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Development of a Benchmark Series of Cask Drops for Validation of Explicit Dynamic Finite Element Analyses

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Abstract

Package designers are increasingly relying on explicit dynamic finite element analyses to determine the response of packages to impact events. In order for regulators to accept these analyses, the designer must demonstrate that the analyses are valid. One way to accomplish this is by comparison between analysis results and test results, in a process known as benchmarking. Often times, this is done by subjecting a scale model version of the package being designed to a physical test and using the data generated from that test to benchmark the analyses. Usually the results of these tests are held as proprietary information by the package designers and are not available for others to use for benchmarking their own analyses. In order to have a benchmark problem that was accessible to all designers, the US Nuclear Regulatory Commission contracted Sandia National Laboratories to produce a benchmark problem statement report and test results report based upon earlier tests conducted on the Structural Evaluation Test Unit. This paper summarizes these two reports.

Introduction

The use of explicit dynamic finite element programs to determine the response of spent fuel and high-level radioactive waste storage and transport casks to impact loadings is becoming more prevalent. Many cask designers rely upon this tool to demonstrate that their casks meet their regulatory requirements. One problem that is often raised in this approach is the lack of benchmark problems that can be used to demonstrate that the analysis tools and the analysts are capable of accurately determining the response of the cask. In some package certifications, cask designers perform scale model drop tests, and use the results of these tests as benchmark problems to demonstrate analytical accuracy. Because of the high cost of these tests and the proprietary nature of the data that is obtained from them, there are very few benchmark problems available in the open literature.

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During the early 1990s, the Department of Energy (DOE) sponsored a series of tests at Sandia National Laboratories on the Structural Evaluation Test Unit (SETU). This stainless steel-lead-stainless steel sandwich wall test unit was designed so that the stresses resulting from a 30-foot drop would be very close to the allowable stresses permitted by the U.S. Nuclear Regulatory Commission (NRC) Regulatory Guide 7.6 [1]. The goal of this test program was to determine the minimum margin of safety against release of radioactive material that casks designed to the standards of Regulatory Guide 7.6 would exhibit. To achieve this, the SETU was first dropped from 9 meters onto an essentially rigid target. The same test unit, with a new impact limiter, was then dropped from a height of 36 meters onto the unyielding target. A second test unit was dropped first from a height of 20.25 meters and then from a height of 36 meters. This series of tests included accelerometers on the cask body, its lid, and the cask contents; strain gages on the inner and outer surface of the cask; load-indicating bolts attaching the lid to the cask, and displacement gages to measure any separation of the lid from the cask. Pre-test and post-test dimensional inspections were made at various points on the cask and lid.

This test series provides an excellent benchmark problem. The 9-meter drop provides cask response that is typical for casks designed to the requirements of Regulatory Guide 7.6, while the higher drops provide responses with a greater amount of plasticity, which are better for demonstrating the finite element method can accurately predict responses in the regime that is allowed by the strain-based acceptance criteria that was added to Section III, Division 3 of the ASME Boiler and Pressure Vessel Code in 2013 [2].

Differences between Benchmark Tests and Certification Tests

In some package certifications, cask designers perform a limited number of drop tests and attempt to use the results of these tests as benchmark problems to demonstrate analytical accuracy. These certification-based tests generally are limited in the amount of information collected that can be used to benchmark analyses. Certification testing is aimed at demonstrating package compliance with the regulations, whereas, ideally, benchmark testing should be aimed at demonstrating analytical accuracy. While it is possible to use certification tests as benchmark problems, there are reasons why this may not be an ideal method to generate benchmark results. Certification testing is expensive, and adding additional channels for the purpose of demonstrating analytical accuracy increases the cost and often decreases the utility of the test for certification. Most package designers maintain their test results as proprietary information, so while these tests may be used by that company for benchmark problems, they generally are not publically available for others.

The Structural Evaluation Test Unit

The structural evaluation test unit (SETU) overcomes many of the problems associated with using certification tests as benchmark problems. The SETU program was sponsored by the US Department of Energy in the early 1990s to determine the minimum margin of safety provided by packages designed to meet the requirements of NRC Regulatory Guide 7.6. The SETU was a stainless steel-lead-stainless steel sandwich wall package that was designed so that the stresses resulting from a 9-meter free drop would be very close to the allowable stresses from Reg. Guide 7.6. These tests were heavily instrumented and inspected, thereby providing ample data for benchmarking finite element analyses. Figure 1 shows a diagram of the SETU. It had relatively simple geometry. The upper and lower lids, the top and bottom flange, and the inner and outer shells were all 304L stainless steel. The contents were carbon steel. The area between the inner and outer shells was filled with lead. The impact limiters were uniaxial pre-crushed aluminum honeycomb.

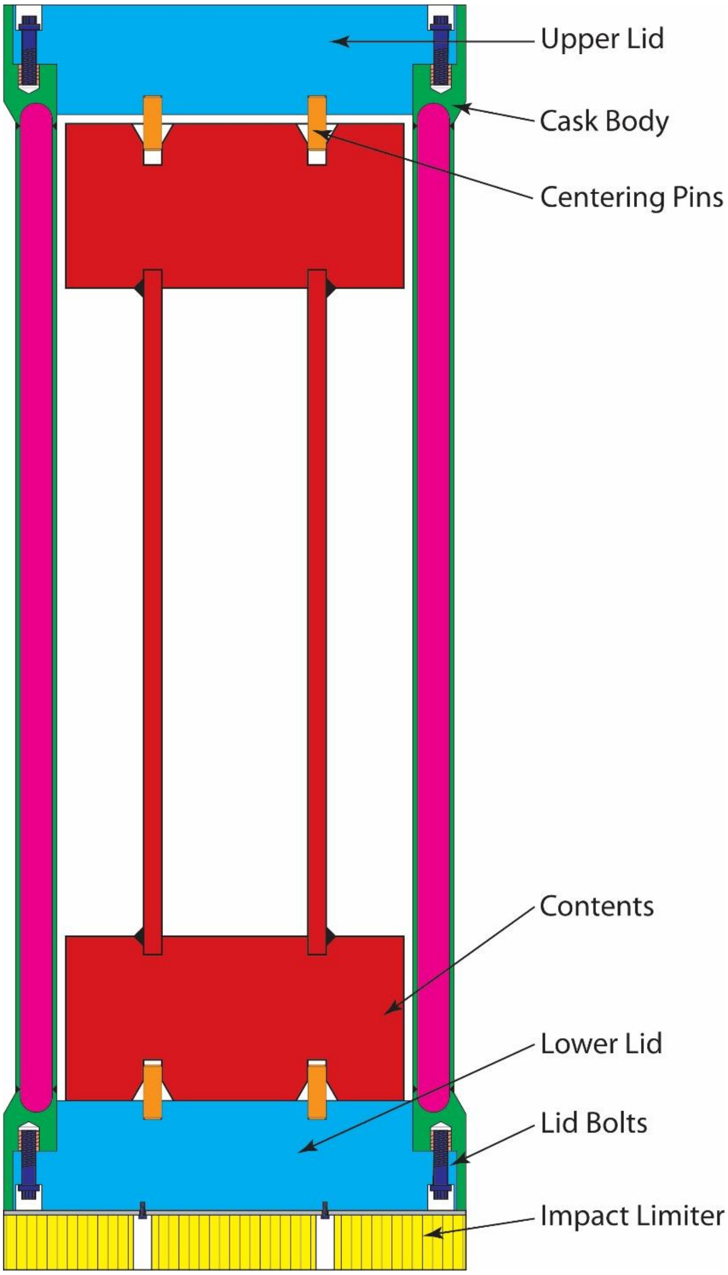


Figure 1 – Schematic view of the SETU

Benchmark Problem Statement

The SETU was subjected to four different drop tests conducted in two sequences. The first test was a 9-meter drop in an end-on orientation. This test was performed to determine if the SETU behaved as expected in a regulatory impact. All subsequent tests were at higher impact speeds. The behavior of the SETU was as expected, with only minor plasticity, so the same test unit, with a new impact limiter was subjected to a 36-meter drop at an impact angle 6.3° from vertical. Following this test, the SETU was repaired and subjected to a second sequence of drops. The repairs consisted of replacing both the inner and outer shells and pouring new lead between them as well as minor machining of the flanges and lids. The center tube of the contents was also replaced. The first test of the second sequence was a 20.25-meter drop in an end-on orientation. This impact caused some plastic strain in the shells near the impact end and some slumping of the lead. For the second test in this sequence the impact limiter was replaced and the package was dropped from 36 meters in an end-on orientation. Each of the tests was heavily instrumented and dimensionally inspected.

Instrumentation

For the first sequence of drops the instrumentation consisted of two accelerometers installed in pockets just inboard of the closure bolt circle on the impact end lid, two accelerometers in a similar location on the upper lid, two accelerometers located on the inboard side of the impact end solid weight of the contents, and four accelerometers mounted 90° apart around the outside of the SETU at its mid-height. All of these accelerometers were oriented to measure accelerations in the direction of the axis of the SETU. Bi-axial strain gages were mounted every 90° around the outside and on the inside of the SETU at a location 24.1 cm above the impact end of the body. Four of the lid bolts on the impact end were instrumented to provide bolt loads and there were four linear variable displacement transducers (LVDTs) measuring the displacement of the impact lid relative to the body in between the lid bolts. For the second sequence of drops the same instrumentation was used, except that load indicating bolts and LVDTs were installed on the upper lid as well.

Dimensional Inspections

Prior to and after each test, key dimensions on the SETU were measured. For the tests that were done in sequence, the post-test measurement from the first test served as the pre-test measurement for the next test. The dimensional inspection locations for the lids are shown in Figure 2. Lengths and diameters were measured every 45° around the circumference.

The dimensional inspection locations on the cask body are shown in Figure 3. Lengths and diameters were measured every 45° around the circumference. The inspection location OD4, ID4 is located 5.08 cm down from OD3, ID3 and OD5, ID5 is located 10.16 cm down from OD4, ID4. OD8, ID8 is located 5.08 cm up from OD9, ID9 and OD7, ID7 is located 10.16 cm up from OD8, ID8. OD6, ID6 is located at the center of the body.

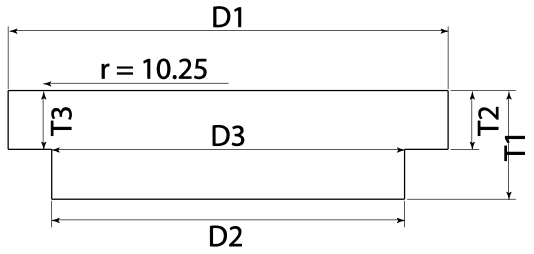


Figure 2 – Dimensional inspection locations for the SETU lids

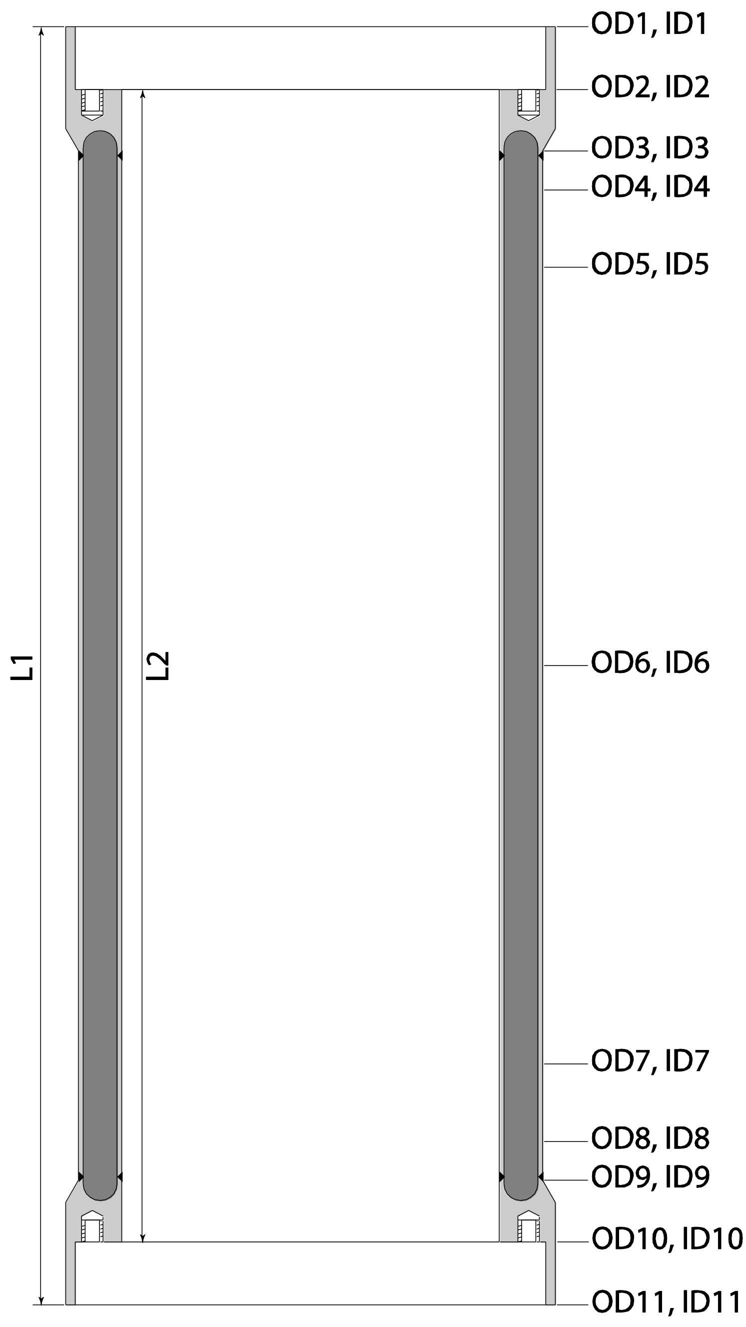


Figure 3 – Dimensional inspection locations for the SETU body

A detailed description of the problem statement is given in a SETU Benchmark Problem Statement SAND Report [3]. This report gives the material properties of SETU components, provides additional detail on the instrumentation and dimensional inspections, and describes the tests in more detail.

Benchmark Test Results

<u>Results from the 9-meter drop</u>

The deformed shape of the SETU following the 9-meter end impact is shown in Figure 4. This impact was very nearly perfectly axial, and the only visible sign of damage is the partially crushed impact limiter. Table 1 shows an example of the dimensional inspection data of the cask body lengths (L1 and L2 from Figure 3). In addition to this data, the amount of crush of the impact limiter was measured as 1.4 inches. Figure 5 shows typical acceleration results.

Figure 4 – Deformed shape from the 9-meter drop

Table 1 – Change in body length from the 9-meter drop

Location	0 Degrees			45 Degrees			90 Degrees			135 Degrees		
	Pre	Post	Δ	Pre	Post	Δ	Pre	Post	Δ	Pre	Post	Δ
L1	66.049	66.069	0.02	66.039	66.056	0.017	66.057	66.052	-0.005	66.049	66.058	0.009
L2	59.587	59.589	0.002	59.58	59.582	0.002	59.579	59.574	-0.005	59.577	59.571	-0.006

Location	180 Degrees			225 Degrees			270 Degrees			315 Degrees		
	Pre	Post	Δ	Pre	Post	Δ	Pre	Post	Δ	Pre	Post	Δ
L1	66.05	66.059	0.009	66.049	66.06	0.011	66.051	66.063	0.012	66.052	66.069	0.017
L2	59.584	59.577	-0.007	59.585	59.581	-0.004	59.578	59.587	0.009	59.581	59.59	0.009

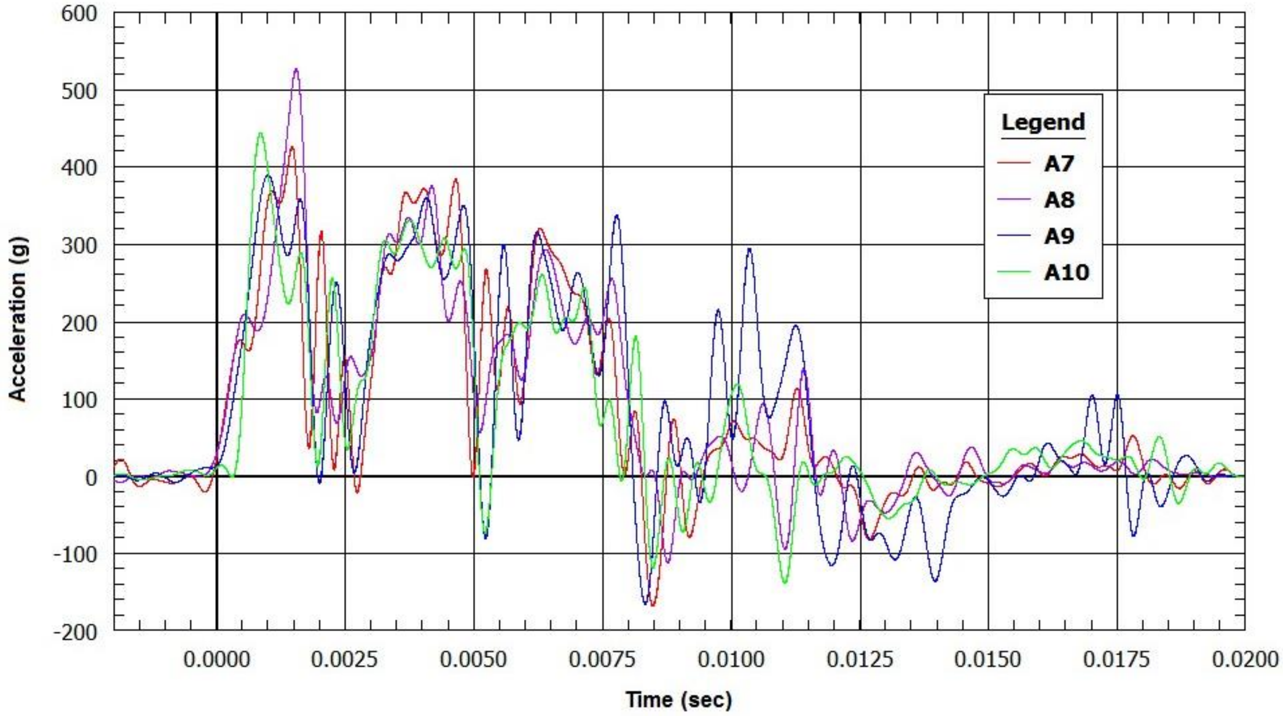
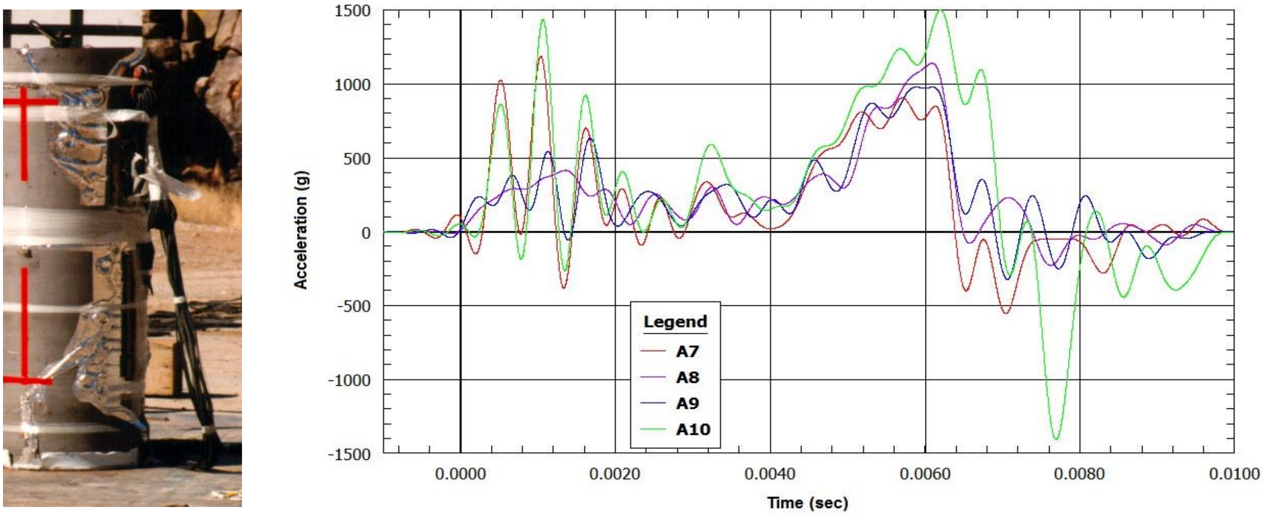


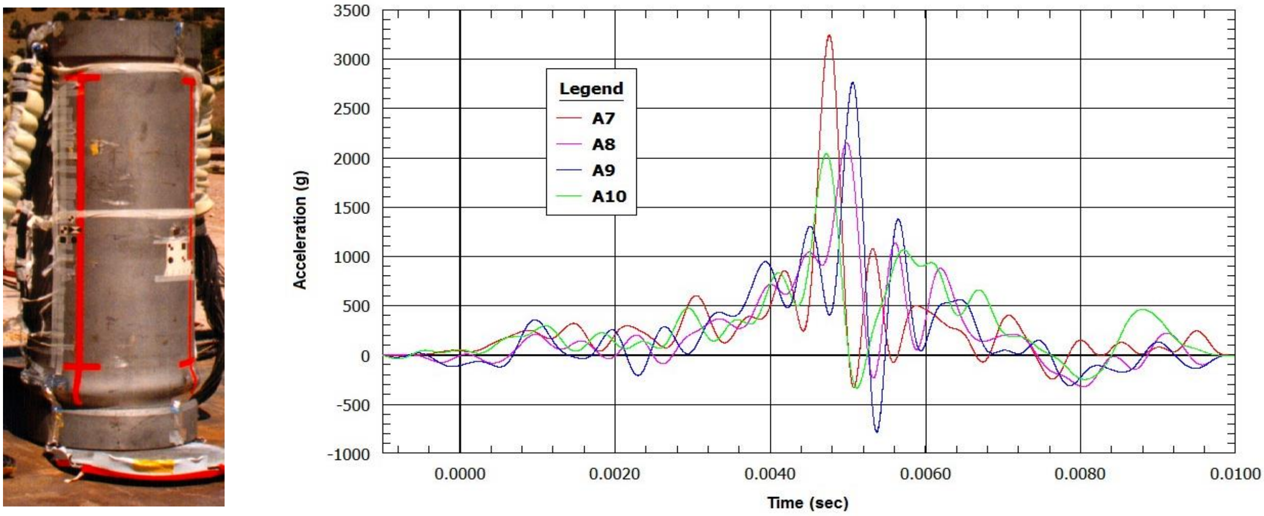
Figure 5 – Accelerations at the cask hid-height from the 9-meter drop

Results from the other drops

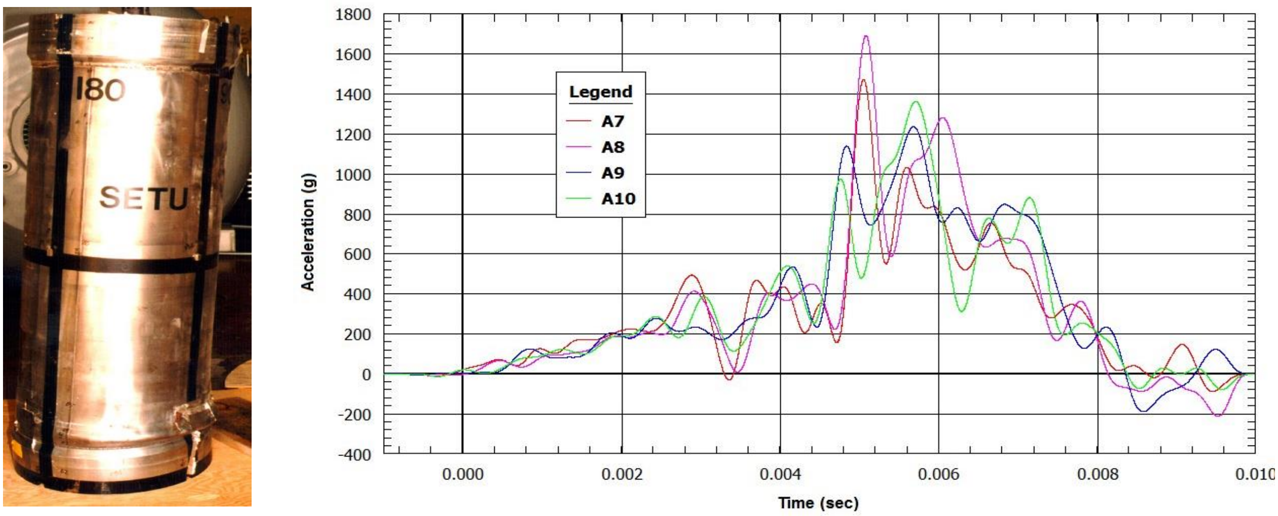
Figure 6 shows the deformed shapes and mid-height accelerations from the other three impact tests. Complete dimensional inspection results and response curves from the instrumentation are provided in a SETU Benchmark Test Results SAND report [4].



a) 20.25-meter end drop



b) 36-meter end drop



c) 36-meter corner drop

Figure 6 – Deformed shapes and mid-height accelerations from the 20.25-meter end impact, the 36-meter end impact, and the 36-meter corner impact

Conclusions

The SETU test sequence provides an excellent problem set for benchmarking of finite element analyses programs used in the design and certification of radioactive material transportation and storage casks. The 9-meter drop impact has behavior very similar to that expected from casks designed to meet the requirements of NRC Reg. Guide 7.6, with very little plastic deformation. The higher speed impacts provide results with greater plastic deformation, which are ideal for demonstrating that the finite element method can accurately predict the response that is allowed by the ASME strain-based acceptance criteria.

Acknowledgments

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References

[1] U.S. Nuclear Regulatory Commission, *Design Criteria for the Structural Analysis of Shipping Cask Containment Vessels*, Reg. Guide 7.6, NRC, Washington, DC, March 1978.

[2] American Society of Mechanical Engineers, ASME *Boiler and Pressure Vessel Code, Section III, Division 3*, ASME, New York, 2013.

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