bottom impact limiter crushed about 6 in. as the cask came to a stop. Figure 17 shows the system on the target after the test. The rotation of the cask system during impact caused the corner of the top limiter to come

Figure 15. The Test System Before Impacting the Target in the Slapdown Drop Test

**TIME
(SEC)**

$t=0.0$

$t=0.005$

$t=0.010$

Figure 16. Sequence From High-Speed Film of the Slapdown Drop Test

**TIME
(SEC)**

$t=0.015$

$t=0.020$

$t=0.025$

Figure 16. Sequence From High-Speed Film of the Slapdown Drop Test
(continued)

**TIME
(SEC)**

$t=0.030$

$t=0.040$

Figure 16. Sequence From High-Speed Film of the Slapdown Drop Test
(continued)

**TIME
(SEC)**

$t=0.045$

$t=0.050$

Figure 16. Sequence From High-Speed Film of the Slapdown Drop Test
(concluded)

to rest approximately 2-1/2 in. off the target surface (Figure 17, lower photograph). Some tearing of the impact limiter skin in the crushed areas was evident. Scuff marks on the target surface indicated the system slid approximately 6 in. in the direction of the bottom end of the cask. It was also immediately evident that the limiter retaining bolts on the bottom end of the cask had failed, allowing the limiter to move outward slightly. Measurements of the distance between the cask body and the target indicated that near the bottom limiter the cask came to rest 2-7/8 in. from the target surface. A similar measurement near the top limiter indicated a clearance of 3-7/8 in. Figure 18 shows the crushed surfaces on both impact limiters. The flattened surfaces were about 22 in. wide. Detailed deformation measurements are included in Appendix C.

Figure 19 shows the fractured bottom impact limiter bolts. The bolts shown in the upper photograph of Figure 19 were placed at the upper locations and the bolts shown in the lower photograph of Figure 19 were in the lower (impact side) locations. The upper bolts failed in a mode that was almost purely shear. The failure surface was nearly perpendicular to the bolt axis. The lower bolts appeared to have failed in a combined tensile and bending mode; the fracture surface was angled. The inclined failure surface was composed of ductile fracture dimples. Roots of threads were stretched on the top surface, indicating tensile loading. There was no evidence of flaws, which could have initiated fracture, in any of the bolts and there was no evidence of brittle fracture modes. Micrographs of the fracture surface and a more detailed discussion of the bolt failures are included in Appendix D.

As in the first test, high-speed film recordings were digitized to study the motion of the cask during the impact. These studies concentrated on following the CG of the cask, measuring vertical and horizontal displacement and the attitude of the cask body.

Figure 20 illustrates the vertical displacement of the CG of the cask as a function of time. The CG displaced approximately 11 in. downward after the top corner of the system contacted the target.

Figure 17. The Test System After the Slapdown Drop Test

Figure 18. Deformations Sustained by Impact Limiters in the Slapdown Drop Test

Figure 19. Failed Impact Limiter Retaining Bolts

Figure 20. Vertical Displacement vs. Time for the Center of Gravity of the Cask During the Slapdown Drop Test

Superimposed on these results are dotted lines indicating points in time for the primary and secondary impacts and the point in time when the bolts failed. Figure 21 illustrates the cask attitude as a function of time during the impact. The cask rotated very slightly during the first 8 ms of the impact. The system then rotated about 12 degrees in the following 17 ms. The displacement data of Figure 20 with the rotational data of Figure 21 can be used to determine the displacement of each point on the cask as a function of time.

Figure 22 illustrates the velocity-time results obtained for the CG from the digitized film data. These results were obtained by differentiating the displacement data. The CG decelerated from the impact velocity of 44 ft/sec to rest in about 35 ms. This represents an average deceleration of about 40 g.

Figure 23 illustrates angular velocity results for the CG from the digitized film data. These results were obtained by differentiating the cask attitude data. The maximum rotational velocity is about 13 rad/s at 22 ms after start of impact.

The accelerometer data were digitized and filtered to different levels. The results presented here are for a filtering level of 1000 Hz. The results were grouped according to the plane of the accelerometer location. (A complete data set on microfiche is included inside the back cover of this report.) Results for the top end (first plane) are included in Figure 24. The accelerometer results were quite consistent, indicating a pulse that corresponds to crushing the top impact limiter. The duration of the pulse is about 15 ms and the deceleration level is approximately 100 g. The secondary pulse is not discernible. Figure 25 includes results from accelerometers located at the approximate center of the cask (third plane). Both the primary and secondary impact pulses are evident in these data. Three of four accelerometers at this location yielded consistent results. The pulses for both the primary and secondary impacts appear to be approximately equivalent at this location. The peak deceleration levels indicated by the pulses were about 50 g. Figure 26 includes results from an accelerometer located between the

Figure 21. Cask Attitude vs. Time for the Cask During the Slapdown Drop Test

Figure 22. Vertical Velocity of the Center of Gravity of the Cask vs. Time During the Slapdown Drop Test

Figure 23. Angular Velocity of the Cask vs. Time During the Slapdown Drop Test

Figure 24. Acceleration vs. Time From Accelerometers on the First Plane Measured During the Slapdown Drop Test

Figure 25. Acceleration vs. Time From Accelerometers on the Third Plane Measured During the Slapdown Drop Test

Figure 26. Acceleration vs. Time From Accelerometers on the Fourth Plane Measured During the Slapdown Drop Test

center and bottom end of the cask (fourth plane). These results indicate much less sensitivity to the primary pulse and more sensitivity to the secondary pulse. Levels for the secondary pulse were about 100 g for this location. Figure 27 includes results from accelerometers located at the bottom end of the cask (fifth plane). These accelerometers predominantly read the secondary impulse. The results from these units were quite consistent and indicated a peak deceleration level for the pulse of about 140 g. Acceleration levels recorded for the axial direction of the cask were low. The maximum levels were recorded during the primary impact. Figure 28 includes results from axial accelerometers located at the approximate center of the cask. These units indicated maximum values on the order of 15 g.

Microstrain signals from the instrumented bolts indicated a sharp rise in strain at the time of the secondary impact. The upper bolts (SB5 and SB8) indicated strain levels that rose sharply at the point of contact and peaked at about 23 ms into the impact (Figure 29). Strain levels in the lower bolts (SB6 and SB7) peaked at about 25 ms into the impact (Figure 30).

Figure 27. Acceleration vs. Time From Accelerometers on the Fifth Plane Measured During the Slapdown Drop Test

Figure 28. Acceleration in Axial Direction vs. Time From Accelerometers on the Third Plane During the Slapdown Drop Test

Figure 29. Microstrain Signals From Instrumented Bolts SB5 and SB8 Measured During the Slapdown Drop Test

Figure 30. Microstrain Signals From Instrumented Bolts SB6 and SB7 Measured During the Slapdown Drop Test

5.0 DISCUSSION OF RESULTS

The reliability of drop test results depends upon instrumentation accuracy, which, in turn, relies upon the accuracy of the accelerometer and film data. The accuracy of accelerometer results has been reviewed in detail (Madsen et al., 1987). The review includes a detailed analysis of accelerometer accuracy for the same data acquisition system and data reduction methods applied in this study. Five possible sources of error in the complete process beginning with accelerometer calibration and ending with data reduction were considered. The review concludes that the expected uncertainties are $\pm 15\%$.

For photometric data, the principal error is introduced by reducing poor quality film. If the film is poor, it is difficult to accurately follow the displacement of the structure. Therefore, general judgments regarding the accuracy of film data cannot be made. Based upon a comparison of results from two different cameras, the digitized displacement data are considered reasonably accurate ($\pm 1/2$ in.). For impact velocity (44 ft/sec), results from the streak and the framing cameras agreed within 1 ft/sec.

The impact limiters greatly mitigated the severity of the 30-ft impact and held cask deceleration levels relatively low. In the end-on drop test, the cask tended to punch through the limiter rather than the limiter crushing at the target interface. Either deformation mode was within the performance envelope. The inner impact limiter structure is not sufficiently rigid to distribute the cask loading, thereby causing crushing along the projected area of the cask body on the limiter.

The force-displacement characteristic of the impact limiter for the end-on drop condition was calculated using accelerometer data in conjunction with digitized film data. (Calculations are included in Appendix E.) Figure 31 shows the calculated force-displacement curve for the limiter. The curve indicates a peak force of about 1,750,000 lb. The average stress level in the effective crush area of the impact limiter can be calculated by considering the projected area of the cask

Figure 31. Force vs. Displacement for the Impact Limiter From the End-On Drop Test

(706 in.²) and the peak crush force (1,750,000 lb). This calculation yields an average stress value of approximately 2500 psi, which is significantly higher than the crush value of balsa. Thus, the embedded metal structure (steel gusset plates) significantly contributes to the peak exhibited by the force-displacement curve (Figure 31).

When buckling begins in the metallic structure, the force level drops significantly and remains at a fairly constant level. The generated force-displacement curve indicates the wood crushed at a force level of about 800,000 lb. This value is consistent with the crush strength of balsa. 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 system response to the slapdown drop test was much more complex than for the end-on drop, as expected. Deceleration levels throughout the cask varied significantly. During the primary impact, high deceleration levels on the impact end dropped progressively with distance from the impact point. The secondary impact resulted in decelerations to the bottom end that were higher than those observed on the top end during the primary impact. The peak decelerations recorded on the bottom end were on the order of 140 g, about 40% higher than what was observed on the top end.

During the secondary impact, combined shear and moment loading tended to dislodge the bottom impact limiter from the cask body. The moment loading generated from the frictional and vertical forces separated the limiter from the cask at the bottom side by pivoting the limiter around the cask; thus the loadings to the upper and lower bolts were different in nature. The upper bolts, which were close to the pivot point, were loaded almost completely in shear. The lower bolts experienced tension and shear. End conditions on the bolts approached fixed: one end was fixed into the cask body and the other end fit snugly into heavy collars welded to the ends of the bolt tubes. These end conditions constrained the bolt ends from rotating, resulting in the creation of large bending stresses in the lower bolts when the impact limiter moved laterally away from the cask body.

As with the end-on test results, filtered accelerometer data along with photometrics data were used to generate force-displacement curves for the impact limiters in the slapdown drop test. A newly developed technique, the sum of weighted accelerations technique (SWAT) (Bateman et al., 1989), was used to reduce the accelerometer data to obtain the force input to the cask. A deconvolution technique was used to check the SWAT calculations. (Details for this process are included in Appendix F.) Figure 32 shows force-displacement results for both the primary and secondary impacts. The secondary impact produced a larger peak force, approximately 500,000 lb; the primary impact peak force was approximately 400,000 lb. Figure 32 shows that the crush energy absorbed during the secondary impact was considerably larger than the energy

Figure 32. Force vs. Displacement for the Impact Limiter From the Slapdown Drop Test

absorbed in the primary impact. The sum of the crush energy, corresponding to the areas under both curves, agreed within 6% with the kinetic energy of the system. This good agreement supports the calculated force-displacement curves.

6.0 CONCLUSIONS

The impact limiters are designed to greatly mitigate forces and decelerations to the cask body. In the end-on drop test, decelerations to the cask were limited to about 100 g and were uniform throughout the cask. The limiter deformation mode involved the cask punching into the limiter rather than the limiter crushing at the target interface.

In the slapdown drop test, decelerations levels varied throughout the cask structure. The primary impact resulted in deceleration values of about 100 g at the top end (primary impact end) of the cask. The secondary impact was more severe and resulted in deceleration levels of about 140 g at the bottom end of the cask.

Well-established scaling laws indicate that decelerations in scale model impact tests vary with the full-scale system as the inverse of the scale factor. The scale factor for the model system tested was 3; therefore decelerations in the full-scale system are expected to be one-third of the values observed in the tests.

The secondary impact resulted in extremely severe forces on the bottom impact limiter retention bolts, leading to bolt failure. A strengthened impact limiter retention system should be implemented.

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APPENDIX A

FABRICATION DRAWINGS FOR THE
MODEL CASK AND IMPACT LIMITERS

TN-BRP/REG SCALE MODEL, IMPACT LIMITER TESTS, FRONT IMPACT LIMITER

TN-BRP/REG PACKAGING, TEST BODY FOR IMPACT LIMITER TESTS

TN-BRP/REG SCALE MODEL, IMPACT LIMITER TESTS, REAR IMPACT LIMITER

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- NOTES:

1. FOR TN-BRP/REG-SCALE MODEL ASSEMBLY AND PARTS LIST
SEE DWG 3024-23-B.
2. TOLERANCE, UNLESS OTHERWISE SPECIFIED: $\pm .12"$
3. PIN DIA .500" $\pm .0013"$ HOLE DIA .500" $\pm .0007"$
 $\pm .0009"$ ± 0
4. MATERIAL: PLATES, BUSSETS, LUGS, NPE = JIS S41
PAN - JIS SUS304

OCT 16 1986

FOR INFORMATION

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Q/A	<i>[Signature]</i>	<i>[Signature]</i>					
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DATE		1/4		SIZE		DWC-NO	
1/4		1/4		1/4		1/4	

A-3/A-4

.500"-13 UNC-2B
.75" MIN THD DP
1.00" MAX DRILL DP
8 HOLES ON 21.000" DBC
 $\oplus A \phi .016$

NOTES:

1. MATERIAL: CARBON STEEL (MAY BE CAST)
2. TOLERANCE, U. O. S.:
2-PLACE DECIMALS (.XX) $\pm .03$ "
3-PLACE DECIMALS (.XXX) $\pm .010$ "
3. FINAL DIMENSION TO BE ESTABLISHED TO OBTAIN 3600 $\pm$ 36 KG TOTAL WEIGHT.
4. TOLERANCE ON FORGING OUTER DIAMETER $\pm .00$ "
IN THIS AREA $-.03$ "
5. SST NAMEPLATE TO BE ATTACHED AT 0° NEAR CENTER OF BODY WITH THE FOLLOWING MARKING: "TN-BRP/REG 1/3 SCALE TEST BODY"
6. ALTERNATE WELD LOCATIONS MAY BE PROPOSED.
7. DRDP FORGED STEEL SHOULDER EYEBOLTS -1.50"-6 UNC, SHANK LENGTH = 2.00" $\pm .00$ "
 $-.25$ "

14.75 $\pm$.12"
TO SPOTFACE
8 PLACES

.09 $\pm$.03"
.09 $\pm$.03"
CHAMFER

30.08"
DIA
A

5.68" DIA SPOTFACE
1.50"-6 UNC-2B
2.75" MAX TAP DRILL DP
2.25" MIN THD DP
8 PLACES-NOTE 7.

1.50"
2.88"

SEE NOTE 3
(BARS TO BE CENTERED IN CAVITY)

SECTION A-A

FOR INFORMATION ONLY

NOTES: CON'T.

B. 250/ OUTSIDE SURFACES

9. FOR ACCELEROMETER BLOCK LOCATIONS
SEE DWG 3024-23-2.

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3	08/11/86	SEE DCN 3024-23-3	JTG	C7				
2	07/21/86	SEE DCN 3024-23-2	JTG	C7				
1	06/18/86	SEE DCN 3024-23-1	J.T.G.	4B				
NO.	DATE	REVISIONS	DWN.	CK'D.	Q/A	PROJ.		
APPROVALS		DATE	TRANSNUCLEAR, INC. WHITE PLAINS, N.Y.					
PROJ.		5-13-86						
Q/A			TN-BRP/REG PACKAGING TEST BODY FOR IMPACT LIMITER TESTS					
CK'D. BY		5-13-86						
J.T.G.		13 MAY 86	1/12	B	3024-23-1	3		
DWN. BY			SCALE	SIZE	DWG. NO.	REV.		

.500"-13 UNC-2B
.75" MIN THD DP
1.00" MAX DRILL DP
4 HOLES EQL SP
STRADDLE ϕ 'S ON 21.000" DBC
 $\oplus B \phi .016$

AUG 22 1986

APPENDIX B
INSTRUMENTATION SPECIFICATIONS

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This appendix presents information on the test instrumentation used in the drop tests, including manufacturer's specifications and other pertinent information.

Three types of accelerometers were used. These are listed below, along with their g limit and frequency response.

<u>Model</u>	<u>g Limit</u>	<u>Frequency Response (kHz)</u>
2262	1000	1.5
2264A-5K-R	5000	8
7270A	2000	10

Figures B-1 through B-3 include specifications for these devices. Some of the Model 7270A accelerometers were soft-mounted, as indicated in the text. Figure B-4 details how this was accomplished. Special aluminum mounting blocks were fabricated as illustrated. Each mounting block contained two small aluminum plates bonded with a 0.010-in. layer of polysulfide rubber.

All accelerometers were calibrated using a shaker table and centrifuge. Figures B-5 through B-8 include sample calibration results for 7270A accelerometers using both hard and soft mountings.

The instrumented bolts used to measure forces tending to dislodge the impact limiters were Strainert SDH-QB-1/2-13NC x 2 1/2 Lg. Each bolt was calibrated to 18,200 lb. Figure B-9 shows the results of a calibration test conducted at Sandia National Laboratories. Each instrumented bolt was capable of carrying a load of about 27,000 lb.

ENDEVCO® MODELS 2262-1000/2262C-1000 PIEZORESISTIVE ACCELEROMETERS

±1000 g Damped

The Models 2262-1000 and 2262C-1000 are rugged, damped accelerometers that measure static and dynamic acceleration. ENDEVCO's PIEZITE® Type P-9 piezoresistive elements are employed in a full bridge circuit to obtain a high level, low impedance output at ±1000 g full scale. The Model 2262C is a six-wire device with a pair of fixed precision resistors in half the bridge designed especially for shunt calibration. The Model 2262 utilizes four-active arms for acceleration measurement. The units will withstand up to 2.5 times their rated range without damage or calibration shift. The use of subcritical viscous damping extends their useful frequency range and reduces the effect of spurious, high frequency vibrations. The broad frequency response from steady state to 2000 Hz makes these transducers ideal for measurement of transient type phenomena such as encountered in rocket engine ignitions, package testing, transportation shock and automotive crash studies.

(All values are typical at -75° F [+24° C] unless otherwise specified)

	MODEL 2262-1000	MODEL 2262C-1000
PERFORMANCE		
RANGE	g ±1000	±1000
SENSITIVITY (at 10 Vdc excitation, ref 100 Hz) Typical/Minimum	mV/g 0.5/0.375	0.25/0.187
NON-LINEARITY & HYSTERESIS (% of reading, max. to full range)	% ±1	±1
FREQUENCY RESPONSE ¹ (±5% max. ref 100 Hz)	Hz 0 to 1500	0 to 1500
MOUNTED NATURAL FREQ	Hz 6000, typical	6000, typical
DAMPING RATIO ²	0.7 +0.15 -0.10	0.7 +0.15/0.10
TRANSVERSE SENSITIVITY (max)	% 3	3
THERMAL SENSITIVITY SHIFT (ref +75° F [+24° C])	% -2/0/-4 °F 0 +75/+200 °C -18 +24 +93	2/0/-4 0/+75/+200 -18/+24/+93
ZERO MEASURAND OUTPUT (max)	mV ±10	±10
THERMAL ZERO SHIFT (max) ³	mV ±10	±10
BASE STRAIN SENSITIVITY (at 250 µstrain)	EQ/g 0.05	0.05
ELECTRICAL		
EXCITATION ^{4,5}	Vdc 10.0	10.0
INPUT RESISTANCE ⁶	Ω 560	1000
OUTPUT RESISTANCE	Ω 350	1000
INSULATION RESISTANCE (minimum at 100 Vdc)	MΩ 100 leads to case	100, leads to case
GROUNDING	Cable shield common to case Case isolated from sensors	Cable shield common to case Case isolated from sensors
PHYSICAL		
WEIGHT (excluding cable)	oz (gm) 1 (28)	1 (28)
CASE MATERIAL	Stainless steel, type 416	Stainless steel type 416
ELECTRICAL CONNECTIONS	Integral six-pin connector	Integral six-pin connector
MOUNTING TORQUE	Hole for 10-32 mounting stud 18 lbf-in (2 Nm)	Hole for 10-32 mounting stud 18 lbf-in (2 Nm)
ENVIRONMENTAL		
ACCELERATION LIMITS (in any direction)		
Static	g 1000	1000
Sinusoidal	g 1000	1000
Shock	g 2500 half-sine pulse	2500 half-sine pulse
TEMPERATURE		
Operating	°F (°C) 0 to +200 (-18 to +93)	0 to +200 (-18 to +93)
Non-Operating	°F (°C) -20 to +220 (-29 to +104)	-20 to +220 (-29 to +104)
HUMIDITY	Hermetically sealed by welding and glass-to-metal fusion	Hermetically sealed by welding and glass-to-metal fusion
CALIBRATION DATA SUPPLIED (at 75° F [24° C] and 10.00 Vdc excitation)		
FREQUENCY RESPONSE	Range in Hz	
SENSITIVITY (at 100 Hz)	mV/g	
ZERO MEASURAND OUTPUT	mV	
MAXIMUM TRANSVERSE SENSITIVITY	% of calibrated sensitivity	
MOUNTED NATURAL FREQUENCY	Hz	
DAMPING RATIO	Ratio of critical damping	
INPUT AND OUTPUT RESISTANCE	Ω

NOTES

- ¹Frequency Response is 5 - 8% maximum 0 to 2000 Hz
- ²Damping ratio is 2.2 ± 0.2 typical at 0 +200 F (-18 +93 C)
- ³Thermal Zero Shift millivolts specified are at 0 +200 F (-18 +93 C) reference +75 F (+24° C)
- ⁴Rated excitation is 10.0 Vdc. The strain gage elements have a positive temperature coefficient of resistance of approximately 0.5% per °F
- ⁵Other excitation voltages may be used to 15.0 Vdc but should be specified at time of order to obtain a more accurate calibration. Warmup time to meet all specifications is one minute maximum. Endevco Model 4423 Signal Conditioner is recommended as the excitation source.
- ⁶Measured at approximately 1 Vdc. Bridge resistance increases with applied voltage.

ACCESSORIES INCLUDED

- Model 2981 3 (10-32) or Model 2981 4 (M5 metric) mounting stud
- Model 2262** Model 3022B 30 Cable Assembly 4 conductor shielded 30 in (76 cm) long
- Model 2262C** Model 3023B 30 Cable Assembly 6-conductor shielded 30 in (76 cm) long
- U.S. Patent Number 3,351,881 applied for this transducer. "B" A 226 1000-508L A

Figure B-1. Data Sheet for an Endevco 2262-1000 Piezoresistive Accelerometer

ENDEVCO PRODUCT DATA			2264A SERIES		
			Small, Lightweight to 50 000 g		
			PIEZORESISTIVE SHOCK ACCELEROMETERS		
<p>The Model 2264A Series of Piezoresistive Accelerometers is designed for use in high shock applications. Their small size and low mass assure minimum loading of the test structure.</p> <p>With a nominal full scale output of 500 mV at 10 Vdc excitation the accelerometers can be operated directly into voltmeters, oscilloscopes and many recorders without amplification. High resonance frequencies and essentially zero damping allow the accelerometers to respond accurately to fast rise time short duration shock motion.</p> <p>Piezite® Type P-16 Elements are utilized in two active arms with fixed internal bridge completion resistors to provide a low impedance full bridge circuit. With a frequency response extending down to dc or steady state acceleration these accelerometers are ideal for the measurement of long duration motion.</p>			<p>Two times actual size</p>		
COMMON SPECIFICATIONS FOR THE 2264A SERIES ACCELEROMETERS (According to ANSI and ISA Standards)					
<p>DYNAMIC</p> <p>RANGES AVAILABLE $\pm 2\ 000$, $\pm 10\ 000$, $\pm 20\ 000$, $\pm 50\ 000$ g pk</p> <p>OUTPUT, FULL SCALE 500 mV nominal</p> <p>THERMAL SENSITIVITY SHIFT $+15\ 0/-15\%$ nominal, at $0\ 75/150^{\circ}\text{F}$</p> <p>Q, AT RESONANCE 50 dB, nominal</p> <p>DAMPING FACTOR 0.002 nominal</p> <p>TRANSVERSE SENSITIVITY 5%, Maximum</p> <p>ELECTRICAL</p> <p>EXCITATION¹ 10.00 Vdc</p> <p>ZERO MEASURAND OUTPUT ± 50 mV maximum, at 75°F (24°C)</p> <p>THERMAL ZERO SHIFT ± 25 mV maximum, at 0°F and 150°F (-18°C and $+66^{\circ}\text{C}$) reference 75°F (± 30 mV maximum, — 50 K-R only)</p> <p>INPUT RESISTANCE (full bridge) $500 \pm 100\ \Omega$ (— 50 K-R $700 \pm 225\ \Omega$)</p> <p>OUTPUT RESISTANCE (full bridge) $500 \pm 100\ \Omega$ (— 50 K-R $850 \pm 275\ \Omega$)</p> <p>BRIDGE COMPLETION RESISTORS $500 \pm 100\ \Omega$</p> <p>INSULATION RESISTANCE² 100 MΩ minimum at 100 Vdc</p>			<p>NOTES:</p> <p>¹Unit is calibrated with 10.00 Vdc excitation. Warmup time to meet all specifications is one minute. The Endevco® Model 4470 Universal Signal Conditioner is recommended as the excitation source.</p> <p>²The sensing elements case and cable shield are insulated from each other. To shield the sensing elements from stray electric fields ground the case by removing the anodize on the flange under a screw head.</p> <p>³The suffix R after the part number indicates that bridge completion resistors are mounted within the transducer.</p> <p>⁴Model 2264A 50K R has been designed to withstand 100 000 g in sensitive axis but is not tested to this level.</p> <p>⁵Recommended minimum pulse duration for half sine or triangular pulses to avoid excessive high frequency ringing. See Endevco® Piezoresistive Instruction Manual.</p>		
TABLE OF SPECIFIC CHARACTERISTICS					
Dash Number ³	-2K-R	-5K-R	-10K-R	-20K-R	-50K-R
Range g pk	$\pm 2\ 000$	$\pm 5\ 000$	$\pm 10\ 000$	$\pm 20\ 000$	$\pm 50\ 000$
Sensitivity, mV/g at 10 Vdc, nominal	0.250	0.130	0.065	0.025	0.010
minimum	0.175	0.070	0.035	0.0175	0.007
Mounted Resonance Frequency, Hz nominal	30 000	50 000	70 000	100 000	180 000
Useful Frequency Response Hz dc to	5 000	8 000	12 000	16 000	30 000
Environmental Acceleration Limits Sensitive Axis g pk	$\pm 5\ 000$	$\pm 12\ 500$	$\pm 25\ 000$	$\pm 50\ 000$	$\pm 100\ 000^4$
Transverse Axis g pk	$\pm 5\ 000$	$\pm 12\ 500$	$\pm 25\ 000$	$\pm 30\ 000$	$\pm 50\ 000$
Minimum Half Sine Pulse Duration ⁵ , μs	200	125	80	65	30

Figure B-2. Data Sheet for an Endevco 2264 Piezoresistive Accelerometer

ENDEVCO® SERIES 7270A

PIEZORESISTIVE ACCELEROMETERS

High g High Resonant Frequency

The Model 7270A Series of Piezoresistive Accelerometers are rugged undamped units designed for shock measurements. ENDEVCO chemically sculpts the sensing system of the 7270A from a single piece of silicon. This etched silicon chip includes the inertial mass and strain gages arranged in an active four-arm Wheatstone bridge circuit complete with a novel on-chip zero balance network. The low mass, extremely small size and unique construction of the element blends an exceptionally high resonant frequency with characteristics such as low impedance, high overrange, and zero damping for no phase shift. The high resonant frequency of these sensors permits their survival in the presence of these high frequency components in a shock pulse that could shatter the seismic system of accelerometers having lower resonance. High resonance frequencies and zero damping allow the accelerometers to respond accurately to fast rise time, short duration shock motion. With a frequency response extending down to dc or steady state accelerations, these transducers are ideal for measurement of long duration transients.

(All values are typical at +75° F [+24° C] with 10 volts excitation applied unless otherwise specified.)

		MODEL 7270A-2K	MODEL 7270A-6K	MODEL 7270A-20K	MODEL 7270A-60K	MODEL 7270A-200K
PERFORMANCE						
RANGE	g	2000	6000	20 000	60 000	200 000
SENSITIVITY						
(at 10 Vdc excitation, ref 100 Hz)						
Minimum/Maximum	$\mu\text{V/g}$	50/150	15/50	5/15	15/5	0.5/1.5
NON-LINEARITY & HYSTERESIS						
(% of reading, max, to full range)	%	± 1	± 1	± 2	± 2	± 2
FREQUENCY RESPONSE ¹						
($\pm 5\%$ max, ref 100 Hz)	kHz	10	20	50	100	150
MOUNTED RESONANT FREQ	kHz	90	180	350	700	1200
TRANSVERSE SENSITIVITY (max)	%	5	5	5	5	5
THERMAL SENSITIVITY SHIFT						
(ref +75° F [+24° C])	$\%/^{\circ}\text{F}$	~ 06	06	$- 06$	$- 06$	$- 06$
	$\%/^{\circ}\text{C}$	$- 12$	$- 12$	$- 12$	$- 12$	$- 12$
ZERO MEASURAND OUTPUT (max)	mV	± 100	± 100	± 100	± 100	± 100
THERMAL ZERO SHIFT (max) ²	mV	± 30	± 30	± 30	± 30	± 30
BASE STRAIN SENSITIVITY						
(at 250 μstrain)	mV	≤ 5	≤ 5	≤ 5	≤ 5	≤ 5
OVERRANGE LIMITS						
	g	10 000	18 000	60 000	180 000	200 000
ELECTRICAL						
EXCITATION ^{3,4}	Vdc	10.0	10.0	10.0	10.0	10.0
INPUT RESISTANCE ⁵	Ω	550	550	550	550	550
OUTPUT RESISTANCE ⁵	Ω	550	550	550	550	550
INSULATION RESISTANCE						
(minimum at 100 Vdc)	M Ω	100, between sensors, cable shield or case				
GROUNDING						
		Cable shield isolated from sensors and case				
		Case isolated from sensors				
PHYSICAL						
WEIGHT (excluding cable)	oz (gm)	0.05 (1.5)				
CASE MATERIAL		17-4 ph CRCS				
ELECTRICAL CONNECTIONS		Integral 4-conductor shielded cable 4 ft (1.2 m), minimum				
MOUNTING TORQUE ⁶		Two holes for 4-40 high strength screws and #4 washers				
ENVIRONMENTAL						
TEMPERATURE						
Operating	$^{\circ}\text{F}$ ($^{\circ}\text{C}$)	-30 to $+150$ (-18 to $+66$)				
Non-Operating	$^{\circ}\text{F}$ ($^{\circ}\text{C}$)	-65 to $+250$ (-54 to $+121$)				
HUMIDITY						
		Sealed by epoxy

NOTES

¹Frequency response should deviate by less than $\pm 5\%$ from dc to indicated frequency. Acceleration levels of conventional techniques are too low for accurate analysis of the frequency response of the higher range models. Measurement uncertainties above 10 kHz prevents stating $\pm 5\%$ as a specification limit for all but the 2000 g range.

²Thermal zero shift specified is at 0 to +150 F (-18 to +66° C) reference +75° F (+24° C).

³Rated excitation is 10.0 Vdc. The strain gage elements have a positive temperature coefficient of resistance of approximately 0.14% per ° F.

⁴Other excitation voltages may be used to 12.0 Vdc but should be specified at time of order to obtain a more accurate calibration. Warmup time to meet all specifications is two minutes maximum.

⁵Measurand at approximately 1 Vdc. Bridge resistance increases with applied voltage.

⁶Use 8 ± 2 lb in (2.7 Nm) mounting torque. acoustic couplant and high strength steel screws to (1) insure intimate contact between accelerometer and mounting surface and (2) to prevent yielding of the screw and loss of force due to shocks above 100 000g. Loss of meaningful data and possible damage to the accelerometer due to rattling on its mounting surface can result from using either too high or too low a value of mounting torque. If large transverse shocks are anticipated the use of liquid thread-locking compounds is recommended to reduce loss of screw preload.

The use of low strength mounting material (such as aluminum) is not recommended. However if such is the case epoxy should be used between the transducer and mounting surface to supplement the strength of the threads.

The cable should be mounted securely with tape or glue leaving a strain relief of between 1/4 inch and 1/2 inch at the transducer.

IMPORTANT Frequency content of shocks which exceed the overrange limits of the 7270A often contain significant signal amplitudes well above 100 kHz. Signal conditioning with insufficient bandwidth may attenuate the signal and give significantly lower indicated peak accelerations.

ACCESSORIES INCLUDED

Two EH137 4-40 $\times$ 1/2 socket head cap screw two 17147 size 4 special flat washers

7 6" PS7270A E

CALIBRATION DATA SUPPLIED
(at 75° F [+24° C] and 10.00 Vdc excitation)
SENSITIVITY at 10 000 g or full scale whichever is smaller
INPUT AND OUTPUT RESISTANCE
INPUT AND OUTPUT RESISTANCE
LEVEL OF OVERRANGE SHOCK

$\mu\text{V/g}$
 Ω
 Ω
Kg

Figure B-3. Data Sheet for an Endevco 7270A Piezoresistive Accelerometer

PSR = POLYSULFIDE RUBBER
Distributed by Tracon, Inc.

Figure B-4. Schematic of a Soft-Mounted Endevco 7270A-2K Piezoresistive Accelerometer

TRANSDUCER CALIBRATION REPORT
SANDIA LABS 7241 10/12/1988

MANUFACTURER ENDEVCO
MODEL 7270A-2k
SERIAL B625F DATAFILE # 7
TRANSDUCER TYPE SEMICONDUCTOR STRAINGAGE
CERTIFIED BY BG
EXPIRATION DATE 5/ 1/1989
TEMPERATURE AMBIENT FACILITY USED SHAKER
REQUESTING ORG. 6323
COMMENTS: D. BRONOWSKI SOFT MOUNTED.

REFERENCE UNITS	FREQUENCY HERTZ	TRANSDUCER OUTPUT uV/V/G	PERCENT DEVIATION FROM 100HZ
30.00	100.00	9.26259	0.00
30.00	200.00	9.25899	-.04
30.00	500.00	9.27967	.18
30.00	1000.00	9.31743	.59
30.00	1500.00	9.36443	1.10
30.00	2000.00	9.43334	1.84
30.00	2500.00	9.53315	2.92
30.00	3000.00	9.64387	4.12
30.00	3500.00	9.76785	5.45
30.00	4000.00	9.91798	7.08
30.00	4500.00	10.04354	8.43
30.00	5000.00	10.08588	8.89
30.00	5500.00	10.36513	11.90
30.00	6000.00	10.54446	13.84
30.00	6500.00	10.76269	16.20
30.00	7000.00	11.11137	19.96
30.00	7500.00	11.37444	22.80
30.00	8000.00	11.58826	25.11
30.00	8500.00	11.90390	28.52
30.00	9000.00	12.13323	30.99
30.00	9500.00	12.25934	32.35
30.00	10000.00	12.41848	34.07
INPUT RESISTANCE		476. OHMS	
OUTPUT RESISTANCE		471. OHMS	
INSULATION RESISTANCE		>10MEG	
ZERO OFFSET		0.0000 VOLTS	
TEST EXCITATION		9.96 VOLTS

uV V/G @ 100HZ: 9.2626

Figure B-5. Shaker Calibration of a Soft-Mounted Endevco 7270A Accelerometer

TRANSDUCER CALIBRATION REPORT
SANDIA LABS 7241 11/ 4/1988

MANUFACTURER ENDEVCO
MODEL 7270A-2K
SERIAL BG25F DATAFILE # 8
TRANSDUCER TYPE SEMICONDUCTOR STRAINGAGE
CERTIFIED BY FR EXPIRATION DATE 6/ 1/1989
TEMPERATURE AMBIENT FACILITY USED 5000-G CENTRIFUGE

REQUESTING ORG. 6323

COMMENTS: DAVE BRONOWSKI 6-4676
POSITIVE DIR. ONLY ; SOFT MOUNTED...

REFERENCE UNITS	TOTAL RAW OUTPUT	TRANSDUCER OUTPUT	PERCENT DEVIATION	PERCENT DEVIATION
G	μV	$\mu V/V/G$	FULLSCALE	BEST FIT LINE
399.0	25547.00	9.30886	-.02	-.10
799.5	62754.01	9.29863	-.08	-.21
1199.0	100129.0	9.31708	-.01	-.01
1601.8	137700.0	9.31922	.01	.01
1997.8	174650.0	9.32136	.03	.03

***** SENSITIVITY = 9.3181534 $\mu V/V/G$ *****

BEST FIT STRAIGHT LINE SENSITIVITY EQUATIONS:

$G = (.1073 * \mu V) / \text{EXCITATION VOLTAGE}$

$\mu V = (9.3182 * G) * \text{EXCITATION VOLTAGE}$

RESISTANCE(OHMS) INPUT= 476.0 OUTPUT= 471.0 INSULATION= 10MEG

TEST EXCITATION 10.0 VOLT

ZERO: -11599.000 μV TREATED AS OFFSET

Figure B-6. Centrifuge Calibration of a Soft-Mounted Endevco 7270A Accelerometer

TRANSDUCER CALIBRATION REPORT
SANDIA LABS 7241 10/12/1988

MANUFACTURER	ENDEVCO		
MODEL	7270A-2K		
SERIAL	CE56F	DATAFILE #	4
TRANSDUCER TYPE	SEMICONDUCTOR STRAINGAGE		
CERTIFIED BY	B6		
EXPIRATION DATE	5/ 1/1989		
TEMPERATURE	AMBIENT	FACILITY USED	SHAKER
REQUESTING ORG.	6323		
COMMENTS:	D. BRONOWSKI		

REFERENCE UNITS	FREQUENCY HERTZ	TRANSDUCER OUTPUT	PERCENT DEVIATION FROM 100HZ
6		$\mu V/V/6$	
30.00	100.00	7.69337	0.00
30.00	200.00	7.67937	-.18
30.00	500.00	7.68687	-.08
30.00	1000.00	7.69237	-.01
30.00	1500.00	7.69327	-.00
30.00	2000.00	7.69809	.06
30.00	2500.00	7.70354	.13
30.00	3000.00	7.71010	.22
30.00	3500.00	7.71318	.26
30.00	4000.00	7.71816	.32
30.00	4500.00	7.72415	.40
30.00	5000.00	7.73799	.58
30.00	5500.00	7.75179	.76
30.00	6000.00	7.74825	.71
30.00	6500.00	7.75670	.82
30.00	7000.00	7.76092	.88
30.00	7500.00	7.74256	.64
30.00	8000.00	7.77067	1.00
30.00	8500.00	7.78255	1.16
30.00	9000.00	7.80625	1.47
30.00	9500.00	7.78183	1.15
30.00	10000.00	7.79727	1.35
INPUT RESISTANCE		498. OHMS	
OUTPUT RESISTANCE		495. OHMS	
INSULATION RESISTANCE		>10MEG	
ZERO OFFSET		0.0000 VOLTS	
TEST EXCITATION		9.96 VOLTS

$\mu V/V/6$ @ 100HZ: 7.6934

Figure B-7. Shaker Calibration of an Endevco 7270A Accelerometer

TRANSDUCER CALIBRATION REPORT
SANDIA LABS 7241 10/12/1988

MANUFACTURER ENDEVCO
MODEL 7270A-2K
SERIAL CE56F DATAFILE # 3
TRANSDUCER TYPE SEMICONDUCTOR STRAINGAGE
CERTIFIED BY FR EXPIRATION DATE 5/ 1/1989
TEMPERATURE AMBIENT FACILITY USED 5000-G CENTRIFUGE

REQUESTING ORG. 6323
COMMENTS: DAVE BRONOWSKI 6-4676

REFERENCE UNITS	TOTAL RAW OUTPUT	TRANSDUCER OUTPUT	PERCENT DEVIATION FULLSCALE	PERCENT DEVIATION BEST FIT LINE
6	μV	$\mu V/V/G$		
-1997.5	-185720.	7.82694	.13	.13
-1600.0	-154420.	7.81570	-.01	-.02
-1199.8	-123340.	7.83244	.12	.20
-801.0	-92007.0	7.82081	.02	.05
-401.0	-60733.0	7.82236	.01	.07
401.0	2050.00	7.83107	.04	.18
798.1	33025.00	7.81536	-.01	-.02
1203.4	64646.01	7.81044	-.05	-.09
1605.1	96008.00	7.80964	-.08	-.10
1993.5	126330.0	7.80886	-.11	-.11

***** SENSITIVITY = 7.8171282 $\mu V/V/G$ *****

BEST FIT STRAIGHT LINE SENSITIVITY EQUATIONS:

$G = (.1279 * \mu V) / \text{EXCITATION VOLTAGE}$

$\mu V = (7.8171 * G) * \text{EXCITATION VOLTAGE}$

RESISTANCE(OHMS) INPUT= 498.0 OUTPUT= 495.0 INSULATION= >10MEG

TEST EXCITATION 10.0 VOLT

ZERO: -29358.000 μV TREATED AS OFFSET

Figure B-8. Centrifuge Calibration of an Endevco 7270A Accelerometer

B-12

Figure B-9. Force Calibration Test for an SDH-QB-1/2-13NC x 2 1/2 Lg Strainsert Bolt

APPENDIX C
POSTTEST MEASUREMENTS

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This appendix contains tabulated measurements of dimensional differences observed on the impact limiters after each test. Measurements were made pre- and posttest (Figure C-1). The differences observed after the first test, with only one limiter in place, are listed in Table C-1. Differences observed on both limiters after the slapdown drop test are listed in Tables C-2 and C-3. In Table C-2, the impact line of the limiter corresponds to location D1 (zero degrees), and the L1-L3 deformations range from 4.083 to 2.654 in. Because of a change in the test procedure, necessitated by the inability to remove the top impact limiter, the bottom limiter was rotated 180 degrees and the impact line for this limiter was at location D9 (180 degrees). Table C-3 shows the L1-L3 deformations, which ranged from 3.41 to 3.288 in.

As described in the text, the cask "punched" into the impact limiter about 3 in. This is reflected in the B1 and B2 as well as the F1 and F2 readings of Table C-1.

In the slapdown drop test, damage to the limiters occurred where the sides of the limiters contacted the target. The resulting deformations are reflected in differences in dimensions L1, L2, and L3. Figure C-2 illustrates the magnitude of the deformations sustained by the limiters at a section through the contact area.

Figure C-1. Schematic of Measurements From the Impact Limiter

TABLE C-1

DIMENSIONAL DIFFERENCES FOR THE TOP END IMPACT LIMITER
AFTER THE END-ON DROP TEST

Differences Impact Limiter Inspection Data

Limiter Designation: F1 Drop Test No.: NFS-1 Accuracy: ± 0.030

Internal Cavity Measurements

Long. Loc.	R1	R2	R3	R4	R5	R6	R7	R8
A1	not applicable							

Exterior Surface Measurements

Tan. Loc.	B1	B2	Longitudinal Location			F1	F2
			L1	L2	L3		
D1	+3.137	*	+0.024	-0.008	-0.070	-3.199	-3.109
D2	+3.152	+2.708	-0.003	lug	-0.100	-3.186	----
D3	+3.153	+2.785	-0.033	-0.076	-0.151	-3.221	-3.133
D4	+3.153	+2.748	-0.066	-0.091	-0.135	-3.153	----
D5	+3.045	*	-0.083	-0.084	-0.125	-3.117	-3.137
D6	+2.980	+2.677	-0.080	-0.076	-0.106	-3.027	----
D7	+2.878	+2.496	-0.049	-0.069	-0.102	-2.952	-3.002
D8	+2.783	+2.484	-0.067	-0.062	-0.109	-2.828	----
D9	+2.629	*	-0.028	+0.034	-0.019	-2.785	-2.962
D10	+2.683	+2.295	-0.017	0.000	-0.041	-2.754	----
D11	+2.763	+2.361	+0.008	+0.038	-0.033	-2.825	-2.930
D12	+2.867	+2.424	+0.016	-0.002	-0.044	-2.883	----
D13	+2.946	*	+0.028	+0.025	-0.037	-2.987	-3.016
D14	+3.001	+2.685	+0.050	+0.023	-0.042	-3.024	----
D15	+3.063	+2.720	+0.069	+0.034	-0.013	-3.073	-3.065
D16	+3.101	+2.720	+0.058	lug	-0.023	-3.130	----

Measured by: D. R. Bronowski.

*Unable to measure: Accelerometer, Blocks.

TABLE C-2

DIMENSIONAL DIFFERENCES FOR THE TOP IMPACT LIMITER
AFTER THE SLAPDOWN DROP TEST

Differences Impact Limiter Inspection Data

Limiter Designation: F1 Drop Test No.: NFS-2 Accuracy: .030

Internal Cavity Measurements

Long. Loc.	Radial Location							
	R1	R2	R3	R4	R5	R6	R7	R8
A1	limiter on body/unable to measure							

Exterior Surface Measurements

Tan. Loc.	Longitudinal Location						
	B1	B2	L1	L2	L3	F1	F2
D1	+1.054	*	-4.083	-3.333	-2.654	-3.96	+0.023
D2	+1.161	+0.759	-2.440	*	-1.077	-0.803	----
D3	+0.547	+0.499	+0.015	-0.014	-0.050	-0.521	-0.055
D4	+0.130	+0.175	+0.045	+0.074	+0.134	-0.131	----
D5	-0.273	*	-0.020	+0.119	+0.241	+0.254	+0.179
D6	-0.614	-0.487	+0.005	+0.157	+0.311	+0.569	----
D7	-0.846	-0.703	-0.072	+0.137	+0.317	+0.787	+0.499
D8	-0.965	-0.855	-0.060	+0.132	+0.298	+0.902	----
D9	-0.999	*	-0.079	+0.097	+0.243	+0.923	+0.587
D10	-0.953	-0.825	-0.087	+0.116	-0.298	+0.869	----
D11	-0.840	-0.675	-0.357	+0.124	+0.311	+0.717	+0.504
D12	-0.616	-0.451	+0.010	+0.173	+0.357	+0.525	----
D13	-0.288	*	+0.042	+0.159	+0.317	+0.272	+0.175
D14	+0.104	+0.182	+0.073	+0.084	+0.144	-0.095	----
D15	+0.521	+0.492	+0.021	-0.069	-0.144	-0.507	-0.084
D16	+1.018	+0.934	-2.158	*	-.0708	-0.806	----

Measured by: D. R. Bronowski.

*Unable to measure: Accelerometer, Blocks.

TABLE C-3

DIMENSIONAL DIFFERENCES FOR THE BOTTOM IMPACT LIMITER
AFTER THE SLAPDOWN DROP TEST

Differences Impact Limiter Inspection Data

Limiter Designation: R2 Drop Test No.: NFS-2 Accuracy: +.030

Internal Cavity Measurements

Long. Loc.	Radial Location							
	R1	R2	R3	R4	R5	R6	R7	R8
A1	-0.019	+0.009	+0.138	+0.461	+0.405	+0.127	+0.035	+0.008

Exterior Surface Measurements

Tan. Loc.	Longitudinal Location						
	B1	B2	L1	L2	L3	F1	F2
D1	+0.151	+0.080	+0.052	+0.023	+0.012	-0.097	-0.035
D2	+0.115	+0.079	+0.052	lug	+0.017	-0.082	----
D3	+0.043	+0.040	+0.042	+0.021	+0.010	-0.056	-0.043
D4	+0.004	+0.010	+0.020	+0.015	+0.029	-0.004	----
D5	-0.042	-0.024	-0.005	+0.021	+0.039	+0.027	+0.014
D6	-0.019	+0.018	-0.013	+0.044	+0.111	+0.039	----
D7	+0.133	+0.279	-0.038	-0.001	+0.157	-0.010	-0.011
D8	+1.180	+1.054	-1.411	-1.577	-1.668	-0.584	---
D9	+0.504	+1.181	-3.241	-3.115	-3.288	-0.656	+0.086
D10	+0.149	+0.252	-1.002	-1.131	-1.230	-0.419	----
D11	-0.026	+0.028	-0.047	-0.183	-0.094	+0.053	+0.027
D12	-0.061	-0.039	-0.019	+0.030	+0.082	+0.072	----
D13	-0.019	-0.014	-0.005	+0.026	+0.047	+0.046	+0.034
D14	+0.037	+0.021	+0.013	+0.018	+0.067	+0.018	----
D15	+0.089	+0.057	+0.029	+0.022	+0.038	-0.016	-0.006
D16	+0.116	+0.088	+0.048	lug	+0.025	-0.084	----

Measured by: D. R. Bronowski.

Figure C-2. Lateral Deformations Sustained by Impact Limiters

APPENDIX D

MICROGRAPHS OF BOLT FAILURE SURFACES

AND A DISCUSSION OF BOLT FAILURE MECHANISM

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The fracture surfaces of the failed instrumented bolts were analyzed in detail by visual inspection and by micrographs obtained with a scanning electron microscope. Figures D-1 and D-2 illustrate micrographs of the upper and lower bolts, respectively. The upper bolts exhibit flat, smeared surfaces perpendicular to the bolt axis. These surface conditions indicate that the upper bolts failed in shear. The failure surfaces on the lower bolts exhibit ductile fracture dimples. There is no evidence of flaws that could have initiated the fractures. The lower bolts appear to have failed as a result of both axial tension and bending.

The mechanism by which the bolts failed can be deduced from the bolt strain data and the observed motion of the cask during the impact based on the photometric data. The microstrain traces from the two upper bolts indicate relatively low peak strain levels (about 1700) which were well below the yield point of the bolt material. Therefore these bolts were not highly stressed in tension. The peak strain levels for the lower bolts were quite high (about 6000), indicating that these bolts failed in a combination of tension and bending.

To determine cause of failure for the bolts, the nature of the forces acting on the impact limiter at the time of bolt failure must be determined. Two principal forces acted on the impact limiter to produce tension in the lower bolts during the secondary impact: the force generated by the tendency of the tapered end of the cask to push the limiter away as the cask is forced against the limiter and a frictional force at the target/limiter interface. The direction and magnitude of the frictional force can easily be estimated by examining the kinematics of the cask during the secondary impact and the magnitude of the normal impact force acting on the limiter at the time of bolt failure. The magnitude of the vertical velocity (lateral velocity was negligible) and rotation of the center of gravity of the cask at the time of bolt failure are indicated in Figure D-3. The normal force acting on the impact limiter at this time was about 450,000 lb, as indicated by the SWAT data (Appendix F, Figure F-9). The direction and magnitude of the velocity of

Flat sheared surface, low mag.

Shear ductile fracture dimples

Figure D-1. Micrographs of Fracture Surface of Upper Bolt

Ductile fracture ridges, low mag.

Tensile ductile fracture dimples

Figure D-2. Micrographs of Fracture Surface of Lower Bolt

Figure D-3. Velocity Conditions of the Cask at Time of Bolt Failure

points on the impact limiter adjacent to the target can easily be calculated using a basic kinematic equation for plane motion:

$$V = V_{CG} + \omega \times r \quad .$$

The horizontal component will come from the rotational term. The position vector from the center of gravity to the limiter/target interface is approximately 3 ft. Considering the rotational velocity of 11 rad/sec, the rotational term will be about 33 ft/sec. This velocity component will be down and to the right making an angle of approximately 30 degrees with the vertical. The horizontal component will then be to the right with a magnitude of approximately 15 ft/sec and the frictional force on the limiter will be to the left.

The forces acting on the impact limiter are illustrated in Figure D-4. As the cask moves downward it presses on the inside surface of the impact limiter. Because of the tapered edge there is a component that would tend to load the bolt in tension. There are also frictional

Figure D-4. Forces Acting on Limiter at Time of Bolt Failure

forces at the cask/limiter interface, however, and these tend to negate the outward force on the tapered surface. Estimating the magnitude of these would be very difficult and would require a known force distribution on the inner surface of the limiter and a value for the coefficient of friction. The frictional force at the limiter/target interface tends to load the bolt in tension. The magnitude of this force can be easily calculated using the value of the coefficient of friction for steel on cast iron (0.2). Based on this, the frictional force would have a value of 90,000 lb. The load at the bolt would be somewhat amplified since the limiter is trying to pivot about a point near the upper bolt. The frictional force then has a larger moment arm than the bolt force. However, even neglecting the moment arm effect, the 90,000-lb frictional force is larger than the ultimate strength of the bolts. The ultimate bolt force is estimated to be about 27,000 lb per bolt for a total of 54,000 lb. It is believed that the forces at the cask/limiter interface generated by the tapered end of the cask are much less significant and did not greatly contribute to the bolt failure.

The shearing action that resulted from the secondary impact was more severe at the upper bolt location. This is probably because the impact limiter moved outward slightly at the bottom bolts, whereas it was forced against the cask at the upper bolt location. This allowed some amount of elongation and bending of the lower bolts resulting in a different failure mode. The upper bolts were not loaded in tension because the impact limiter was forced up and against the cask causing a concentrated shearing action. The required shearing force per bolt is estimated to be about one-half of the tension force needed for failure (about 13,500 lb). While much of the lateral force was absorbed by crushing of the limiter, a sufficient amount was transmitted through the limiter body to shear the upper bolts.

The original bolts were undersized and were not able to handle the forces generated by the secondary impact. It is believed that this situation can be corrected by simply increasing the bolt diameter.

APPENDIX E

DERIVATION OF FORCE-DISPLACEMENT CURVES FOR
IMPACT LIMITERS FROM ACCELEROMETER AND FILM DATA

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After the first test, the force-displacement characteristics for the impact limiter in an end drop situation were estimated by fitting an idealized pulse to accelerometer data filtered to 2000 Hz. This frequency rate was selected to capture the rise time of the deceleration pulse to the greatest extent possible. Figure E-1 illustrates the raw data and the idealized curve fitted to it. The force on the impact limiter was calculated by multiplying the deceleration value by the weight of the system (8210 lb including the weight of the cask body and one impact limiter). These data were used in conjunction with film data which provided vertical displacement as a function of time. Results are presented in Table E-1.

TABLE E-1

FORCE-DISPLACEMENT RESULTS FOR THE END-ON DROP TEST

<u>Time (s)</u>	<u>Deceleration (g)</u>	<u>Force (lb)</u>	<u>Displacement (ft)</u>
0.0	0	0	0
0.00085	210	1,724,100	0.038
0.00200	162	1,330,020	0.075
0.00300	122	1,001,620	0.110
0.00350	100	821,000	0.120
0.00500	100	821,000	0.160
0.00700	100	821,000	0.200
0.00900	100	821,000	0.230
0.01100	100	821,000	0.243
0.01280	100	821,000	0.250
0.01580	0	0	0.245

E-4

Figure E-1. Accelerometer Trace Used to Estimate Force for End-On Drop Test

After the second test, sum of weighted accelerations technique (SWAT) data from the accelerometers became available to generate the force-displacement curves for the impact limiters in the slapdown configuration. Figure E-2 illustrates the SWAT results for the forces acting on the cask. Displacement data were again obtained from high-speed film data. Displacement data with the time-varying cask attitude were used to calculate crush distance (including crush at the inside and outside surfaces of the limiter). Kinematic relationships were used to calculate the motion of a point adjacent to the crush area in terms of the displacement and rotation of the center of gravity (CG) of the cask.

The calculation method will be reviewed by referring to Figure E-3, which illustrates the geometry of the cask in the primary and secondary impacts. For the primary impact, Point A was assumed to be at the centroid of the crush area of the impact limiter. At the time of contact, the impact angle was equal to 12.4 degrees, and Point A was 1.747 ft below the CG of the cask. The relationship (Figure E-3(a)) of the motion of Point A, in feet, relative to the displacement of the CG and the angular position of the cask can be shown to be

$$\Delta Y_A = -\Delta Y_{CG} - r \sin (26.75 + \beta) + 1.747 \quad .$$

This equation utilizes absolute values, from Table E-2, for the displacement of the CG and cask rotation, β . Table E-2 presents the displacement data, for the CG, used in the analysis. Figure E-3(b) illustrates the geometry for the secondary impact. The vertical displacement of Point B can be calculated as the vertical displacement of the CG plus the displacement relative to the CG as follows:

$$\Delta Y_B = \Delta Y_{CG} + r \sin \Delta\beta \cos \Delta\beta \quad .$$

The data listed in Table E-2, with the SWAT force-time data included in Figure E-2, were used to generate impact limiter force-displacement curves. Table E-3 lists the force-displacement result for the primary and secondary impacts.

Figure E-2. SWAT Data Used to Estimate Forces on the Cask During Slapdown Drop Test

Figure E-3. Geometric Relationships Used to Calculate Displacement at End of Cask Relative to the Center of Gravity

TABLE E-2

DISPLACEMENT AND ROTATION OF THE CENTER OF GRAVITY
OF THE CASK DURING THE SLAPDOWN DROP TEST

<u>Time (ms)</u>	<u>Displacement of Center of Gravity (in.)</u>	<u>Cask Rotation, B (degrees)</u>
0	0.0	-12.40
1	-0.50	-12.40
2	-0.95	-12.40
3	-1.40	-12.40
4	-2.00	-12.40
5	-2.58	-12.40
6	-3.00	-12.25
7	-3.58	-12.05
8	-4.00	-11.90
9	-4.38	-11.70
10	-4.77	-11.50
11	-5.25	-11.25
12	-5.78	-10.90
13	-6.25	-10.40
14	-6.55	-9.90
15	-6.95	-9.40
16	-7.30	-8.80
17	-7.65	-8.20
18	-8.00	-7.50
19	-8.25	-6.70
20	-8.50	-5.90
21	-8.78	-5.00
22	-9.07	-4.40
23	-9.32	-3.60
24	-9.56	-2.90
25	-9.79	-2.10
26	-10.00	-1.50
27	-10.20	-1.10
28	-10.36	-0.70
29	-10.50	-0.20
30	-10.65	0.20
31	-10.75	0.60
32	-10.82	0.70
33	-10.90	0.80
34	-10.95	0.80
35	-11.00	0.90
36	-11.02	0.80
37	-11.02	0.80

TABLE E-3

CALCULATED IMPACT LIMITER FORCES AND
DISPLACEMENTS FOR THE SLAPDOWN DROP TEST

<u>Primary Impact</u>			<u>Secondary Impact</u>		
<u>Time</u>	<u>Force</u>	<u>Displacement</u>	<u>Time</u>	<u>Force</u>	<u>Displacement</u>
<u>(ms)</u>	<u>(lb)</u>	<u>(ft)</u>	<u>(ms)</u>	<u>(lb)</u>	<u>(ft)</u>
0	0	0.0	20	0	0.0
1	60,000	0.041	21	35,000	0.065
2	60,000	0.079	22	195,000	0.117
3	100,000	0.116	23	315,000	0.175
4	195,000	0.161	24	360,000	0.227
5	265,000	0.215	25	395,000	0.283
6	355,000	0.245	26	420,000	0.315
7	370,000	0.285	27	425,000	0.363
8	385,000	0.314	28	460,000	0.395
9	355,000	0.338	29	490,000	0.430
10	350,000	0.364	30	440,000	0.460
11	360,000	0.404	31	400,000	0.487
12	350,000	0.423	32	365,000	0.497
13	390,000	0.446	33	340,000	0.508
14	400,000	0.448	34	300,000	0.512
15	395,000	0.463	35	200,000	0.520
16	350,000	0.470	36	100,000	0.518
17	265,000	0.474			
18	160,000	0.478			
19	85,000	0.466			
20	50,000	0.454			

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APPENDIX F

DETAILS OF THE SUM OF WEIGHTED ACCELERATIONS AND DECONVOLUTION TECHNIQUES

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This appendix includes detailed descriptions and results of two techniques used to reduce the accelerometer data and analyze the results of the slapdown test in terms of forces and the moment input to the cask. The techniques include the sum of weighted accelerations technique (SWAT) and the deconvolution technique (DECON). The information presented in this appendix has been extracted from Bateman et al. (1989). In addition to the information presented here, Bateman et al. include a detailed structural characterization of the cask in terms of its vibrational characteristics and a description of laboratory calibration tests.

SWAT determines the external force and moment applied to a structure with free boundary conditions from a sum of weighted acceleration measurements (Gregory et al., 1986; Priddy et al., 1988; Priddy et al., 1989). Two sets of weighting factors are determined from modal analysis results: one set of weighting factors, W_i , having the units of mass, is used in the SWAT reconstruction of the resultant force vector; and the second set of weighting factors, G_i , having units of first-moment-of-mass, is used to reconstruct the resultant moment vector. These factors, when used in SWAT, eliminate the elastic response of the cask so that one sum of accelerations yields the rigid body translational acceleration (acceleration of the center of mass) from which the resultant applied force may be determined, and the other sum yields the rotational acceleration from which the resultant applied moment may be determined. The number of accelerometers, N , required for force reconstruction in a particular frequency bandwidth is determined by the number of elastic and rigid body modes of the structure in that bandwidth.

The weighting factors for a set of accelerometer measurements can be determined using the mode shape coefficients from a free-body modal analysis. The theoretical development and method for determining the weighting factors are discussed in detail elsewhere (Gregory et al., 1986; Priddy et al., 1988; Priddy et al., 1989). Briefly, the mode shape coefficients are used in a set of N simultaneous algebraic equations to solve for the N unknown weighting factors for each component of the force and moment vectors. The equations used to calculate the weights for a force vector particular component are equivalent to a statement of

orthogonality between the rigid body translational modes and each of the elastic and rigid body modes. Similarly, the weight equations for a moment vector component are equivalent to a statement of orthogonality between the rigid body rotational modes and each of the elastic and rigid body modes.

The weighting factors are used directly with the measured acceleration signals, a_i , to reconstruct the applied force, F , and moment, T , with the scalar equations for the one dimensional case:

$$F = \sum_{i=1}^N W_i \bullet a_i \quad (1)$$

and

$$T = \sum_{i=1}^N G_i \bullet a_i \quad (2)$$

A set of weights can be calculated for each vector component of the force and moment. The acceleration measurements (or the weighted sum) must be low pass filtered consistent with the bandwidth (number of modes) for which the problem was formulated.

The strategic placement of accelerometers can also allow additional modes to be cancelled to extend the usable bandwidth of the force and moment measurements for a given number of accelerometers. One strategy places the accelerometers on the nodal lines for a particular mode (Priddy et al., 1988). A second strategy, used here, allows the elimination of several modes for axisymmetric structures. Rings of symmetrically located accelerometers, where the weights are of equal magnitude, can be used to eliminate certain circumferential harmonic modes.

To measure the axial force component, rings of four accelerometers, equally spaced around the circumference with the sensitive axis of the accelerometers oriented in the axial direction, can be used. This

accelerometer arrangement is illustrated in Figure F-1. The axial components of the first (bending, $n = 1$) and second (ovaling, $n = 2$) harmonic mode shapes at these locations will sum to zero for each ring. This can be shown if the axial acceleration component of the n th harmonic mode shape in cylindrical coordinates is expressed as

$$a_n(x, \theta, t) = A_n(x, t) \cdot \sin(n\theta + \phi) \quad . \quad (3)$$

The acceleration at the i th accelerometer of a ring can then be written as

$$a_{ni}(x, t) = a_n(x, \theta_i, t) = A_n(x, t) \cdot \sin(n\theta_i + \phi)$$

for $i = 1, 2, 3, 4$ (4)

where x is the axial coordinate of the ring, θ_i is the angular coordinate of the i th accelerometer, and ϕ is a mode shape position angle. It can be shown that the sum of the axial accelerations at the four accelerometer locations will be zero for all n not divisible by four ($n = 1, 2, 3, 5, 6, 7, \dots$). To illustrate this concept, an example is shown for $n = 1$, in which the angular locations of the four accelerometer are

Figure F-1. Accelerometer Placement to Measure Axial Force Component

$$\begin{aligned}
\theta_1 &= \theta \text{ (Arbitrary),} \\
\theta_2 &= \theta + \pi/2, \\
\theta_3 &= \theta + \pi, \text{ and} \\
\theta_4 &= \theta + 3\pi/2.
\end{aligned}
\tag{5}$$

These four locations are substituted into Equation 4, and a summation of the four acceleration is

$$\begin{aligned}
\sum_{i=1}^4 a_{1i}(x,t) &= A_1(x,t) \cdot \left[\sin(\theta_1 + \phi) + \sin(\theta_2 + \phi) + \sin(\theta_3 + \phi) \right. \\
&\quad \left. + \sin(\theta_4 + \phi) \right] .
\end{aligned}
\tag{6}$$

This expression may be simplified with the trigonometric identities,

$$\begin{aligned}
\sin(\alpha + \pi/2) &= \cos \alpha, \\
\sin(\alpha + \pi) &= -\sin \alpha, \text{ and} \\
\sin(\alpha + 3\pi/2) &= -\cos \alpha.
\end{aligned}
\tag{7}$$

The relations in Equation 7 are substituted into Equation 6 as

$$\begin{aligned}
\sum_{i=1}^4 a_{1i}(x,t) &= A_1(x,t) \cdot \left[\sin(\theta + \phi) + \cos(\theta + \phi) - \sin(\theta + \phi) - \cos(\theta + \phi) \right] \\
&= 0 .
\end{aligned}
\tag{8}$$

In the same manner, the sum of the axial accelerations for the other harmonic modes can also be shown to be zero.

The axial components of the zero harmonic ($n = 0$) modes will be equal for each ring. As a result, each ring of accelerometers can be treated as a single measurement point in the calculation of the weighting factors, and the calculated weight is equally divided among the four accelerometers. The required number of rings of accelerometers is then equal to the number of nontorsional, zero harmonic modes, including the axial rigid body translational mode, within the desired frequency bandwidth.

For lateral force component measurement, accelerometer pairs located 180 degrees apart at different axial stations can be used. The sensitive axis of the accelerometers is oriented in the lateral direction, tangent to the axisymmetric structure, as shown in Figure F-2. The tangential components of even harmonic ($n = 0, 2, \dots$) mode shapes will sum to zero for each pair of gages. This can be shown in a manner similar to that for the previous example for the axial component. The tangential components of the first harmonic ($n = 1$) modes will be the same for each accelerometer pair. The pairs can be treated as a single measurement point in the calculation of the weights, and the calculated weight for each axial station is divided equally between the two accelerometers. The required number of accelerometer pairs is equal to the number of first harmonic modes, including the rigid body translational and rotational modes, within the desired frequency bandwidth.

Figure F-2. Accelerometer Placement to Measure Lateral Force Component

By eliminating certain circumferential harmonic modes, the gage placement strategy described above effectively decreases the modes in a particular bandwidth and increases the number of modes that can be cancelled by the SWAT. As a consequence, the problem formulation for an axisymmetric structure such as the cask is simplified to that which is required for a rod or a beam.

The DECON technique infers the applied force by combining the measured acceleration with impulse response functions. Deconvolution requires that the point of application of the forces on the structure be known. Forces applied at other points contaminate the deconvolution force reconstruction and cannot be separated from the desired forces without reformulation of the problem. Theoretically, the number of accelerometers required is equal to the number of forces to be reconstructed; but the technique is more successful if there are more accelerometers than forces (Hillary and Ewins, 1984). Also, the technique can be implemented with either accelerometers or strain gages and can be used in situations where the number of instrumentation channels is limited (Bateman, 1989).

The deconvolution technique is a solution to the general measurement convolution integral,

$$\underline{a}(x,t) = \int_0^t \int_0^L \underline{h}(x,\xi;\tau) \underline{f}(\xi,t-\tau) d\xi d\tau \quad , \quad (9)$$

where $\underline{a}$ is a vector of the accelerometer measurements, $\underline{h}$ is a matrix of characterizations for the cask in the form of impulse response functions for the locations x , and $\underline{f}$ is the vector of forces applied at the ξ locations which excite the accelerometer response. The formula in Equation 9 takes into account the spatial distribution of lateral forces which are applied at either end of the cask as shown in Figure F-3. The $\underline{h}(x,\xi;\tau)$ functions were measured from forces applied to the two ends of the cask by an instrumented hammer which is typically used for modal analysis. The responses, $\underline{a}$, were measured at four locations as shown in Figure F-3, but it was found that by averaging the responses at the same axial location, but 180 degrees apart along the circumference, the effect

Figure F-3. Accelerometer Locations and Assumed Input Force Points for DECON

of the circumferential harmonic modes was eliminated as explained previously for the SWAT technique. Consequently, both $\underline{a}$ and $\underline{h}$ were calculated from averaged responses, which reduced the dimension of the vectors and matrices and gave simpler, smoother functions in the frequency domain. The force is calculated from a discrete form of Equation 9 transformed into the frequency domain as

$$\underline{A}(j\omega) = \underline{H}(j\omega) \cdot \underline{F}(j\omega) \quad , \quad (10)$$

where $\underline{A}(j\omega)$ is a 2x1 vector of the Fourier transforms of the measured responses, $\underline{H}(j\omega)$ is a 2x2 matrix of frequency response functions (FRF) which are Fourier transforms of the elements in the impulse response function matrix, and $\underline{F}(j\omega)$ is a 2x1 vector of the Fourier transforms of the forces applied to the cask. Equation 10 may be solved for the force vector of the two lateral forces applied on either cask end; the Fourier transform of the force vector is

$$\underline{F}(j\omega) = \underline{H}^{-1}(j\omega) \bullet \underline{A}(j\omega) \quad . \quad (11)$$

The solution of Equation 11 implicitly assumes that the forces applied in the lateral direction are applied at the two cask ends, which are the same locations the cask was excited for the measurement of $\underline{H}$. Additionally, the force vector, $\underline{F}$, represents two separate forces that must be added to determine the resultant force applied to the cask.

To measure the axial force component, one axial force is assumed, as shown in Figure F-1. A ring of four accelerometers is used to eliminate the circumferentially harmonic modes and to simplify the frequency response functions. Because there are four response measurements and one force, the inverse of the frequency response function matrix, $\underline{H}^{-1}$, is formed from

$$\underline{H}^{-1} = [[\underline{H}^*]^T \bullet \underline{H}]^{-1} \bullet [\underline{H}^*]^T \quad (12)$$

where $[\underline{H}^*]^T$ is the conjugate transpose of $\underline{H}$. In this formulation, $\underline{H}^{-1}$ is the pseudo-inverse and represents an equivalent least-squares solution to the force in Equation 11 (Stevens, 1987). The accelerometer ring furthest from the force input is chosen for the deconvolution because the anti-resonances in the FRFs are less severe in magnitude, so there is less noise in the force reconstruction.

As mentioned above, Bateman et al. (1989) also include a description of laboratory calibration tests performed to validate these techniques before implementing them in the drop test. For the SWAT, eight accelerometer responses are each multiplied by the appropriate weight for the force or moment; a summation of weighted accelerations is formed for the force and for the moment. For the DECON technique, a matrix of FRFs from all the force input points to the measured accelerometers is required. There are two force input points assumed and two accelerometer responses; each response was the average of two accelerometer signals. Both techniques were implemented in algorithms on the interactive GENRAD 2515 data acquisition and computer system so that the reconstructed forces could be computed and displayed momentarily after the

accelerometer responses were acquired both in the laboratory and at the slapdown site.

With the two force reconstruction algorithms implemented for the cask, the cask becomes a force transducer which will measure the externally applied force. The theory discussed previously describes the relationship between the accelerometer responses and the applied force; however, as with any force transducer, the cask must be calibrated to verify the assumed relationships. For the calibration test, the cask was suspended on elastic straps. Instrumented impact hammers were calibrated and used to apply one or more forces, and the accelerometer responses on the cask were measured simultaneously and input to the algorithms. The input forces were measured and stored so that the measured forces could be directly compared with the reconstructed forces. A similar series of calibration tests was performed to validate the DECON algorithm. Because DECON assumes separate input forces at either cask end, two separate force-time histories are computed in contrast to the composite force computed with the SWAT algorithm. Both for the SWAT and the DECON technique, the calibration experiments showed that the algorithms produced accurate applied force reconstructions during the force pulse.

For the slapdown test, the cask was instrumented with numerous transducers, but only eight accelerometers were used for the force reconstruction. Two accelerometers at each of four axial locations were mounted 180 degrees apart and aligned circumferentially with the cask so that they pointed in the vertical direction. All eight acceleration responses were used for the SWAT algorithm, but only four were used in the DECON algorithm. In both cases, the two acceleration responses at an axial location were first added in the time domain to eliminate some of the circumferentially harmonic modes. Since the cask was dropped with a ten-degree inclination to the horizontal, an impact first on one end and then an impact on the other end was expected to produce two separate impact forces. It was uncertain to what extent the forces would overlap in time. The DECON algorithm computes both of these impact forces as separate functions. In contrast, the SWAT algorithm computes the sum of

the external force as a single function and the moment about the center-of-mass. The calculated forces and moments are those applied to the cask body by the impact limiters and are not the total force applied to the entire system including the limiters. The results of the slapdown test using these two algorithms are discussed below.

Displayed in Figure F-4 is the force time-history computed for the slapdown using the SWAT algorithm. One can see that the impact force lasted approximately thirty-five milliseconds with a peak value of about 500,000 pounds. Also, the two separate force pulses that result from the slapdown impact are clearly visible; the second pulse has a slightly higher peak value as expected for the slap-down (Sjaardema and Wellman, 1988). As a check on the validity of the reconstruction, the force in Figure F-4 was integrated to calculate the impulse, which is equal to the momentum at impact. The calculated impact momentum was within one percent of the theoretical free-fall momentum.

Figure F-4. Reconstructed Lateral Force for Slapdown Test Using SWAT

Figure F-5 shows the corresponding moment about the center-of-mass, calculated using SWAT, and reflects the two-lobed character of the applied force. The moment is at first positive and then changes sign as the cask slaps down. The second part of the moment is more severe than the first because it has a higher peak magnitude, a faster rise-time, and more sharp peaks. This moment is the total moment resulting from all external loads on the cask and includes moments from forces perpendicular and parallel to the cask axis and moments applied by the impact limiters.

The applied moment is integrated and divided by the cask moment of inertia to calculate the angular velocity during the impact; the angular velocity is shown in Figure F-6. This calculation serves as another check on the reconstruction because the angular velocity was zero at the beginning and the end of the event. The angular velocity shows only a very slight deviation from zero at the end of the record. These data were also compared to angular velocity measurements from high-speed photography; the two results were virtually identical. Angular position was measured from a 400-frame/sec camera and differentiated once to obtain the angular velocity.

Figure F-5. Reconstructed Moment for Slapdown Test Using SWAT

Figure F-6. Reconstructed Angular Velocity for Slapdown Test

Using DECON, the external forces were also reconstructed, assuming two impact forces perpendicular to the cask axis applied at either cask end. The two reconstructed forces are shown in Figure F-7 and F-8. The same character is evident in these forces as those reconstructed using SWAT: a large positive force initially at the primary impact followed by another large force at the second impact end. The two reconstructions also show interactions between the cask and the limiters outside the respective impact durations.

A comparison of the force reconstruction from SWAT to that from DECON is made by adding the two forces from DECON to obtain the total external force. This comparison is in Figure F-9; the results are remarkably similar. The primary impact shows extremely close agreement between the two reconstructions. For the second impact, DECON produces slightly larger values, but the shape of the force is quite similar including all the high-frequency spikes.

Figure F-7. Force Reconstruction for Primary End Using DECON

Figure F-8. Force Reconstruction for Secondary End Using DECON

Figure F-9. Comparison of Reconstructed Forces from SWAT and DECON

Figure F-10 compares the SWAT results to results obtained from a single accelerometer with the data filtered to 1500 Hz. As can be seen, there is good agreement. However the accelerometer trace contains a considerable amount of high-frequency response which is not representative of the cask body as a whole. That is, it does not represent the rigid body motion of the cask. Filtering accelerometer data to a frequency below the fundamental frequency of the cask body greatly smooths the data but also affects the rise time and peaks. Figure F-11 is a plot of force versus time for the cask from the slapdown test with data from the two techniques superimposed. The filtered accelerometer data is from an accelerometer trace filtered to 500 Hz. As can be seen there is good general agreement; however, the filtered data fails to accurately capture the rise time of the pulse and, in the secondary impact, underestimates the peak value by about 20%.

Figure F-7. Force Reconstruction for Primary End Using DECON

Figure F-8. Force Reconstruction for Secondary End Using DECON

Figure F-9. Comparison of Reconstructed Forces from SWAT and DECON

Figure F-10 compares the SWAT results to results obtained from a single accelerometer with the data filtered to 1500 Hz. As can be seen, there is good agreement. However the accelerometer trace contains a considerable amount of high-frequency response which is not representative of the cask body as a whole. That is, it does not represent the rigid body motion of the cask. Filtering accelerometer data to a frequency below the fundamental frequency of the cask body greatly smooths the data but also affects the rise time and peaks. Figure F-11 is a plot of force versus time for the cask from the slapdown test with data from the two techniques superimposed. The filtered accelerometer data is from an accelerometer trace filtered to 500 Hz. As can be seen there is good general agreement; however, the filtered data fails to accurately capture the rise time of the pulse and, in the secondary impact, underestimates the peak value by about 20%.

Figure F-10. Comparison of Normalized SWAT and 1500-Hz Filtered Accelerometer Data

Figure F-11. Comparison of Reconstructed Forces From SWAT and DECON with Force Estimated by Conventional Filter Technique

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