# Testing of the Structural Evaluation Test Unit*

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## INTRODUCTION

In the evaluation of the safety of radioactive material transportation it is important to consider the response of Type B packages to environments more severe than that prescribed by the hypothetical accident sequence in Title 10 Part 71 of the Code of Federal Regulations (NRC 1995). The impact event in this sequence is a 9-meter drop onto an essentially unyielding target, resulting in an impact velocity of 13.4 m/s. The behavior of packages when subjected to impacts more severe than this is not well known. It is the purpose of this program to evaluate the structural response of a test package to these environments. Several types of structural response are considered. Of primary importance is the behavior of the package containment boundary, including the bolted closure and O-rings. Other areas of concern are loss of shielding capability due to lead slump and the deceleration loading of package contents, that may cause damage to them. This type of information is essential for conducting accurate risk assessments on the transportation of radioactive materials. Currently, very conservative estimates of the loss of package protection are used in these assessments. This paper will summarize the results of a regulatory impact test and three extra-regulatory impact tests on a sample package.

## DESIGN OF TEST UNIT

The design criteria of NRC Regulatory Guide 7.6 were followed in the design of the test unit wherever possible. The basic configuration of the test unit has a lead shielding layer sandwiched between two stainless steel structural shells. Since the most likely place for a failure is at the closure, and it was not determined if the impact end closure or the opposite end closure was most vulnerable, the test unit has a closure on both ends. One of the possible failure mechanisms for this type of package is caused by the impact of the contents against the lid. For this reason it was decided to make the contents a very stiff block, thereby maximizing the amount of damage it can cause when impacting the lids.

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## Impact Limiter

The test package is loosely based (approximately one-third scale) on current casks used in rail transport. The impact limiters used with these full-scale casks typically yield accelerations in the 60 G range for the 9-meter drop test. Therefore, the first task in designing the test package was to define an impact limiter that would yield a peak acceleration of about 180 G (three times full-scale) for the one-third scale test unit.

Metallic honeycomb was chosen for construction of the impact limiters to be used in this program. Honeycomb materials provide good repeatability in crush behavior, a great advantage in a test program. In addition, their major disadvantage of anisotropy is mitigated because the end-on drop orientation to be used in this program provides uniaxial crushing of the impact limiter. The impact limiter covers the entire cross-sectional end of the package but does not extend around to the package sides, similar to the eraser on a pencil. The desired 180 G acceleration level and the desire to have the impact limiter very near lock-up led to the choice of 7.6 cm of 16.5 MPa crush strength aluminum honeycomb.

## Test Unit Body

The major task in design of the test unit was the establishment of the inner and outer wall thickness. The wall thickness had to be sufficient to withstand the loading imposed by the 9-meter drop onto an unyielding surface with the impact limiter in place. Following Regulatory Guide 7.6 (NRC 1978) led to a final design with inner wall outside diameter of 51 cm and outer wall outside diameter of 61 cm. Both the inner and outer wall thicknesses were 0.64 cm. This thickness was chosen because of the availability of stainless steel tubing of this dimension and that the stresses for this design would be very near the allowable stress values from Regulatory Guide 7.6.

## Bolted Closures

The typical method for design of bolted closures is to assume the package contents impacts the closure lid with the same acceleration as the steady-state acceleration of the cask. No credit is taken for forces acting on the other side of the closure from the impact limiter. For the test unit, this led to a design with 24 3/4-inch (1.9 cm) diameter Grade 8 bolts.

## Summary

It was desired for the test unit for this program to behave in a manner that is worse than the behavior of any real radioactive material transportation packages when subjected to impacts more severe than that required by regulations. For this reason every effort was made in the design to minimize the conservatism that is inherent in any design process. This process resulted in the test unit shown in Figure 1. The as-built mass of the test unit, including contents and impact limiter, is 2,960 kg. As stated previously, the starting point for the design was a one-third scale of a typical rail cask. It can be seen that a package three times as large as this test unit will have inner and outer shell thicknesses of 1.9 cm. While this thickness is not terribly unrealistic for the inner shell, it is significantly less than the

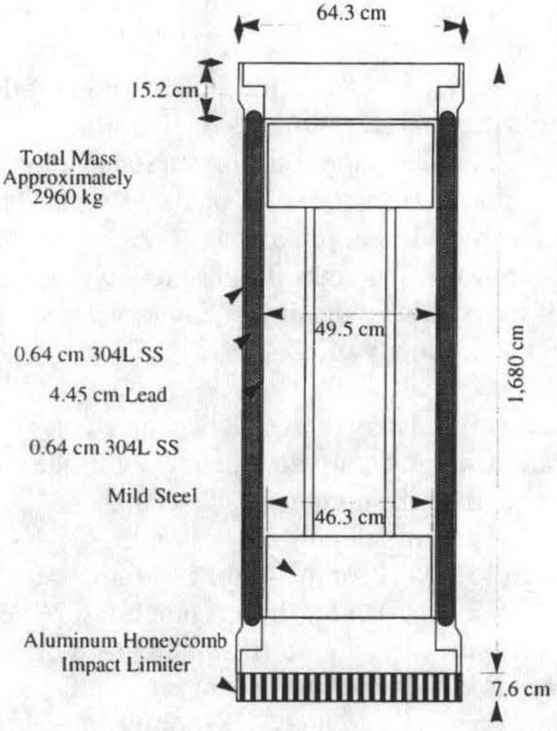

**Figure 1.** Schematic view of test unit final design.

typical outer shell thickness. This indicates the thickness for the outer shell for this type of packages is probably not controlled by the end-drop orientation of this study.

## TEST INSTRUMENTATION

The purpose of the instrumentation is to determine the response of the test unit body, the two lids, and the contents to the impact and to serve as data points for comparing finite element analyses to the test results. To accomplish this there are two accelerometers mounted on each lid, two accelerometers mounted on the contents, four accelerometers mounted to the outer shell at the mid-height, four strain gages in each the axial and hoop directions on the inner and outer shells near the impact end, four strain gage bolts attaching the lids to the test unit body, and four linear variable displacement transformers (LVDTs) measuring differential displacements between the lids and the test unit body. Other means of assessing the response of the test unit to the impact tests are obtained via high-speed films of the tests, dimensional inspections of the impact limiter, test unit body, and lids, and measuring the gas leak rate for the O-ring seals on the two closures.

All of the accelerometers for the tests have a ±20,000 G measurement range. The strain gages are all 350 ohm biaxial gages with 3 mm gage length. These gages are capable of measuring strains of about three percent. The LVDTs used for measuring the displacement of the impact lid relative to the test unit body have a measurement range of ±1.27 mm. The strain gage bolts have a tensile load limit of 160 kN. These bolts are identical to the other closure bolts. The output of all of these gages is recorded at a sample rate of 1,000,000 samples per second using the MIDAS trailer (Uncapher 1995).

High-speed film coverage of the impact tests includes cameras operating at 400 frames per second and at 2,000 frames per second from two orthogonal directions. The field of view of the two 400-frames-per-second cameras and one of the 2000-frames-per-second cameras is such that the entire test unit is in view throughout the impact event. The field of view of the other 2000-frames-per-second camera is a close-up of the impact point.

Dimensional inspection were conducted prior to and after each test. These inspections document any permanent deformations of the test unit. Detailed inspections are performed on the two lids and on the test unit body.

## 9-METER DROP TEST RESULTS

A 9-meter drop test of the structural evaluation test unit was performed to determine if the construction of the test unit was such that it could pass the requirements of 10CFR71. Prior to the test the dimensions of the test unit were measured and the instrumentation discussed in the preceding section was calibrated (where applicable) and installed on the test unit. The 24 closure bolts on each end were tightened to a preload of approximately 49 kN. The O-ring face seals on each closure lid were determined to be leak tight. The test unit was raised so the lowest point of the impact limiter was 9 meters above the unyielding target and allowed to fall in a free fall to impact the target at a velocity of 13.4 m/s.

This test resulted in an impact limiter crush of approximately 3.6 cm. This value is considerably less than the predicted amount of crush, indicating that the impact limiter aluminum honeycomb had a higher crush strength than the nominal 16.5 MPa. This crushing of the impact limiter was the only visible deformation of the test unit. The maximum unfiltered accelerations recorded were 13,000 G for the impact end lid, 950 G for the opposite end lid, 5,000 G for the contents, and 4,500 G for the test unit body. When the acceleration time histories were filtered with a low-pass digital filter using a cutoff frequency of 500 Hz to remove the high-frequency content the maximum accelerations were 420 G for the impact end lid, 450 G for the opposite end lid, 720 G for the contents, and 360 G for the test unit body. The steady acceleration level is somewhat lower than the peak level of 360 G, at a level of about 230 G. The 230 G level indicates an impact limiter crush strength of 20.5 MPa, higher than the assumed design value of 16.5 MPa. The data from the strain gages showed that there was a slight amount of yielding in the inner wall (maximum strain of about 0.2%), but no significant amount of plasticity. The strain level in the outer wall was just below the strain that corresponds to yielding. These levels of strain indicate the test unit design performed as intended. The instrumentation used to measure the response of the impact lid relative to the test unit body indicated no relative motion between the two parts and only a slight change in the load of the bolts.

After the test, a dimensional inspection of the tests unit was performed and a nondestructive evaluation of the amount of lead slump was made. The dimensional inspection indicated no permanent deformations in either the test unit body or the two closure lids. The non-destructive evaluation of the lead slump indicated a maximum lead slump of about 0.15 cm. This amount of slump can easily be accommodated by the gap formed when the lead cools after the lead pouring process during fabrication of the test unit. The post-test leak rate of the closure seals was $6.9 \times 10^{-9}$ std atm cc/sec for the impact end lid and $3.4 \times 10^{-8}$ std atm cc/sec for the opposite end lid, indicating leak tight seals remained for both closures.

## 20.6-METER DROP TEST RESULTS

The lowest energy extra-regulatory impact test was from a drop height of 20.6 meters. This test had 2.25 times the kinetic energy of the regulatory drop test and resulted in an impact velocity of 20.1 m/s (45 mph). In this test the impact limiter was crushed 83%, well above its lock-up strain, and further energy was absorbed by plastic deformation of the test unit body. There was noticeable bulging of the outer shell near the bottom of the lead shielding layer. The yielding of the shells resulted in a 1.2% increase in the diameter of the test specimen at this location. This increase in diameter is also indicated by permanent strain measured by the strain gages. The maximum permanent axial strain recorded is 2.5% and the maximum permanent hoop strain recorded is 2%.

The results from the radiographic inspection indicate a lead slump of approximately 2 in. Even though the impact was very close to perfectly symmetric, there was a rather wide variation in the amount of lead slump. Measurements indicated a range from slightly over 1 in. to almost 3 in. around the lead column. It is possible this variation is due to differing degrees of friction between the lead and the stainless steel shells.

The strain gage bolts on the impact lid showed a decrease in load, as the impact tends to force this lid onto the cask body. The maximum change indicated during the drop was about 35 kN, which is less than the bolt preload of about 49 kN, indicating there was still a 14kN clamping force on each bolt. The maximum permanent change in bolt load is about 7 kN. The strain gage bolts on the top end indicated an increase in bolt force. This is caused by the contents hitting the lid and trying to push it off. The maximum magnitude of these loads was about 89 kN. Adding this to the bolt preload gives a total bolt load of about 138 kN, which is less than the yield strength for these bolts. As the contents rebounds away from the top end lid this load is eliminated, and the maximum permanent change in bolt load at the top end is less than 4.5 kN.

The peak unfiltered accelerations measured on the impact end lid are about 20,000 G. The peak unfiltered accelerations measured on the top lid are about 7,000 G. The peak unfiltered accelerations measured on the contents are about 3,000 G. The maximum unfiltered accelerations measured on the outside of the cask body at mid-height are about 7,000 G. If these acceleration pulses are filtered to remove the high-frequency contribution, an acceleration of about 1000 G is indicated.

The LVDT's on the impact end indicated no relative movement between the lid and the test unit body. This is to be expected, as the bolt preload is sufficient to cause metal-to-metal contact between these two elements, and the loading is such as to try to push these two elements together. The LVDT's on the top end also indicate essentially no movement between the lid and the test unit body. This is expected since the strain gage bolts indicated loads below their yield strength, and the amount of elastic strain corresponding to the maximum indicated load is less than 0.05 mm. These results from the LVDT's indicate the package should have remained leak tight during and following this test. Post-test helium leak testing of the closure seals indicated this was indeed the case, with the closures on both ends remaining leak tight.

## 36-METER DROP TEST RESULTS

The ability of the test package to survive an impact with 2.25 times as much energy as the design basis impact inspired a test with 4 times as much energy, a 36-meter drop test. This drop height results in a impact velocity of 26.8 m/s. For this test, the test unit from the 20.6-meter drop test was fitted with a new impact limiter and retested in the same orientation.

There was no attempt to repair the bulges in the test unit body or to fill the void left from the lead slump. In this test the impact limiter was crushed 87%. As expected, this was slightly higher than in the 20.6-meter drop test. Again the remaining energy had to be absorbed by plastic deformation of the test unit body. There was significant buckling of the inner and outer shells near the bottom of the lead shielding layer. The yielding of the shells resulted in a 8.8% increase in the diameter of the test specimen at this location. This level of strain is greater than the adhesive used to attach the strain gages to the test unit can withstand, and all of the strain gages separated from the package. Figure 2 shows the deformations of the test unit following this test.

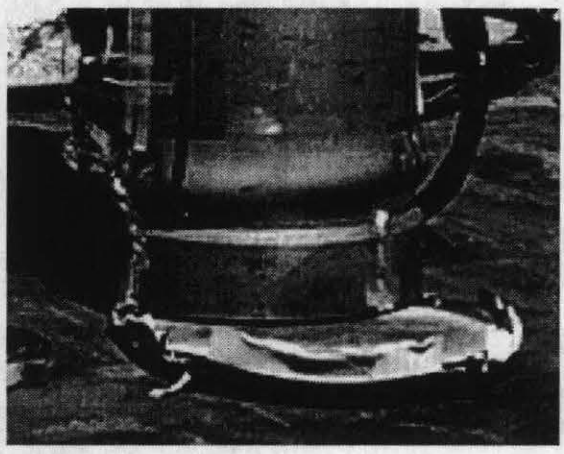

**Figure 2.** View of the impact end following the 36-meter impact test.

The results from the radiographic inspection indicate a total lead slump of approximately 1.5 in. This amount of lead slump is less than that seen following the 20.6-meter drop test. The reason for this was the buckling of the test unit wall effectively shortened the lead cavity, resulting in an apparent decrease of lead slump.

The buckling of the test unit wall also caused a shortening of the internal cavity. This caused the axially stiff contents to be pressed between the impact lid and the top lid. At about 5 ms into the impact is the time when the top lid first contacts the contents. This contact produces the highest accelerations seen by the top lid and the highest bolt loads in both lids. This loading was high enough to cause the bolts in the upper lid to yield slightly, which made the load indication from the internal strain gages invalid.

The peak unfiltered accelerations measured on the impact end lid are about 5,100 G. The peak unfiltered accelerations measured on the top lid are about 13,000 G. The peak unfiltered accelerations measured on the contents are about 12,500 G. The maximum unfiltered accelerations measured on the outside of the cask body at mid-height are about 6,000 G. If these acceleration pulses are filtered to remove the high-frequency contribution, an acceleration of about 1,050 G is indicated.

The LVDT's on both the impact end and opposite end indicated relative movement between the lid and the test unit body of about 1.2 mm. These results are significantly different than those from the 20.6-meter drop test because the shortening of the test unit body in this test resulted in the contents pushing the lids away from the body. The results from the LVDT's indicate the package would probably remain leak tight during and following this test. Post-test helium leak testing of the impact end closure seal indicated the test unit remained leak tight.

## 36-METER CORNER DROP TEST RESULTS

A 36-meter corner drop test of the structural evaluation test unit was performed to have test data to validate 3D finite element analyses. This test resulted in an impact limiter crush of approximately 90%. This value is beyond the lock-up crush of the aluminum honeycomb material, indicating that the impact limiter absorbed the total amount of energy that it is capable of absorbing. Any remaining kinetic energy of the test unit must be absorbed by deformation of the stainless steel walls and plastic flow of the lead. Because of the corner impact, the deformations of the test unit were not symmetric, but rather there was a significantly greater amount of deformation on the side of initial impact than on the opposite side. There was a large outward buckle of the outer wall near the location of where the wall is welded to the closure flange. This buckle resulted in about a 6.3 cm shortening of the test unit on that side. Since the contents were only 1.2 cm shorter than the length of the internal cavity, this amount of test unit shortening indicates that the contents were also shortened. The amount of force required to shorten the contents was sufficient to cause the closure bolts on the end opposite from impact to yield and elongate. Figure 3 shows the deformations following this test.

**Figure 3.** View of the impact end following the 36-meter corner impact test.

The maximum unfiltered accelerations recorded were 50,000 G for the impact end lid (above the 20,000 G range of the accelerometer), 10,000 G for the opposite end lid, 40,000 G for the contents (above the 20,000 G range of the accelerometer), and 2,800 G for the test unit body. When the acceleration time histories were filtered with a low-pass digital filter using a cutoff frequency of 500 Hz to remove the high-frequency content the maximum accelerations were 12,000 G for the impact end lid, 1,400 G for the opposite end lid, 21,000 G for the contents, and 1,050 G for the test unit body. The data from the strain gages showed that there was a significant amount of yielding in both the outer and the inner walls The amount of plasticity was beyond the amount expected and the strain gages were not able to capture the maximum amount of strain. The strain gage bolt data indicate an initial decrease in the 49 kN preload to an average value of about 18 kN and then an increase in the amount of load as the test unit body shortened and the contents came into compression at approximately 8 ms into the impact event. The increased load ranged from about 62 kN to about 165 kN. This behavior is duplicated in the data from the LVDTs on the impact end closure lid. There is an initial slight decrease in the measurement as the lid is pushed into the body and then an increase in the measurement as the contents pushes the lid away from the body. The maximum amount of measured separation is 0.2 mm.

The post-test dimensional inspection indicated a maximum increase in diameter of nearly 10%. This is the location of the outward buckle of the outer shell. There was also both inward and outward buckles of the inner shell at this approximate location. The amount of inward deflection at this location is limited by the presence of the contents.

The post-test leak rate of the closure seals was $5.7 \times 10^{-6}$ std atm cc/sec for the impact end lid and $1.2 \times 10^{0}$ std atm cc/sec for the opposite end lid, indicating significant leakage from both seals. It should be noted that this test unit was not designed to withstand an off-axis impact, and would have had unacceptably large strains even in a 9-meter drop in this orientation. Analyses indicate this test was about as severe as a 46-meter drop in an end-on orientation. A 46-meter drop has about five times the energy as the regulatory impact.

The leakage of the seals in this test is due to the contents pushing the lids away from the test unit body. If the contents had smaller axial stiffness the lids would have seen much smaller loads and the seals would have probably survived the test. It is possible, however, that the contents also acted as a support for the buckling of the walls near the impact end. If the contents had lower axial stiffness it is possible that this buckling could have been more severe.

## CONCLUSIONS

The results of these tests indicate a high level of safety inherent in the design of radioactive material shipping packages. This package was designed to just meet the requirements of NRC Regulatory Guide 7.6 when subjected to the regulatory 9-meter drop onto an unyielding target. This test series subjected the package to an impact with 2.25 times as much energy as the regulatory impact and to an impact with four times as much energy as the regulatory impact and the package remained leak tight. An additional off-axis impact with four times the energy of the regulatory impact produced some leakage of the seals, but no gross failure of the package. This information is valuable for arguing that there is no need to increase the severity of the regulatory impact accident, because of the conservative approach taken in the design of these packages they can withstand impacts much more severe than the design basis impact.

## REFERENCES

Uncapher, W. L. and Arviso, M. A., The Collection and Analysis of Transient Test Data Using the Mobile Instrumentation Data Acquisition System (MIDAS), Proceedings of PATRAM '95, Las Vegas, NV (1995).

U.S. Nuclear Regulatory Commission, *Design Criteria for the Structural Analysis of Shipping Cask Containment Vessels*, Regulatory Guide 7.6, Washington, DC (1978).

U.S. Nuclear Regulatory Commission, *Title 10, Code of Federal Regulations, Part 71*, Office of the Federal Register, Washington, DC (1993).