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Instrumentation and testing of a prestressed concrete containment vessel model

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ABSTRACT

Static overpressurization tests of two scale models of nuclear containment structures—a steel containment vessel (SCV) representative of an improved, boiling water reactor (BWR) Mark II design and a prestressed concrete containment vessel (PCCV) for pressurized water reactors (PWR)—are being conducted by Sandia National Laboratories for the Nuclear Power Engineering Corporation of Japan and the U. S. Nuclear Regulatory Commission.[1] This paper discusses plans for instrumentation and testing of the PCCV model.

Background

Several tests of large-scale models of prestressed containment vessels have been conducted in the past. A test of a 1:10-scale model of a prestressed containment vessel was conducted in Poland in the late 1970s [1]. A 1:14-scale model of a prestressed containment vessel was tested in Canada in the 1970s [2]. The most recent test was a 1:10-scale model of a prestressed concrete containment vessel tested in Great Britain in July 1989 [3]. None of these models incorporated a steel liner and all were tested hydrostatically. Also, the data collected from the instrumentation on the prestressing tendons was inconclusive due to high instrument mortality rates and unexplained inconsistencies in the expected behavior.

The current test will consist of a uniform 1:4-scale model of an existing PCCV in Japan [4]. The model will include a steel liner and scaled representations of the equipment hatch, personnel airlock, and main steam and feedwater line penetrations. The overall geometry of the model is shown in Figure 1. The model will be tested pneumatically, using nitrogen, beginning with a series of low-level tests, including an integrated leak rate test (ILRT) and a structural integrity test (SIT), and finally pressurized to failure during the limit state test (LST). Failure, for the purposes of this test, is the inability to maintain containment pressure at the capacity of the pressurization system. Construction of the model at Sandia National

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Laboratories is scheduled to begin in early 1997 and the tests are scheduled to occur in late 1999 or early 2000.

The model will be constructed of normal concrete and will include both conventional and prestressed reinforcing. The area of the conventional reinforcing is based on the scaled area of the reinforcing in the actual plant. There is a one-to-one correlation between the prestressing tendons in the model and the tendons in the existing plant. The model includes ninety vertical, "hairpin" tendons, which cross the dome in an orthogonal pattern and are anchored at the tendon gallery inside the basemat. One hundred and eight hoop tendons, each spanning 360°, are alternately anchored in two vertical buttresses. Each tendon consists of three, seven-wire strands, with each strand having a nominal diameter of 13.7 mm. These strands are being specially manufactured to match the scaled area of the tendons in the actual plant. The tendons will be placed inside lightly corrugated metal ducts of the same type used in the actual plant and will not be grouted or greased except for a light coating of a corrosion inhibitor.

Model Instrumentation

Objectives

The objectives of this test program include validation or improvement of numerical simulation methods for predicting the response of containment structures to loadings beyond the design basis accident. As such, it is necessary to obtain data on the behavior of the various elements of the structure in order to gain insight into the general behavior of these elements and to compare this behavior with predicted responses.

To meet this objective, an extensive suite of instrumentation will be incorporated into the model. The instrumentation plan currently includes approximately 1800 channels of data consisting of displacement transducers to measure global and local model movements; strain gages for liner, liner anchor, rebar, tendon, and concrete measurements; load cells for tendon anchor loads; pressure sensors to monitor internal pressure; and temperature sensors to monitor the gas temperature for leak rate calculations and for strain gage compensation. The placement of the various sensors has been determined from the results of preliminary analyses to characterize model response and investigate possible failure modes [5].

One important aspect of the instrumentation plan is that we are planning to obtain data on the model's response during construction, beginning with the prestressing operations, and will continue to monitor the response of the model for approximately 12 months until the pressurization tests occur. At present, we are planning to use a separate suite of high-resolution, low-range transducers for these low-level measurements, including the ILRT and SIT tests. In 1991 and 1992 SITs were carried out on the containments of the Ohi Nuclear Power Station (Units 3 and 4). The PCCV model is a 1:4 scale representation of the prestressed containments at Ohi. In order to show if scaling affects the model response, we will obtain measurements at several points identical to the Ohi SIT measurements for comparison. The SIT at Ohi was performed at 1.125 times design pressure and will be the same for the 1:4 scale model.

Another important objective of the instrumentation is to provide insight into potential failure modes. Following the LST, an investigation of the strains, displacements, etc. near the point of failure should provide additional insights into the mechanism that caused failure to occur. A list of the potential failure modes being considered for the PCCV model includes the following:

- Free-field liner tearing
- Liner tearing at a discontinuity (i.e., near penetrations, wall-base juncture)

- Liner anchor failure
- Shear failure at wall-basemat juncture
- Shear failure in basemat
- Equipment hatch (E/H) leakage
- Personnel air lock (A/L) leakage
- Small penetration leakage
- Tendon wire failure
- Tendon anchor or bearing plate failure

For each of these potential failure modes, a number of instruments (gages, transducers, etc.) will be placed to measure local response. These response measurements will be used to validate analytical models and investigate failure mechanisms.

Table 1 shows the relationship between instrument location, instrument type, measurement type, and measurement objective. The measurement objectives are either to capture global or local response at specified locations in the PCCV or to observe behavior related to the potential failure modes.

Types of Measurements

Pressure

Pressure transducers will be installed in the vessel to control and accurately relate model response to load for comparison with pre- and post-test analyses and to determine the integrated gross leak rate of the vessel during low pressure testing.

Temperature

Material temperature measurements will be made to provide thermal compensation of all strain gages within the PCCV model. Internal gas temperature measurements will also be made to provide data for estimating leak rates from the vessel during the ILRT and for detecting the onset of leakage.

Displacements

Displacement measurements will be made to measure the response of the model at each step during the various loading sequences for comparison with the pre-test predictions of global response. Typical displacement measurements will include:

- radial displacements of the cylinder wall at regular azimuths and elevations relative to an internal datum,
- vertical displacements at the springline at regular azimuths relative to the basemat near the cylinder wall junction,
- horizontal and vertical displacements in the dome at regular azimuths and elevations,
- vertical displacements at the apex of the dome,
- ovalization of the equipment hatch and air lock barrel,
- uplift of the basemat.

Concrete Cracking

In order to thoroughly model and understand concrete cracking mechanisms, several parameters will be measured:

- the strain in the concrete,
- when and where a crack first occurs,
- crack propagation, and
- crack width.

Detecting when and where cracks occur will be performed several ways: with video cameras, of crack detecting gages, and possibly a system of acoustic monitors. Measuring crack propagation is of greatest interest near the base of the cylinder. These data are useful to the analyst in order to understand how the neutral axis in the concrete is shifting. Measuring crack width is also useful in understanding concrete strain, and possible strain concentrations that may influence where liner failure occurs.

Reinforcing Bar Strain

Strain gages will be mounted to the reinforcing steel to measure hoop, meridional, and radial strains throughout the basemat, cylinder and dome of the model. These strain measurements will be used to determine the global "free-field" or local membrane, bending and shearing strains in the model as a function of location and pressure.

Reinforcing strain measurements will generally not be made in areas where the reinforcing is highly congested, such as around penetrations, or to determine local strain concentrations. In areas of highly congested reinforcing, rebar strains will be measured at the "perimeter" of the reinforcing grid to confirm boundary conditions for comparison with pre-test analyses. Typical reinforcing strain measurements include:

- Free-field strain measurements of meridonal and hoop reinforcing steel at regular azimuths and elevations. Typically, both inner and outer reinforcing strains will be measured to resolve membrane and bending behavior.
- Near-field strain measurements of meridional and hoop reinforcing steel at the "boundaries" of local reinforcing areas, (e.g. equipment hatch, tendon buttresses) will be acquired to check local pretest analysis assumptions and to provide boundary conditions for post-test analysis, if necessary.
- Near-field strain measurements of radial ties will be taken in the vicinity of structural discontinuities or where large shears or large bending moments are predicted to occur in order to measure the triaxial state of strain (stress) for evaluation of failure models.

Concrete Strain

Concrete strain gages, both surface and embedded, will be monitored to help evaluate the relationship between the concrete and rebar strains as well as to provide information regarding the loads at which cracks are initiated. However, only a limited number of these measurements will be made based on past experience about the utility of this data.

Liner and Liner Anchor Strain

Both the membrane and bending strain in the liner as well as strains in the liner anchors will be measured. These strain gages will be used to measure both "free-field" and local strains for direct comparison with the SIT as well as pretest analysis. At particular locations where tearing of the liner is possible, several gages will be placed in order to characterize the failure mechanism leading up to tearing of the liner. Gages will be placed on both sides of the liner where local liner bending is likely and only on the inside of the liner where membrane behavior is expected to be dominant.

Prestressing System Instrumentation

The feature that distinguishes this test from previous large-scale containment tests in the United States and Japan is the prestressing system. For this reason and because the behavior of the prestressing system is not well understood at high load levels, the prestressing system itself may be the critical element in determining the ultimate (structural) capacity of the containment vessel.

A great deal of emphasis has therefore been placed on gaining reliable and accurate data on the behavior of the prestressing system. The nature of the data desired is twofold:

- First, to understand the global behavior of the prestressing system, and,
- second, to understand the behavior of individual tendons in terms of the variation of stress along the length of the tendon.

To achieve the first of these objectives, 132 load cells will be placed on the tendons, one each at both ends of one third of the tendons in the model. This is being done to monitor the effective prestress in the model for comparison with the design conditions and to monitor the change in prestress, both temporally and spatially, as a function of the internal pressure. We are planning to use a through-hole type load cell which has been integrated with the tendon anchor system.

The second of these objectives is more difficult to achieve, as reflected by the attempts to measure tendon stress levels in the earlier containment tests. The requirements of the tendon instrumentation are that it provide reliable measurements of the total force on the cross section of the tendon without having the transducer alter the behavior of the tendon. Current plans are to use a combination of strain gages mounted on individual strand wires and specially fabricated gages to measure overall tendon strain[6].

Acoustic Monitoring System

A series of highly sensitive acoustic monitors may be used to detect and record any major occurrence during testing of the PCCV. These monitors may be capable of detecting where and when a wire or anchorage failure occurs in the prestressed tendons or failure of rebars. In addition, this system may be capable of measuring when and where liner tears occur as well as the location of major cracking in the concrete.

Visual Observations

Video cameras will be placed at several locations around the outside of the PCCV and some will be placed inside. These cameras will assist in visually monitoring large displacements, concrete cracks, and any unusual occurrences.

Test Sequence

Several sets of measurements will be required of the instrumentation on the PCCV because of the various stages of loading and pressure tests. At each stage, measurements of all the instrumentation will be recorded.

Loading on the PCCV model will consist of dead load only following construction, then dead load plus prestressing, followed by dead load plus prestressing plus internal pressure. The first set of data for the PCCV model will be taken during and just after prestressing of the tendons is complete with no internal pressure. Another set of data will be taken prior to low-pressure testing and will occur approximately six months after prestressing is complete. There may also be periodic recording of selected measurements during the period between prestressing and testing. This will allow for measurement of the effects of relaxation and creep in the tendons and the concrete.

Low-pressure testing of the model will consist of several tests as shown in Figure 2. The first test will be an instrumentation functionality test (IFT) to check the instruments and pressurization system and will be tentatively 10% of the design pressure. Next will be the SIT at 1.125 times the design pressure, followed by an integrated leak rate test (ILRT) at 90% design pressure. The last low-pressure tests will be two consecutive design pressure tests (DPT) in order to show repeatability. Following depressurization, if cracks are observed they will be marked and gages attached to those of interest prior to the LST. In addition, a limited number of gages may be attached at predicted cracking locations prior to the LST.

Following these low-pressure tests, the PCCV will be pressurized in steps until failure occurs (LST). Failure may or may not be catastrophic, which could result in nearly instantaneous depressurization of the containment. On the other hand, a large leak may form (i.e., liner tearing), limiting pressure capacity to the amount available from the pressure source. In this case, a slow depressurization of the PCCV will occur.

As a result of this test sequence, testing of the PCCV will require two separate suites of instrumentation. This is necessary to more accurately measure data following prestressing, during the SIT and during the ILRT using some instruments with a smaller range and higher resolution. During the LST, some instruments will be required to measure a wider range of data (i.e., total displacement) and therefore have less resolution than required during low-pressure testing.

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Table 1: Instrumentation Objectives

Location	Material	Measurement Type	Instrument Type	Measurement Objective
Free-Field Cylinder and Dome	Liner	Strain	Strain gage	Response and Liner failure
	Liner anchor	Strain	Strain gage	Response
	Rebar	Strain	Strain gage	Response
	Tendon	Strain	Tensmeg & Strain gage	Response and Tendon failure
		Force	Load cells	Response
	Concrete	Strain	Strain gages	Response
		Cracking	LVDT	Response
	All	Displacement	CPOT & LVDT	Response
Wall-Basemat Juncture	Liner	Strain	Strain gage	Liner failure
	Liner anchor	Strain	Strain gage	Liner failure
	Rebar	Strain	Strain gage	Shear failure
	Concrete	Strain	Strain gage	Shear Failure
		Cracking	LVDT & Fiber optics	Shear failure
On E/H or A/L	Steel hatch	Strain	Strain Gage	E/H or A/L failure
		Displacement	LVDT	Response
Around E/H or A/L	Plate and Liner	Strain	Strain gage	Liner failure
	Liner anchor	Strain	Strain gage	Liner failure
	Concrete	Strain	Strain gage	Response
		Cracking	LVDT	Response
Other Penetrations	Steel Plate	Strain	Strain gage	Penetration failure
	Liner	Strain	Strain gage	Liner failure
	Liner anchor	Strain	Strain gage	Liner failure
Basemat / Tendon Gallery	Tendons	Force	Load cell	Response and Tendon failure
	Rebar	Strain	Strain gage	Shear failure
	Concrete	Uplift Displacement	LVDT	Response
Buttress	Liner	Strain	Strain gage	Response and Liner failure
	Rebar	Strain	Strain gage	Response
	Tendon	Force	Load cell	Response and Tendon failure
	Bearing plate	Strain	Strain gage	Bearing plate failure
	Concrete	Strain	Strain gage	Anchor failure

CPOT - Cable potentiometer
LVDT - Linear variable differential transformers

Table 2: Instruments to be Installed in PCCV

Instrument Type		Approximate No.
Strain	Liner	675
	Rebar	364
	Tendons (Tensmeg)	84
	Tendons (wire)	252
	Concrete	36
Displacements		140
Load Cells (1/3 of Tendons)		132
Temperature and Pressure		91
Total		**1774**

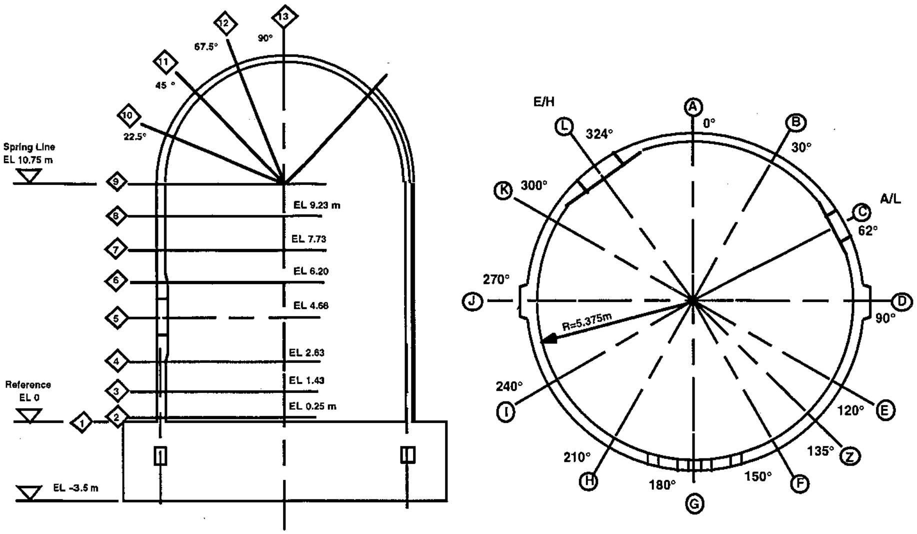

Figure 1: PCCV Model Geometry and Measurement Locations

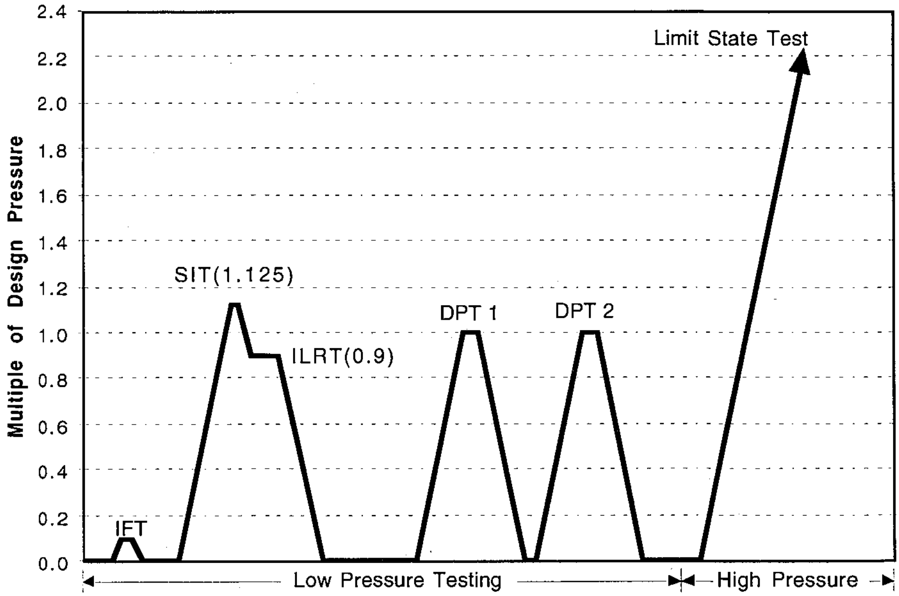

Figure 2: Proposed PCCV Pressurization Sequence