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Plan on test to failure of a steel, a pre-stressed concrete and a reinforced concrete containment vessel model

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ABSTRACT: This paper describes the plan for tests to failure of various (i.e., steel, pre–stressed concrete, and reinforced concrete) containment vessel models. One of the objectives of these tests is to experimentally investigate the ultimate structural behavior of the containment vessel models by slowly increasing the internal pressure, at ambient temperature, until failure occurs. Also, pre– and post–test analyses will be performed to predict and evaluate the test results, and to validate the analytical methods that will be used to evaluate the structural behavior of the actual containment vessels under severe accident conditions. The tests are included in a joint research program involving the Nuclear Power Engineering Corporation (NUPEC) in Tokyo, Japan, the US Nuclear Regulatory Commission (NRC) in Washington, D.C., and Sandia National Laboratories (SNL) in Albuquerque, New Mexico, USA

1 INTRODUCTION

Light–water–reactor (LWR) containment buildings, which are constructed from steel, reinforced concrete, or prestressed concrete, are the last engineered barrier to prevent the release of radioactive materials to the environment. Therefore, several experiments have been done in the world (Blejwas, 1985, Horschel, et al., 1986, and Smith, 1988). However, types of tested containments are few.

In this regard, the Nuclear Power Engineering Corporation (NUPEC), the United States Nuclear Regulatory Commission (NRC), and Sandia National Laboratories (SNL) have been involved in a cooperative research program on structural integrity of various containments (Takumi, et al., 1992, Kobayashi, et al, 1994). The program will include pressure tests on scaled containment vessels of three different types; steel containment vessel (SCV), prestressed concrete containment vessel (PCCV), and reinforced concrete containment vessel (RCCV). The SCV model represents some features of an improved BWR Mark–II containment vessel in Japan. The PCCV model represents a typical two buttress PCCV in actual PWR plant in Japan. The RCCV model represents some features of a typical advanced BWR containment vessel in Japan.

The objectives of these tests are to measure the failure pressure, to observe the mode of failure, and to record the containment structural response up to failure. Pre– and post–test analyses will be performed to predict and evaluate the test results, and to validate the analytical methods that will be used to evaluate the structural behavior of the actual containments under severe accident conditions.

2 STEEL CONTAINMENT VESSEL TEST

2.1 SCV Test Objectives

At the beginning of the SCV test program, the focus of the test was the ultimate structural behavior of a free-standing SCV. In other words, the purpose of the test was, without consideration of contact with a surrounding shield structure (SSS), to provide experimental data useful for the evaluation of the SCV. The experimental data were also to be used for checking the predictive capabilities of analytical methods of a free-standing SCV beyond elastic range (Takumi, et al., 1992).

Later on, the purpose of the test was extended so that the test should also provide experimental data on the SCV behavior after contact with the SSS. Consideration of the contact is important for BWR Mark-I and Mark-II containments since the gap between the containment and the SSS is relatively small (50–90mm) and would likely be closed due to increasing internal pressure under a severe accident well before structural failure of the SCV. In pursuit of this objective, specific features to be examined include: closure of gap, progression of contact, load sharing, etc., between the containment and the shield structure.

2.2 SCV Test Model

The SCV test specimen is a scale model representing some features of an improved BWR Mark-II containment vessel in Japan. A scale of 1:10 is used for the overall geometry of the model with 1:4-scaling of the wall thickness. This selection of scales allows the model to be small enough for transportation from Japan to SNL while being thick enough to ensure quality construction.

Preliminary analysis results (Takumi, et al., 1992) of a typical BWR Mark-II indicate that high strains during over-pressurization will concentrate mainly in the drywell region of the SCV. Therefore, the complete wetwell is not included in the model. The model (Figure 1) includes a drywell top head, a reverse-curvature knuckle, spherical/conical drywell walls, and an upper portion of the wetwell cylindrical wall. The lower portion of the actual wetwell wall is replaced in the model with a hemispherical 'bottom head', which is considerably thicker than the walls above the wetwell region, so that deformations of the bottom head will be minimal. An access hatch, a pressurization port, and 45 instrumentation ports will be included in the bottom head. The model also includes a large equipment hatch sleeve and a ring that represents the drywell top head flange, in order to take account of the stiffening effects of these portions on the model behavior. The bolted flange connections are not modeled here, but a full-scale hatch model with gasket will be tested as a separate NUPEC test program (see section 2.5). Table 1 shows the wall thicknesses of the SCV model.

The model fabrication was completed in 1994, at Hitachi Works, Hitachi, Ltd., in Japan. The model is transported to SNL for instrumentation in March, 1995.

2.3 SCV Test Sequence

A test sequence consisting of two phases has been considered. The purpose of the Phase 1 test will be achieved when the outward displacement of the conical portion of the model becomes approximately equal to the scaled gap between the actual SCV and the shield building. The purpose of the Phase 2 test will be achieved when the model will contact a surrogate of the shield building and will be failed at anyplace due to the over-pressurization.

One single continuous test for the test sequence is considered to combine the above two phases. This test plan is intended to simplify the program for budgetary/technical reasons. Though the details are still being discussed, the concept of the single test is described below.

The contact structure (CS) (Figure 2), which takes account of the contact effect of the shield building around the SCV in the actual plant, will be installed over the SCV model at SNL before the test. Then, one continuous over-pressurization test will be conducted without de-pressurization. The gap between the CS and the SCV model will approximately be doubled comparing to the scaled gap between the actual SCV and the shield building, in order to fulfill the purpose of the Phase 1 test by allowing the SCV model to experience deformation well beyond the elastic range, but without contact with the CS. After the phase 1 test, the continuous over-pressurization will fulfill the purpose of the Phase 2 test.

2.4 Tentative Instrumentation Plan for SCV Test

Described below is the tentative instrumentation plan for the SCV program. Details for the number or the locations of instruments are being discussed. Instruments under consideration mainly include:

- more than 500 strain gages attached on inner and outer surfaces of the SCV model to measure local strains of the model,
- approximately 40 displacement transducers installed on a column constructed along the axis of the model to measure the displacements from inside, and 10 transducers (LVDT) installed on the CS to measure distance between the model and the CS,
- thermocouples and resistance temperature devices to measure the temperature on the surface of, and inside the model,
- and pressure transducers.

2.5 Hatch Model Test

As a separate NUPEC test program, a full–scale equipment hatch model with gasket (Figure 3) in the BWR Mark–II will be tested in 1995, in order to investigate the structural behavior of the hatch during over–pressurization. The test will be conducted hydrostatically until leakage occurs.

Some preliminary analyses have been carried out using an axi–symmetric FEM model to predict stresses, strains, and deformations of the model, and to determine the locations of instruments.

Instruments under consideration include:

- 50 strain gages attached on inner and outer surfaces of the hatch model to measure local strains of the model,
- 17 displacement transducers to measure the displacements of the head cover, the supporting ring, and the sleeve,
- 16 clip gages to measure the relative displacement between the sleeve and the supporting ring,
- and 2 pressure transducers.

3 PRE–STRESSED CONCRETE CONTAINMENT VESSEL TEST

3.1 PCCV Test Model

The PCCV test model will be a scaled representation of an actual PCCV for the PWR in Japan, which was designed in accordance with the Japanese Concrete Containment Vessel Design Code. The actual PCCV consists of a hemispherical dome, a cylindrical wall, and a basemat. Two buttresses are used to anchor the horizontal or 'hoop' tendons. In the vertical direction, a 'hairpin' tendon layout is employed. The vertical tendons are anchored in a tendon gallery that is inside the basemat. A liner plate, which is made of carbon steel, is placed on the inner surface of the concrete wall, dome, and basemat and forms the containment pressure boundary in these areas.

Figure 4 shows the PCCV test model. It consists of a hemispherical dome, a cylindrical wall, and a basemat as same as the actual containment. A uniform scale of 1:4 was adopted for the overall containment dimensions including the liner/anchorage system. As scaled from a typical containment, the thickness of the dome is 275mm, while the cylinder wall is 325mm thick. A thickness of 3.5m was selected for the basemat based on the analysis result comparison between the model and the actual PCCV. The model includes an equipment hatch (E/H), one of the two personnel airlocks (A/L), and main steam (M/S) and feed water (F/W) piping penetrations.

Design of the model was performed with the following basic rules:

1) The liner plate shall be attached to the concrete using the same type of liner anchorage system as used in the actual containment, although the spacing of liner anchors will be increased in regions away from major discontinuities.
2) The reinforcing ratios for reinforcing bars and prestressing tendons shall be equivalent to those in the actual containment.
3) The tendons shall be replaced by the model tendons at the same relative location of the actual containment. The area of the model tendons shall be scaled.
4) The material characteristics of the steel elements and the concrete shall be as close as possible to those of the actual materials.

The basic design of the model has been almost finalized. The construction will be conducted at SNL in 1995–1997. Instrumentation of the model will be conducted in 1997–1998, partly in parallel with the on–site model construction. Testing of the PCCV model will then take place after 1998.

3.2 Some Topics of PCCV Model Design

3.2.1 Liner

A liner is located on the inner surface of the concrete. The scaled thickness of the liner is 1.6mm except for the areas around the penetrations, where 1:4–scale thickened insert plates will be attached.

The liner on the inner surface of the cylindrical wall will be attached to concrete using a scaled anchorage system, which consists of T–sections in the vertical direction and rectangular sections in the horizontal direction. 1:4–scale is also employed for the spacing between vertical liner anchors in the vicinities of the liner discontinuities (e.g., penetrations or cylinder/basemat junction), where liner tearing is most likely to occur, while larger spacing is used for the vertical anchors in free–field areas. The liner on the dome will be bonded to concrete by studs attached to the liner.

The liner has been constructed in sections at Kobe Shipyard & Machinery Works, Mitsubishi Heavy Industries, Ltd., Kobe, Japan. The liner blocks, together with liner jigs, will be shipped from Japan to SNL late in 1995.

3.2.2 Tendon System

Based on one of the above basic design rules, the prestressing system has been modeled by a 'one–to–one' replacement of tendons. Layout conditions in length (e.g., spacing between sheaths, minimum radius of curved sheath, etc.) were selected for the model based on 1:4–scaling.

In the actual structure, a tendon is composed of 55 strands whose diameter is 12.7mm, while the model tendon consists of 3 (custom–made) 13.7mm strands. Thus, the ratio of the area of a model tendon to that of an actual tendon becomes exactly 1:16th, which is consistent with the length scale of 1:4 for the PCCV model. Trial manufacturing of the model prestressing system (including 'custom–made' strands, anchorheads, wedges, etc.) was finalized, and the system has been subjected to a series of tests (ranging from tensile, fatigue, and relaxation tests of a single strand, to tensile tests of the prestressing system) to check the model tendon system equivalence to the actual system.

3.2.3 Rebar

In parallel with the design of the liner/anchorage and the prestressing systems, rebars have been modeled on the following basis:

1) Smaller number of thicker rebars will be used comparing to the rebar arrangement in the actual PCCV, mainly in view of ease of rebar construction. In other words, rebars are not modeled by a 'one–to–one' replacement of actual rebars. However, the reinforcement ratio for rebars shall be equivalent to that in the actual containment.
2) The mechanical characteristics of the model rebars shall be the same as, or as close as possible to, those of the actual one. Rebars that meet the JIS specifications shall be used for the model.

3.3 Preliminary Instrumentation Plan for PCCV Test

Instruments under consideration for the PCCV test covers: internal pressure load, temperature, displacements, and strains or stresses of liner/anchorage, rebars, tendons, and concrete. Locations of instruments such as displacement transducers or strain gages on rebars/concrete will be determined considering the Structural Integrity Test (SIT) activities on a typical PCCV structure in Japan and areas of interest determined by pretest analyses. Regarding the tendon instrumentation, load cells will be installed at both ends of about one third of the whole tendons. Also, strain instrumentation along tendons is currently under consideration in order to obtain data on the variation of tendon load between anchor points. The candidate devices for this purpose include; electrical resistance strain gages (attached directly on strands) and Tensmeg gages.

4 REINFORCED CONCRETE CONTAINMENT VESSEL TEST

4.1 RCCV Model Concept

The proposed RCCV test model will represent some features of a typical advanced BWR in Japan (Figure 5). It will include the containment pressure boundary consisting of a top slab, a cylinder wall and a basemat, which are all made of reinforced concrete, and a liner on the inner surface of concrete. The model also includes some larger penetrations and related sleeves such as access tunnels or equipment hatches. A uniform scale of 1:4 is selected for the dimensions of the liner and the concrete portion. Confining effects, from the concrete floor slabs or the spent fuel pool girder of the reactor building, on the RCCV will be modeled.

4.2 Issues for RCCV Model Design

Confining effects of the structural elements, which surround the RCCV, will be modeled using surrogate structures attached to the RCCV model. Some finite element analyses have been conducted in order to investigate those effects and determine how, and to what extent, the surrounding structures should be included into the model.

The liner on the lower cylinder is made of stainless steel in the actual building. However, construction of thin stainless steel liner is known to be very difficult. Therefore, another focus of the model design will be the constructability of the liner.

5 SUMMARY

Plans have been provided for the pressurization test to failure of three different types of containment vessels: SCV, PCCV, and RCCV. The SCV model, which represents some features of an improved BWR Mark–II in Japan, was fabricated. The model will be tested in 1996–1997. Basic design of the PCCV model has almost been finalized. The PCCV model testing will take place after 1998. The concept for the RCCV model, which will be tested in 2001, is also being developed.

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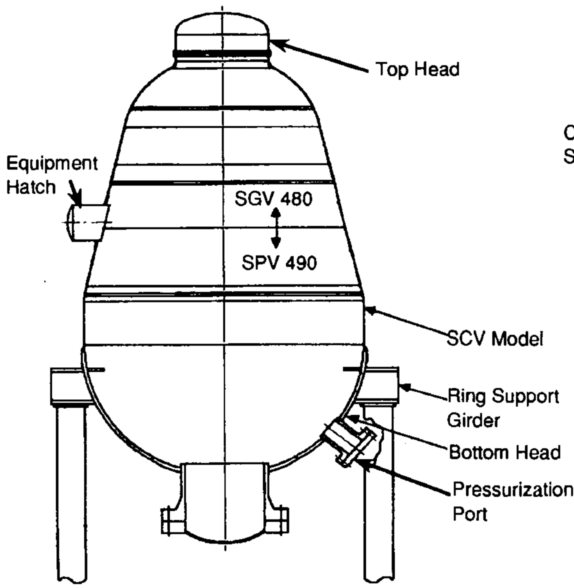

Fig. 1 SCV Test Model

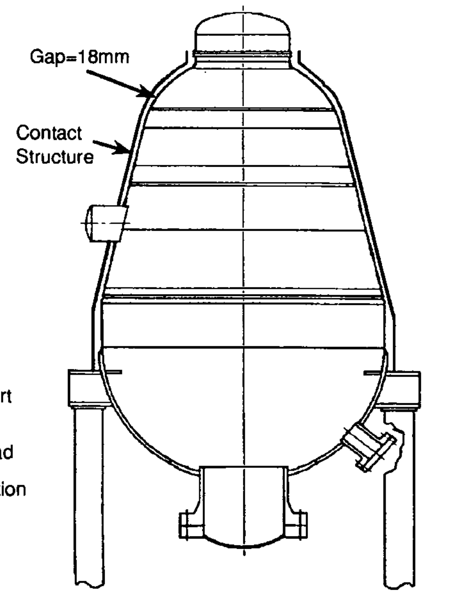

Fig. 2 SCV Test Model with Contact Structure

Table 1 SCV Wall Thicknesses (in mm)

Location			Actual SCV	Model SCV
Drywell Region	Top Head		24.0	6.0
	Reverse-Curvature Knuckle		66.0	16.5
	Spherical Wall		32.0	8.0
	Conical Wall	upper portion	30.0	7.5
		middle portion	34.0	8.5
		lower portion	36.0	9.0
Wetwell Region			36.0	9.0
Hemispherical Shell "Bottom Head"			----	38.0

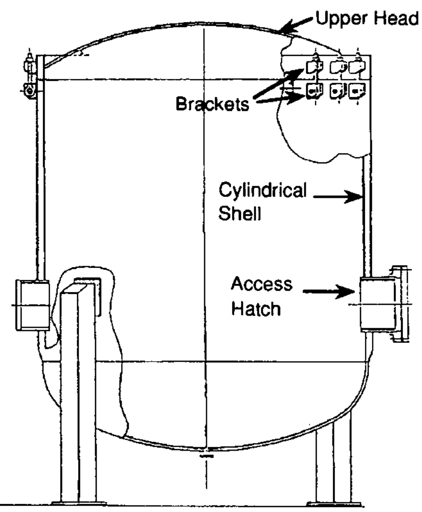

Fig. 3 Hatch Test Model

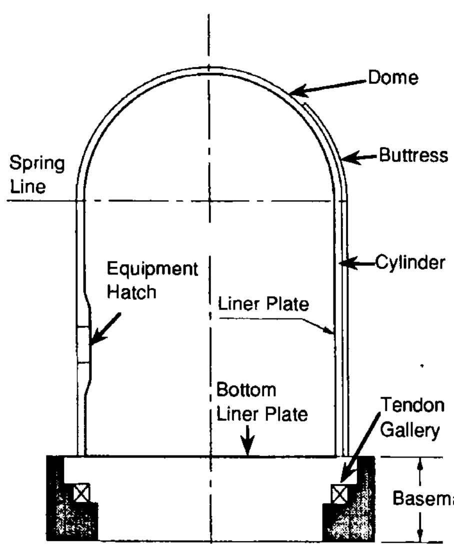

Fig. 4 PCCV Test Model

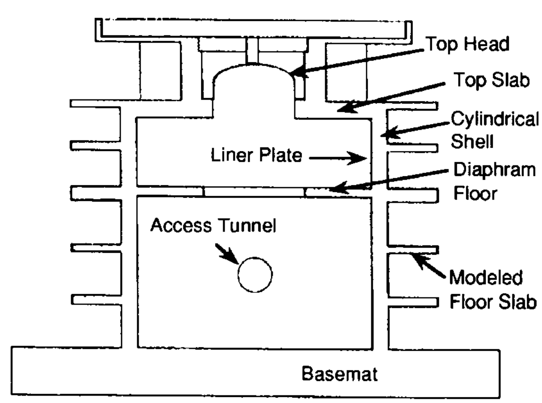

Fig. 5 Tentative RCCV Test Model