Design Verification Testing*

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INTRODUCTION

Type B packagings for transporting radioactive materials are required to survive exposures to environments in accordance with provisions of Title 10 Code of Federal Regulations Part 71. Testing, analyses, or a combination of testing and analysis may be used to demonstrate compliance with the normal and hypothetical accident conditions. This paper will discuss drop and puncture design verification testing. The extensive scale model design verification testing program (Madsen et al., 1987) conducted by Sandia National Laboratories (SNL) to evaluate the structural response of the Defense High Level Waste (DHLW) truck transportation cask (GA Technologies, 1987) will be used as an example. General aspects of design of the scale model, drop orientations, instrumentation, photography, nondestructive evaluations (NDE), data evaluations, test plans, and quality assurance can be applied to other design verification programs.

BACKGROUND

The drop and puncture tests in the hypothetical accident conditions of 10 CFR 71 require sequential conduct of the following tests on a single specimen:

1. Free drop of the specimen through a distance of 9-m (30-ft) onto a flat, essentially unyielding, horizontal surface, striking the surface in a position in which maximum damage is expected and

2. Free drop of the specimen through a distance of 1-m (40-in.) in a position for which maximum damage is expected, onto the upper end of a solid, vertical, cylindrical, mild steel bar mounted on an essentially unyielding, horizontal surface. The bar must be 15-cm (6-in.) in diameter, with the top horizontal and its edge rounded to a radius of not more than 6-mm (1/4-in.) of a length as to cause maximum damage to the package, but not less than 20-cm (8- in.) long. The long axis of the bar must be vertical.

The initial conditions for the tests require the ambient air temperature before and after the tests to remain constant at a value between -29°C (-20°F) and +38°C (100°F) which is most unfavorable for the feature under consideration. The initial internal pressure within the containment system must be the maximum normal operating pressure unless a lower internal pressure consistent with the ambient temperature assumed to precede and follow the tests is more unfavorable.

Both the drop and puncture tests specify a flat, essentially unyielding, horizontal surface. Safety Series Number 37 (International Atomic Energy Agency, 1987) gives the following example of an

* This work performed at Sandia National Laboratories, Albuquerque, New Mexico, supported by the United States Department of Energy under Contract DE-AC04-76DP00789.

** A United States Department of Energy Facility

unyielding target meeting regulatory conditions: "A steel plate as the upper surface of a concrete block. The combined mass of the steel and concrete shall be at least 10 times that of the specimen to be dropped on it. The block should be set on a firm soil and the steel plate should be at least 4 cm thick and floated onto the concrete while it is still wet. The plate should have protruding fixed steel structures on its lower surface to ensure tight contact with the target. Since flexure of the target is to be avoided, especially in the vertical direction, it is recommended that the target should be close to cubic in form, with the depth of the target comparable to the width and length."

DESIGN AND CONDUCT OF TEST PROGRAMS

Type B packagings must maintain containment, shielding, and criticality control following the hypothetical accident conditions. Testing, analysis, or a combination of testing and analysis, may be used to demonstrate compliance. Frequently the drop and puncture events are treated by both analysis and test. Objectives of a test program often include:

- correlating test and analytical results to establish validity of computer analysis,
- verifying post-accident shielding effectiveness,
- confirming the design for orientations that are analyzed with approximate calculations,
- obtaining seal area deformation data,
- providing initial puncture damage assumptions for thermal analysis, and
- confirming the acceptability of components (seals, closure bolts, welds) that cannot be evaluated completely by analysis.

Measurements often made during a test program include deformations, decelerations, strains, and leakage.

Full- or sub-scale testing may be used to verify the cask design. Half- or quarter-scale models are often chosen for economic reasons. These scales allow direct scaling of almost all critical cask body components except the seals, allow adequate scaling of welds, and provide adequate space for instrumentation. To date, relationships between the leakage rates measured from a scale model package and those measured from a full-scale package have not been developed. Therefore, leakage rates from scale models are used in a qualitative manner.

Scale models are fabricated from materials having mechanical properties identical or similar to the full-scale design. Scaling laws derived from Buckingham's π theorem (Buckingham, 1915) incorporate both material and geometric scaling. Application of these laws to the one-half scale yields the following relationships:

- model impact duration is one-half the full-scale impact duration,
- model angular displacements are the same as full-scale angular displacements,
- model linear displacements are one-half the full-scale linear displacements at scaled times and homologous locations,
- model velocities are the same as full-scale velocities at scaled times,
- model accelerations are two times the full-scale accelerations at scaled times, and
- model mass is one-eighth that of full-scale mass.

Early in the design process, test and design engineers identify the need for, and begin planning the tests. Advance planning allows the models to include special machining for test instrumentation or leakage testing. Fabrication often includes construction of spare parts for components that are expected to experience damage which could seriously influence the results of subsequent tests.

Instrumentation measurement devices used to evaluate the structural response of the cask model often include accelerometers, strain gages, and thermocouples. Analytical calculations frequently provide insights for selection of appropriate measurement ranges for the instrumentation. Drop orientation is an important consideration in placement of the instrumentation so that it is not destroyed during the impact.

Pre-test measurements are performed to establish baseline data for dimensional inspections, leakage tests, and other appropriate NDE tests such as radiography. Individual components of the model are inspected according to dimensional inspection drawings that define the dimensional inspection designation and location of each measurement. The dimensional inspection locations are marked on each component so that the inspection orientation can be identified for subsequent inspections. Markings are selected that would not interfere with the structural integrity or functioning of the component. To provide a reference for post-test measurements, it is necessary to identify positions expected not to deform significantly during testing. Pre-test measurements, post-test measurements, and measurement changes of each component during testing are recorded.

Photometric data provide information about impact orientation and duration, rebound height, and times associated with impacts. To aid in interpretation of high-speed photography, a grid is painted on the cask and on background boards surrounding the sides of the target.

In order to perform quality drop and puncture design verification tests a facility should have a drop pad conforming to the International Atomic Energy Agency example, a reliable release system for correct impact angle, NDE capabilities (dimensional, x-ray, leak test), and chilling or heating capabilities. Cameras to record the test event should have event start and stop mechanisms and timing designators. Methods to verify instrumentation data system configuration and performance should be present. Trained and experienced personnel for instrumentation installation, NDE, and for all other aspects of the test are essential. Quality assurance and documentation also play key roles in design verification testing.

EXAMPLE OF TEST PROGRAM

The DHLW cask is being developed by the United States Department of Energy to transport one canister of borosilicate glass waste. The cask body is a thick-wall type 304 stainless steel shell with a bolted closure. Additional gamma shielding is provided by a removable steel-jacketed depleted uranium shield liner. In the DHLW program a combination of testing and analysis was employed for the drop and puncture events. The immersion and thermal events were treated analytically.

The series of seven tests shown in Table 1 was performed using a half-scale model. To differentiate the effects of cask response, different impact angles and orientations were selected. Tests 2 and 3, as well as Tests 4 and 5, were performed as a regulatory sequence (sequential application of a 9-m (30-ft) drop test, followed by a 1-m (40-in.) puncture test) to determine their cumulative effect on the cask. Tests 6 and 7, 9-m (30-ft) drop tests, were performed as a nonregulatory sequence to take advantage of the similar interior instrumentation requirements for both tests. All tests were conducted at ambient temperature except Test 2, which was at -29°C (-20°F). For the cold test, the test unit was placed for about 48 hours in a temperature conditioning shroud. The closed loop circulating system used carbon dioxide and forced air to cool the model.

The scale model tests were used to quantify any permanent deflections in the closure area. These deflections were correlated with leakage testing performed on a full-scale mockup of the DHLW design (Madsen et al., 1986) having a prototype closure area. Tests on the full-scale closure mockup simulated a partial reduction in O-ring compression in several incremental steps.

Figure 1 shows the half-scale canister, cask body, and shield liner. Scale model canisters were fabricated and filled with surrogate borosilicate glass at Battelle Pacific Northwest Laboratories. To optimize the position of accelerometers, special recesses were located in components such as the canister (Figure 2) and depleted uranium shield liner upper sidewall. To protect internal strain gages from damage by adjacent components, grooves for the strain gages were machined on the bottom and top of the closure plate. Four slots were machined along the sides of the shield liner to allow space to install strain gages on the inner cask body wall. Since the containment boundary has several openings for instrumentation wiring, an additional radial seal located on the lower closure sidewall was required to allow closure seal leakage testing. To measure post-test separation of the closure sealing surfaces, special openings were machined in the closure. Linear variable differential

TABLE 1
DHLW SCALE MODEL PRE- AND POST-TEST ACTIVITIES

ACTIVITY	TEST 1 Bottom End Drop	TEST 2 Closure End Drop	TEST 3 Gas Sample Port Puncture	TEST 4 Side Drop No. 1	TEST 5 Closure Center Puncture	TEST 6 CG Over Bottom Corner Drop	TEST 7 Side Drop No. 2
Instrumentation Installation	1	1	1	1	1	1	1
Dimensional Inspection	1,2	1	2	1	2	1	2
Seal Leakage Test	1,2	1,2	2	1,2	2	1,2	2
Cask Weldment Leakage Test		1					2
Cask Weld X-Ray	1						2
Impact Limiter Weldments				1			
Shield Liner X-Ray	1,2		2		2		2
Assembly and Disassembly	3,5	3,6	4,5	3,6	4,5	3,6	4,5
Seal Permeation Test	1						
Gas Sample Port Weldment Leakage Test	1		2				2

KEY: 1 - Pre-Test
2 - Post-Test
3 - Complete Assembly
4 - Partial Assembly
5 - Complete Disassembly
6 - Partial Disassembly

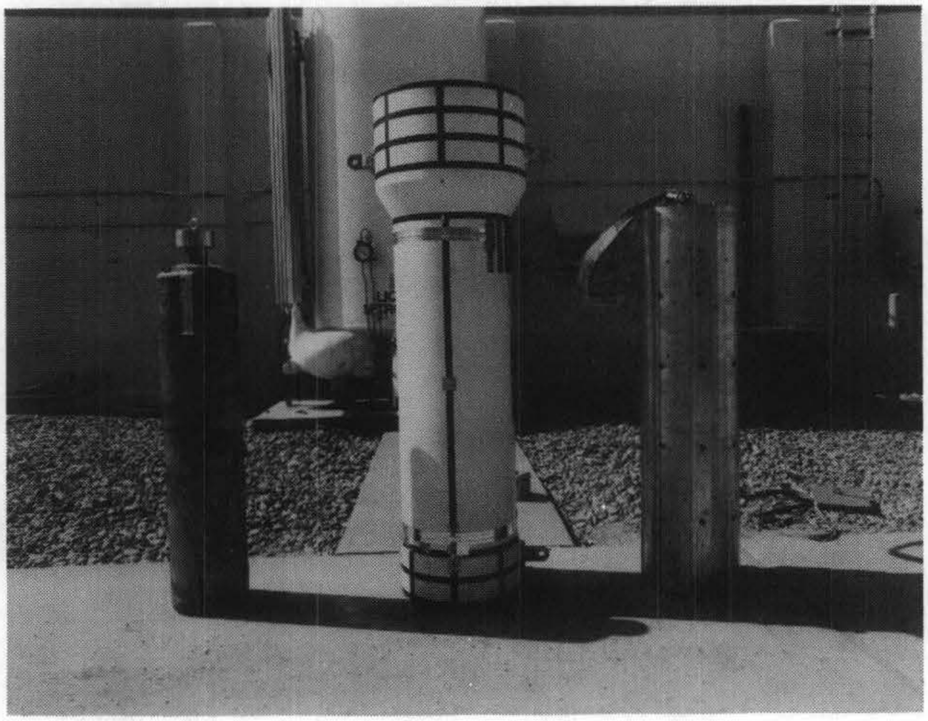

Figure 1. Half-Scale DHLW Canister, Cask Body, and Shield Liner

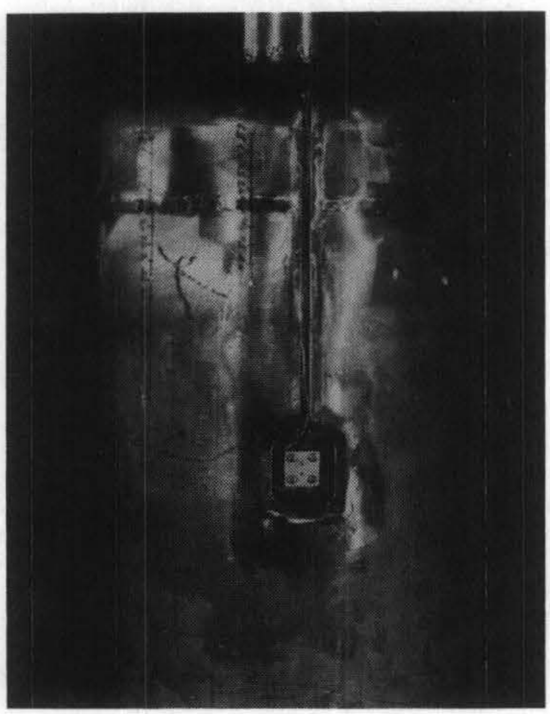

Figure 2. Accelerometer Recess Located in Canister Sidewall

transformers installed in these openings were also used to monitor any separation during the test events.

The model was fabricated under quality assurance (QA) programs that comply with the requirements of 10 CFR 71 and ANSI/ASME NQA-1 (ASME, 1983). The fabricators were required to prepare data packages that included: certified material test reports (chemical and mechanical properties of base materials and weld materials), nondestructive evaluations (NDE), personnel qualification records, weld records, nonconformance reports, process instruction sheets (shop travelers), and purchase orders.

The instrumentation measurement devices used to evaluate the structural response of the cask model were accelerometers, strain gages, strain-gaged closure bolts, linear variable differential transformers (LVDTs), and thermocouples. Accelerometers measured deceleration of the different cask components. Strain gages measured surface strain at varying locations in and along the cask body and closure. Strain gages mounted on the puncture bar measured strain and load. Strain-gaged closure bolts were used to measure changes in closure bolt loads. Linear variable differential transformers measured axial displacement changes between the cask body sealing surface and closure. Thermocouples measured temperatures of several of the cask components during the cold temperature test.

The strain-gaged closure bolts and LVDTs were calibrated at the beginning and end of the program. Accelerometer calibration was performed before and after each test with the exception of those located inside the cask for sequence tests. Strain gages typically are not calibrated after installation.

Pre-test measurements performed to establish baseline data for the cask included detailed dimensional inspections, leakage tests, and radiographs. Table 1 summarizes the pre- and post-test activities for each test. Other nondestructive evaluations performed during the test series include helium mass spectrometer leakage testing of the cask closure seals, the cavity gas sample port welds, and the cask body welds. A permeation leakage test was performed on the closure seal prior to the initial seal leakage tests to provide guidance on the maximum allowable time for the seal leakage test procedure.

Radiography was used to examine the cask body welds and shield liner before and after the test series. The depleted uranium shield liner was radiographed (x-rayed) when it was received at SNL, and after Tests 1, 3, 5, and 7.

Testing was conducted at the SNL 2500-ft aerial cable facility (Uncapher, 1983) in Coyote Test Field. The test unit was suspended above the unyielding target at the height specified for each test. The unit was released by explosive cable cutters and allowed to free fall in the specified orientation to impact the unyielding target. The unyielding target is composed of 500,000 lb of reinforced concrete and steel 20 ft in diameter and 12.5 ft thick. A battleship armor plate 10 ft by 10 ft and nominally 5 in. thick is welded to the concrete reinforcing members. The armor plate is coupled to the concrete by high-strength grout. For the puncture tests, the half-scale puncture bar assembly was welded to the unyielding target in a vertical position.

Still photographs from 35 mm cameras recorded pre- and post-test activities. The target was surrounded on two sides by photometric cameras with frame rates ranging from 24 frames/s (real time) to 2000 frames/s to record the event.

After the data were collected and processed in the form of plots, the data were reviewed. This review included evaluation of instrumentation measurement device parameters, such as comparison of pre-test to post-test calibration data, comparing data to other measurement devices which measure similar responses, and comparing the data with high-speed photometric films and mechanical measurement information. The data were graded against these evaluation criteria. Uncertainties of the reduced data were included based on the individual factors which could contribute to the measurement.

Documentation played an important role in this test program. Detailed written test procedures guided each step of the testing and provided for recording of all data. Step-by-step instructions together with QA holdpoints were prepared for each test. Procedures for the NDE tests (leakage testing, radiography, and dimensional inspections) were prepared. Prior to use, all procedures were approved by two independent reviewers and by project personnel.

SUMMARY

Key elements of design verification test programs include design of the scale model, instrumentation, photography, nondestructive evaluations, data evaluations, test plans, and quality assurance. Consideration should be given to:

- Model size allowing direct scaling of critical components and providing space for instrumentation,
- Multiple drop and impact orientations, regulatory sequences, and temperatures to envelope most severe orientation and initial condition,
- Installation of spare parts when cumulative test damage from a test not in a regulatory sequence would significantly affect results in the next test and
- Comprehensive QA implemented with detailed test plan documenting procedures and test results.

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