Internal Pressure Experiments with Steel and Concrete Containment Models

T.E. Blejwas
Sandia National Laboratories, Containment Integrity Division 6442,
Box 5800, Albuquerque, New Mexico 87185, U.S.A.

Abstract

Models of containment buildings are being tested as part of a combined experimental and analytical effort at Sandia National Laboratories.* The models are slowly pressurized pneumatically until significant leakage or structural failure occurs. The experimental results provide a data base for qualifying analytical methods for predicting containment behavior during severe (beyond design-basis) accidents.

A series of experiments with models of hybrid steel containments at scales of 1/32 and 1/8 has been completed. A large base of data (strains, displacements, leak rates, etc.) for loadings that cause significant nonlinear response was obtained.

Final design of a 1/6-scale model of U. S. reinforced concrete containments has been initiated, and construction of the model is scheduled to begin in 1985.

1. Introduction

To provide data for qualifying analytical methods for predicting containment behavior during severe accidents, models of steel and concrete containments are being slowly pressurized until large leakage or structural failure occurs. These experiments are part of a series of programs at Sandia National Laboratories in the area of containment integrity. An overview of the programs in this area that are sponsored by the U. S. Nuclear Regulatory Commission is presented in a companion paper [1].

A series of experiments with models of hybrid steel containments has been completed and final design of a reinforced concrete model is underway. In all of the experiments, the models are slowly pressurized in discrete steps with nitrogen gas. Extensive structural data (strains, displacements, etc.) are recorded at each pressure level. On the large models with operable equipment hatches, integrated leak rates are determined during periods in which pressure input to the model is shut off.

Descriptions of the four experiments with small steel containment models of about 1/32 scale have been previously reported [2,3] and will be only briefly reviewed here. The experiment with a 1/8-scale steel model was recently completed (November 1984).

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*Work supported by the U. S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, and performed at Sandia National Laboratories which is operated for the U. S. Department of Energy under Contract Number DE-AC04-76DP00789.

The conduct of the test and qualitative behavior of the model are described. Companion papers [4,5] contain additional details on the experiment and pretest analyses. Final design of a reinforced concrete model is underway and construction is scheduled to begin in the third quarter of 1985. A description of the proposed model and the status of the design and construction are reported.

2. Review of Small Steel Model Experiments

Four steel models about 1/32 the size of U. S. hybrid steel containments (often used with PWR ice-condenser or BWR Mark III suppression systems) were tested between December 1982 and December 1983 [2,3]. The three configurations for the models (two had the same clean shell configuration) are shown in Figure 1. The models were fabricated from 0.045 inch (1.2 mm) thick low carbon steel (ASTM 1008). Fabrication methods were not representative of actual containments.

All of the small steel models were pressurized past levels that caused general membrane yielding of the cylindrical walls. Two of the models, a clean shell and the ring reinforced shell, developed cracks and leaked when maximum membrane strains were about 7% and 3% respectively. The cracks were due to fabrication flaws that were not representative of actual containments. The second clean shell and the shell with penetrations were pressurized to rupture. The maximum membrane strains at failure were about 20% and 15% respectively. The penetration model included an equipment hatch representation that buckled prior to membrane yielding of the shell; a thick flat plate was welded to the sleeve of the hatch prior to pressurization to rupture.

Comparisons of experimental data with pretest predictions using the MARC finite element code have been generally good for the small steel models. However, the analyses, which used material properties from uniaxial tensile tests, tended to overpredict the general yielding of the models by as much as 15%. Comparisons of experimental and analytical data in areas of high strain gradients have been of varying quality--probably due to inaccuracies associated with the large size of the high elongation strain gages.

Pretest analyses of the ring reinforced model, which included the effects of finite strains and geometric nonlinearities, indicated that the rings and cylindrical shell would yield and move outward in a smooth manner (with little noticeable bending) as pressure was increased. The model behaved in this manner during the experiment.

Penetrations in the last small model did not cause an early shell failure. Although the free field strains at rupture were a maximum of 15% versus 20% in one of the clean shell models, both levels are such that even the presence of a very small flaw may lead to rupture. Although stress concentrations around penetrations were very high during elastic response, a general smoothing of the strains was observed both experimentally and analytically as plastic flow occurred.

3. Large Steel Model Experiment

A large steel model, about 1/8 the size of typical hybrid steel containments, was successfully tested to high pressures on November 15-17, 1984. The model had been designed and fabricated for Sandia by Chicago Bridge and Iron Co. Dimensions and features of the model are shown in Figure 2. In Figure 3 one of the two equipment hatches can be seen on the white upper structure (the darker base is a test fixture). The model had a design pressure of 40 psig (0.28 MPa) and was fabricated from A516 steel. A complete description of the model is available in [6].

3.1 Test Preparations

The large steel model was heavily instrumented for measurements of structural data and integrated leak rates. Control of the experiment and the acquisition of data were accomplished using computerized systems that were operated from a distance of about 1500 ft. (450 m) from the model. The instrumentation and control system are described in [4].

In a manner similar to that for actual containments, a structural integrity test was successfully performed to a pressure of 46 psig (0.32 MPa) on November 7, 1984. An extended integrated leak rate test (ILRT) conducted from November 9 to 12, 1984 yielded a leak rate of about 0.02 percent mass per day, which is well below specified values for actual containments.

3.2 High Pressure Testing

Pressurization to high levels was successfully completed during a three-day period from November 15 to 17, 1984. Increases in pressure were made during daylight hours only (for safety reasons) and overnight periods were profitably used for integrated leak rate measurements.

On November 15 the model was pressurized to 140 psig (0.97 MPa) in steps of 10 to 20 psi (0.07 to 0.14 MPa) . No leakage was detected with an acoustic emission system during the day. An overnight ILRT at 140 psig stabilized to a value of about 0.2 percent mass per day.

On the second day of testing, November 16, the model was pressurized to 150, 155, 160, 165, and 170 psig (1.03 to 1.17 MPa). Testing proceeded slowly because localized yielding was spreading throughout the model with each step. A single yield plateau at which most of the membrane regions of the cylinder yielded and grew rapidly was not observed.

At 165 psig a theodolite operator in a bunker 250 feet from the model reported a crack in a formed stiffener near equipment hatch 1. The location of the crack is indicated in Figure 4. Although the crack was initially believed to be in the paint only, a post-test interview revealed that the operator observed growth in the crack at higher pressures.

An overnight ILRT at 170 psig stabilized to a value of about 0.2 percent mass per day. A plot of on-line calculated leak rate versus time is shown in Figure 5. The upper curve is the upper confidence level; the dotted line is the leak rate from the total time method; and the dashed line is the leak rate from the mass plot method.

On the final day of testing, November 17, sets of structural data were recorded at pressure levels of 172.5, 175, 180, 185, and 190 psig (1.19 to 1.31 MPa). Some bulging can be seen in the sides of the model at 190 psig (Figure 6). The model ruptured after pressure was raised to 195 psig (1.34 MPa). The last step was taken at 12:17. At 12:24 the strains and displacements in the model were still slowly increasing (a behavior that was typical after yielding). A strain gage located about one inch from the formed stiffener around equipment hatch 1 and midway between two horizontal stiffeners (the nearest gage to the observed crack) was monitored about every four seconds during this pressure step. At 12:24:04 the strain was 3.4%, but by 12:24:24 the reading had increased to 8.2%. At the next and last reading, the gage read only 2.6%. (The gage probably detached from the model). The five other monitored strain and displacement sensors did not record unusually large increases prior to rupture. During the last fifteen seconds before rupture, the model pressure dropped 1.4 psi (9.7 KPa), although the pressure controller had a dead band of only ± 0.25 psi (1.7 KPa). A theodolite operator heard a hissing noise starting about fifteen seconds before rupture.

3.3 Model Rupture

The model fragmented into at least twelve pieces. The dome was divided into two pieces with some cylindrical material staying with one piece. This latter one struck the top of a power pole, continued in a generally stable spinning flight, and landed 1340 feet from the original model location. Although the other pieces did not travel as far, they scattered over the area south and east of the original site, in a direction generally opposite from the side of the model with equipment hatch 1. A view of the site with some of the largest pieces in the distance is shown in Figure 7.

Based upon the location of fragments, an examination of fracture surfaces, and the observations and data described above, the failure of the model is believed to have started with the crack in the formed stiffener adjacent to the welded connnection to the horizontal stiffener (see Figure 4). The crack propagated through the stronger weld material in the connection to the cylinder, and the cylinder tore in a somewhat stable manner until a critical crack size was reached, at which point the model ruptured. The original crack in the formed stiffener is believed to have been due in part to the multiple welds in the region and a complex three-dimensional stress state. Examination of the fracture surfaces revealed only ductile tearing, i.e., there was no evidence of brittle fracture. Also, no material defects were observed. However, comparisons of the strain from the gage nearest the tear and pretest analyses [5] show that the cylinder wall near the formed stiffener yielded at much lower pressures than expected, perhaps due to cold working or welding of the material. This behavior of the wall material probably increased the load in the adjacent stiffeners. To date, an analytical technique for predicting the formation of the crack has not been located.

Descriptions of the recorded data and comparisons with pretest finite-element analyses are contained in companion papers [4,5].

4. Reinforced Concrete Model

A conceptual design for a 1/6-scale model of typical U. S. reinforced concrete containments has been completed [3]. A contract for the final design and construction of the model has been placed with United Engineers and Constructors (UEC). The contract with UEC also includes a series of preconstruction tests to ensure that a satisfactory model can be constructed and that the behavior of certain key areas, e.g. liner-stud-concrete anchorage, are representative of actual containments.

Based upon the conceptual design and initial input from UEC and its subcontractors, the model is expected to have the following features:

1. 1/6 scale
2. #4 reinforcing bar as major reinforcement
3. 1/16 in. (1.6mm) thick steel liner with stud attachments
4. Two operating equipment hatches with seals
5. Two personnel lock representations
6. Pipe penetrations
7. A flat basemat
8. A hemispherical dome
9. Diagonal seismic reinforcing bar
10. A design pressure of 46 psig (0.32 MPa)

Construction of the model is expected to begin in the third quarter of 1985.

5. Acknowledgments

The various components of work described herein are being conducted or directed by Sandia staff members D. S. Horschel, L. N. Koenig, L. D. Lambert, and P. E. Matson. The responsible Sandia supervisor is W. A. von Riesemann, and the NRC technical monitors are H. Ashar and J. F. Costello.

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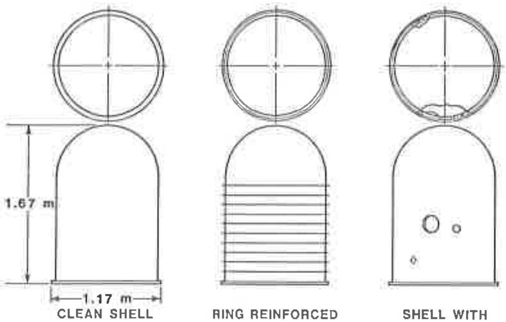

Figure 1. 1/32-Scale Steel Models

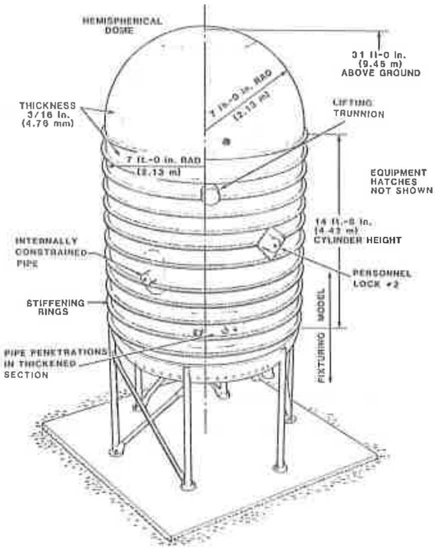

Figure 2. 1/8-Scale Steel Model

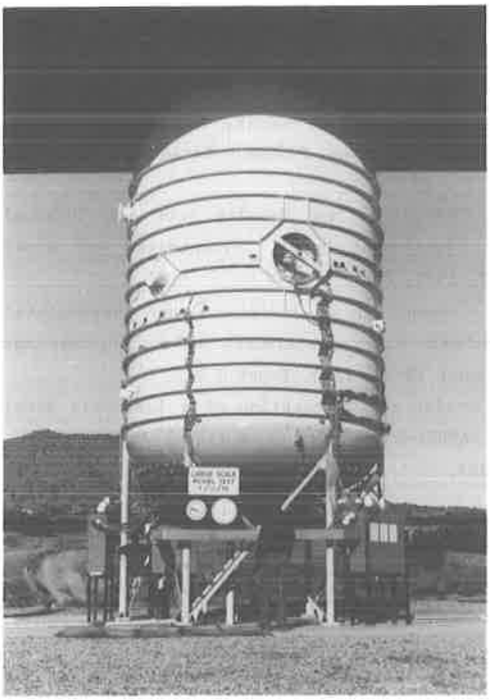

Figure 3. Large Steel Model Just Prior to High Pressure Testing

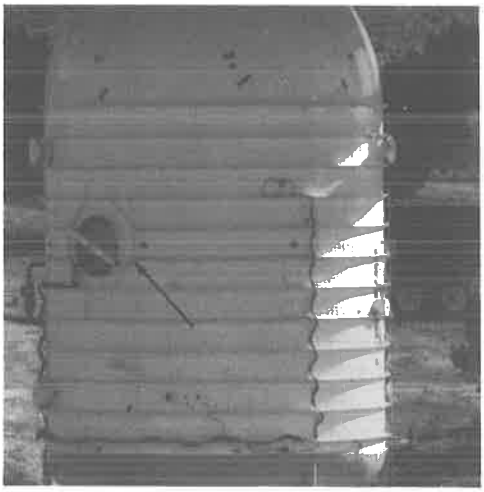

Figure 4. Large Steel Model with Crack Location Indicated

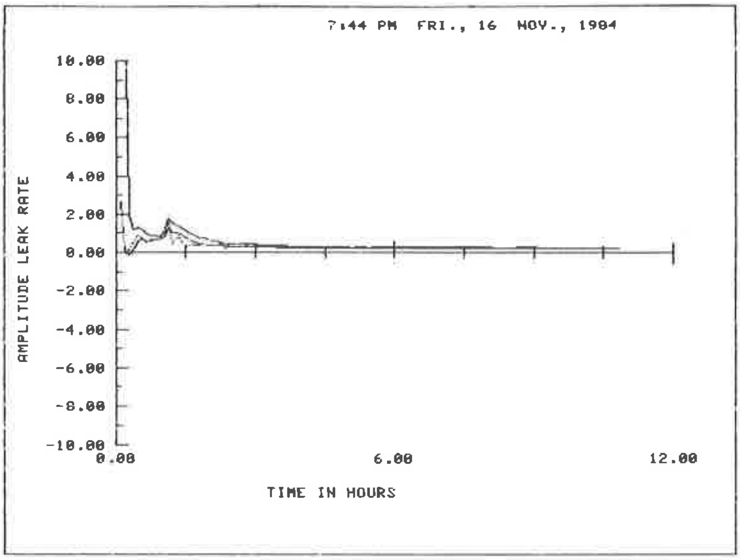

Figure 5. On-Line Integrated Leakrate at 170 psig

Figure 6. Large Steel Model at 190 psig

Figure 7. Test Site after Model Rupture with Pieces in Distance