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# Functional and Structural Failure Mode Overpressurization Tests of 1:4-Scale Prestressed Concrete Containment Vessel Model[a]

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## ABSTRACT

A 1:4-scale model of a prestressed concrete containment vessel (PCCV), representative of a pressurized water reactor (PWR) plant in Japan, was constructed by NUPEC at Sandia National Laboratories from January 1997 through June, 2000. Concurrently, Sandia instrumented the model with nearly 1500 transducers to measure strain, displacement and forces in the model from prestressing through the pressure testing. The limit state test of the PCCV model, culminating in functional failure (i.e. leakage by cracking and liner tearing) was conducted in September, 2000 at Sandia National Laboratories. After inspecting the model and the data after the limit state test, it became clear that, other than liner tearing and leakage, structural damage was limited to concrete cracking and the overall structural response (displacements, rebar and tendon strains, etc.) was only slightly beyond yield. (Global hoop strains at the mid-height of the cylinder only reached 0.4%, approximately twice the yield strain in steel.) In order to provide additional structural response data, for comparison with inelastic response conditions, the PCCV model filled nearly full with water and pressurized to 3.6 times the design pressure, when a catastrophic rupture occurred preceded only briefly by successive tensile failure of several hoop tendons. This paper summarizes the results of these tests.

## KEYWORDS

CONTAINMENT, SEVERE ACCIDENTS, PRESSURE TESTING

## INTRODUCTION

Sandia National Laboratories (SNL) conducted a Cooperative Containment Research Program that was co-sponsored and jointly funded by the Nuclear Power Engineering Corporation (NUPEC) of Japan and the U.S. Nuclear Regulatory Commission (NRC), Office of Nuclear Regulatory Research. The purpose of the program was to investigate the response of representative scale models of nuclear containments to pressure loading beyond the design basis accident and to compare analytical predictions to measured behavior. This objective was accomplished by conducting static, pneumatic overpressurization tests of scale models at ambient temperature. This research program consisted of testing two scale models: a steel containment vessel (SCV) model (tested in 1996) and a prestressed concrete containment vessel (PCCV) model, which is the subject of this paper.

## DESIGN, CONSTRUCTION AND INSTRUMENTATION OF THE PCCV MODEL

The prestressed concrete containment vessel (PCCV) model is a uniform,1:4-scale model of the containment structure of Unit 3 of the Ohi Nuclear Power Station in Japan. Ohi Unit 3 is a 1180 MWe pressurized-water reactor (PWR) plant designed, constructed and operated by Kansai Electric Power Company. The Ohi-3 containment vessel is a steel-lined, prestressed concrete cylinder with a hemispherical dome and two vertical buttresses. Model construction commenced at the Containment Technology Test Facility at Sandia National Laboratories on January 3, 1997. The overall geometry of the model is shown in Figure 1. The design pressure is 0.39 MPa. Details of the design, including the design drawings, and construction are reported in the PCCV test report [1].

Concurrent with the construction of the model, Sandia personnel installed nearly 1500 transducers to monitor the strain, displacement, forces, temperatures and pressures in the model. These transducers were monitored by a data acquisition system (DAS), designed by Sandia, which provided for near -continuous scanning of all transducers while providing real time display of any sensor channel. In addition to Sandia's DAS, additional instrumentation included an independent acoustic monitoring system and concrete strain measurement system using *SOFO* fiber optic gages. Internal and external video and still cameras were also used to record the response of the model during pressure testing.

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Construction and instrumentation of the PCCV model was completed on June 25, 2000. Prior to the completion of construction, tensioning of the model prestressing tendons commenced March 8, 2000 after the majority of the model transducers had been installed and certified. Initial model response was recorded on March 3 and monitored continuously through the prestressing operations and pressure testing and ending October 10, 2000 after conclusion of the limit state test. Data for a reduced instrumentation suite was also collected from November 6, 2001, prior to filling the vessel with water, to November 14 when the model was pressurized to failure.

**PRESSURE TESTING**

Pressure testing of the model consisted of a series of static overpressurization tests of increasing magnitude, beginning with the System Functionality Test (SFT) to $0.5P_d$ on July 18-20, 2000. This test was conducted to confirm the operation of all test and data acquisition systems, verify that the model was leak tight and calibrate the leak detection/measurement system. It also provided some preliminary response data on the model. The next tests were a combined Structural Integrity and Integrated Leak Rate Test (SIT/ILRT). The PCCV model was pressurized to $1.25P_d$ on September 12, 2000 and after holding pressure for approximately 1 hour, the model was depressurized to 0.9 $P_d$ and held at this pressure for 24 hours. During this period a leak rate of less than 0.1% mass/day was calculated, essentially demonstrating that the model was leak-tight.

**Limit State Test**

The Limit State Test (LST) was designed to fulfill the primary objectives of the PCCV test program, i.e. to investigate the response of representative models of nuclear containment structures to pressure loading beyond the design basis accident and to compare analytical predictions to measured behavior. Preliminary results of the LST were reported in [2]. The LST was conducted after the SIT and ILRT were completed and the data from these tests evaluated. The PCCV model was depressurized between the SIT/ILRT and the LST. The LST began at 10:00 AM, Tuesday, September, 26, 2000 and continued, without depressurization, until the test was terminated just before 5:00 PM on Wednesday, September 27. The model was pressurized in increments of approximately $0.2P_d$ to 1.5 $P_d$ when a leak check was conducted yielding a leak rate of 0.48% mass/day. Pressurization of the model continued in increments of approximately $0.1P_d$ to $2.0P_d$ when a second leak check resulted in a calculated leak rate of 0.003%, i.e. essentially zero. Pressurization of the model resumed in increments of $0.1P_d$ to $2.5P_d$. At $2.4P_d$, the acoustic system operator reported hearing a change in the acoustic output which might indicate that "something had happened". The model was isolated for a third leak check and after approximately 1-1/2 hours, a fairly stable leak rate of 1.63% mass per day was calculated, indicating that the model was leaking, most likely from a tear in the liner in the vicinity of the equipment hatch. The average hoop strain at $2.5P_d$, coinciding with the onset of liner tearing and leakage was 0.18%.

After concluding that the model had functionally failed between 2.4 and 2.5 $P_d$, the next goal was to continue to pressurize the model as high as possible to collect data on the inelastic response of the structure and to observe, if possible, a structural failure mode. Pressurization continued in increments of 0.05 $P_d$. The pressure was increased to slightly over 3.3 $P_d$ before the leak rate exceeded the capacity of the pressurization system and the test was terminated. After the model had completely depressurized, it was purged with fresh air, the E/H was removed and a detailed inspection of the inside of the model revealed 26 discrete tears in the liner, all located at vertical field welds. Extensive examination and metallurgical analysis of the liner after the test revealed that fabrication defects contributed to nearly all of the liner tears.

Figure 2 shows the displacement profiles at Azimuths 135º, representing the axisymmetric response, and 324º, at the centerline of the equipment hatch. The profiles are based on interior measurements of the model surface prior to prestressing (3/3/00, 11:47am) and at multiples of the design pressure $0P_d$, $1.0P_d$ (0.389 MPa), $2.0P_d$ (0.776 MPa), $2.5P_d$ (0.978 MPa), $3.0P_d$ (1.162 MPa) and $3.3P_d$ (1.295 MPa). Figure 7 shows the history of the radial displacement at the mid-height of the cylinder wall at various azimuths. The profile at 324º illustrates the buckling of the liner which occurred at Elev. 9200 due to prestressing. This bulge in the liner disappeared when the model was initially pressurized and did not affect the capacity of the liner. At maximum pressure local liner strains approached 6.5% and global hoop strains (computed from the radial displacement) at the mid-height of the cylinder averaged 0.4%. While large liner strains were observed and the liner was torn in several locations, the remainder of the structure appeared to have suffered very little damage with the exception of more extensive concrete cracking at some locations. There was no indication of tendon or rebar failure and the data showed that no tendon strains exceed the elastic limit while only a few dozen rebar strain gages showed strains in excess of 1%.

**Structural Failure Mode Test**

Almost immediately after the completion of the LST, there was a recognition that while the PCCV model had demonstrated its capacity to resist pressures well above the design pressure and confirmed, arguably, liner tearing and leaking as the functional failure mode, the test objectives were not fully met with respect to observing large inelastic deformations, for comparison with analyses, and witnessing the structural failure mode of the PCCV model. NUPEC and NRC approved a concept proposed by SNL to seal the interior surface of the liner with an elastomeric membrane, fill the model with water to 1.5m (5 ft.) from the dome apex, approximately 97% of the interior, and re-pressurize the remaining gas pocket with nitrogen until the model failed or pressure could not be maintained.

The Structural Failure Mode Test (SFMT) began shortly after 10:00 AM on Wednesday, November 14, 2001. The model was continuously pressurized at a rate of approximately 0.035 MPa/min (5 psi/min). All active sensors (approximately 500) were continuously scanned at intervals of approximately 30 seconds and video cameras were continuously recording the response of the model. As the pressure was increased, evidence of leakage was visible by increasing wetting of the concrete surface. At 10:38 AM, the effective pressure in the model equaled the peak pressure achieved during the LST, 3.3 $P_d$. At approximately 10:39 AM, the acoustic system recorded a very high noise level event which was interpreted as the breaking of a tendon wire. At this point in the test, events occurred very quickly. Shortly after detecting the wire break, a small spray of water was observed at approximately 0º azimuth and additional tendon wire breaks were detected by the acoustic system with increasing frequency. The rate of pressurization was decreasing and the nitrogen flow rate was increased to maintain the pressurization rate. Pressurization of the model continued until a second spray of water was observed and then, suddenly, at 10:46:12.3, at an effective pressure of 3.63 $P_d$ (1.42 MPa or 206.4 psig) the PCCV model ruptured violently at ~6º azimuth near the mid-height of the cylinder. Four external video cameras recorded the rupture of the model and the moment of rupture is captured in Figure 3. The condition of the model after the SFMT, viewed from 0º, is shown in Figure 4.

The radial displacement of the model at Az. 135º, Elevation 6200 during the LST and SFMT is illustrated in Figure 5. (The SFMT response was 'offset' in this figure by adding the residual displacement at the end of the LST to facilitate comparison.) This figure demonstrates that the hoop stiffness during the SFMT is essentially identical to the post-cracking stiffness during and after the LST. It also shows that the SFMT displacement is nearly identical to the LST displacement at the maximum LST pressure, suggesting that, if the LST could have been continued, the response would have been almost the same as that measured during the SFMT. It thereby confirms the assumption that, again with the exception of the liner and cracking of the concrete, the model was essentially undamaged by the LST.

The acoustic monitoring system used during the LST was also employed for the SFMT minus the interior sensors which were removed to allow the elastomeric liner to be installed. Since the SFMT was not focused on detecting liner tearing/leaks, this was not a significant compromise. The focus of the acoustic system during the SFMT was to detect tendon wire breaks and any other events which might indicate structural damage. Fifty seven wire break or probable wire break events were identified between 10:39:47 and rupture of the model at 10:46:12. Figure 6 plots the time history of all the wire break events along with the effective pressure time history and radial displacement time history. It is readily apparent that the frequency and magnitude of the wire break events increases just prior to rupture.

The displacement profiles at Azimuths 135º and 324º during the SFMT are shown in Figures 7 and 8. Since the displacement transducers used during the LST were removed and replaced by water-proof transducers for the SFMT, the initial profile was taken as that prior to prestressing. In Figures 7(a) and 8(a), the displacement profiles are plotted for the hydrostatic pressure (0.18 MPa) and multiples of the design pressure, approximately 1.0$P_d$ (0.389 MPa), 2.0$P_d$ (0.776 MPa), 2.5$P_d$ (0.978 MPa), 3.0$P_d$ (1.162 MPa), 3.5$P_d$ (1.295 MPa) and the peak pressure of 3.63$P_d$ (1.42 MPa). The maximum average hoop strain at the peak pressure of 3.63 $P_d$ was 1.02%. The profiles are expanded between 3.0$P_d$ and 3.63$P_d$ in Figures 7(b) and 8(b). These figures also show that after reaching the peak pressure, the model continued to expand significantly, even though the pressure decreased to 3.57$P_d$ (1.40 MPa) yielding a maximum hoop strain of 1.65% just prior to rupture

## SUMMARY

The over-pressurization tests of the 1:4-scale PCCV model represent a significant advance in understanding the capacity of nuclear power plant containments to loads associated with severe accidents. The data collected during the tests, as well as the response and failure modes exhibited, will be used for many years to come to benchmark numerical simulation methods used to predict the response of concrete containment structures. While lessons for actual plants can and should be drawn from this and previous large scale containment model tests, these insights are beyond the scope of this project and will be addressed in the future . The reader is cautioned **not** to draw direct conclusions regarding the pressure capacity of actual plants from these tests or interpret these results as a demonstration of the prototype capacity. The PCCV model tests have demonstrated the importance of the unique details and as-built characteristics of the model on the ultimate capacity. Any efforts to estimate the capacity of an actual containment must address the unique features of the plant under consideration.

With the conclusion of the PCCV tests and the demolition of the model and restoration of the test site completed, the NUPEC/NRC Cooperative Containment Research Program was formally concluded on December 31, 2002.

## REFERENCES


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2. Hessheimer, M. F., E. W. Klamerus, G. S. Rightley, R. A Dameron,. S. Shibata, S. Mitsugi and J. F. Costello, "Preliminary Results of a 1:4-Scale Prestressed Concrete Containment Vessel Model Test," *Proceedings of the 16th International Conference on Structural Mechanics in Reactor Technology*, Washington D.C., USA, August, 2001.

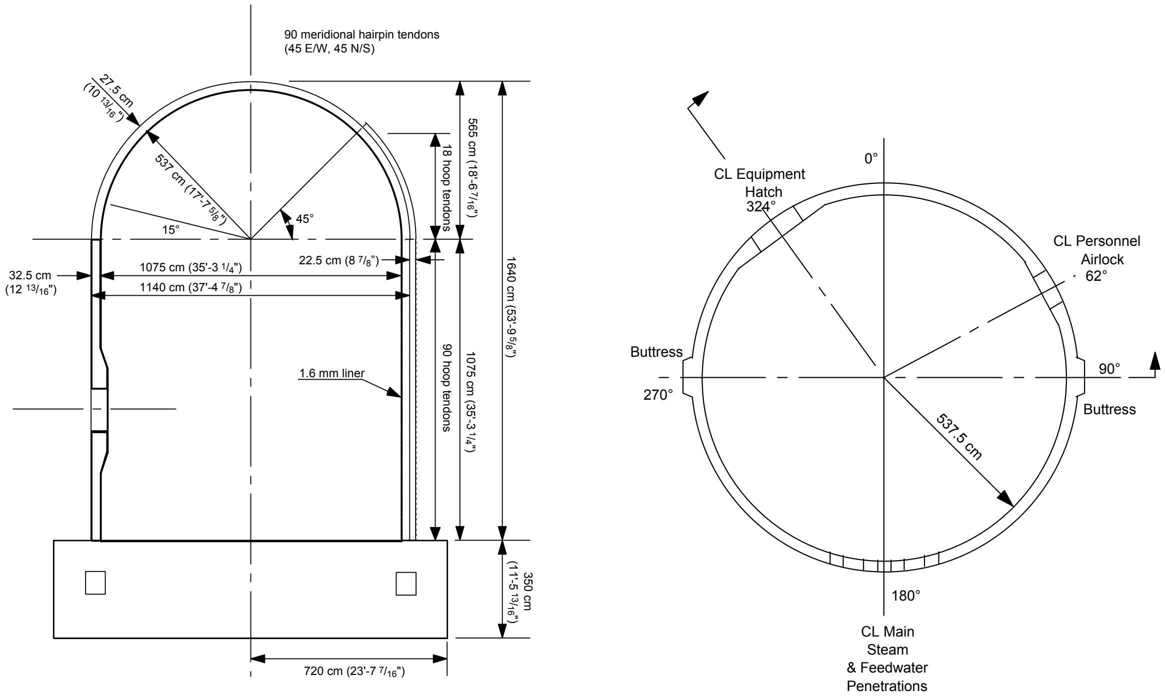
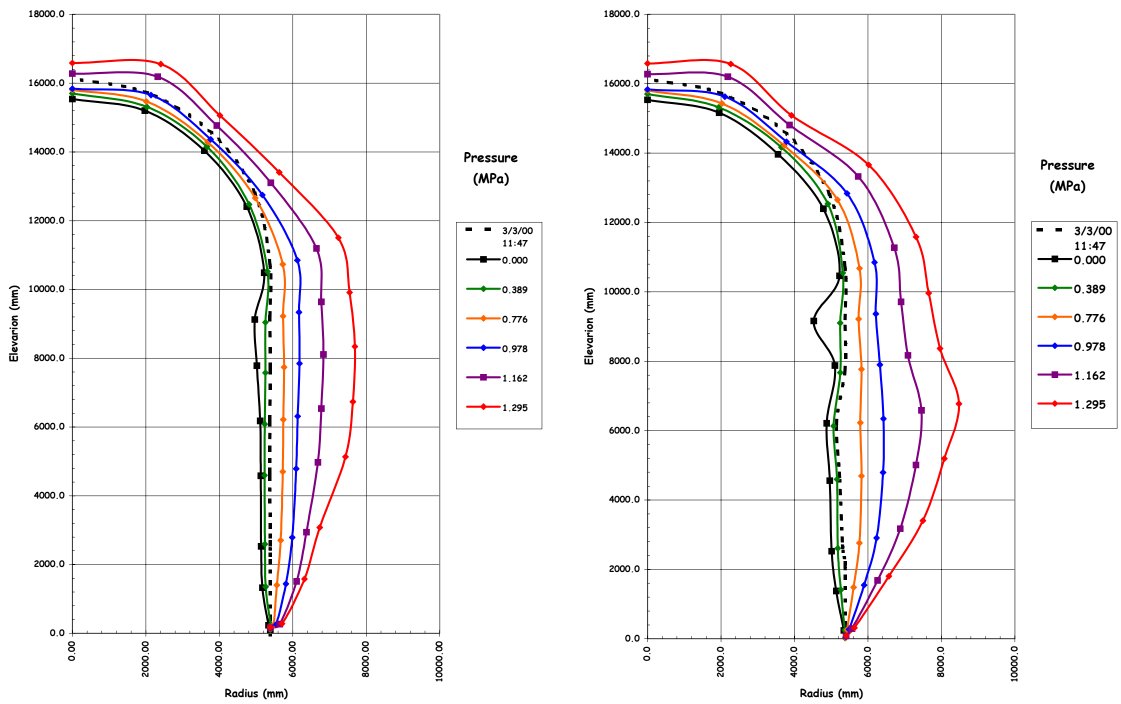




**Figure 1 Prestressed Concrete Containment Vessel (PCCV) Model Geometry**




**(135º) (324º)**

**Figure 2 LST - Deformation @ Az. 135º and 324º (Z and L) x 100**


(a) 0º Azimuth


(b) 90º Azimuth


(a) 180º Azimuth


(b) 270º Azimuth

**Figure 3 SFMT: Rupture of the PCCV Model**

**Figure 4 PCCV Model after the Structural Failure Mode Test**

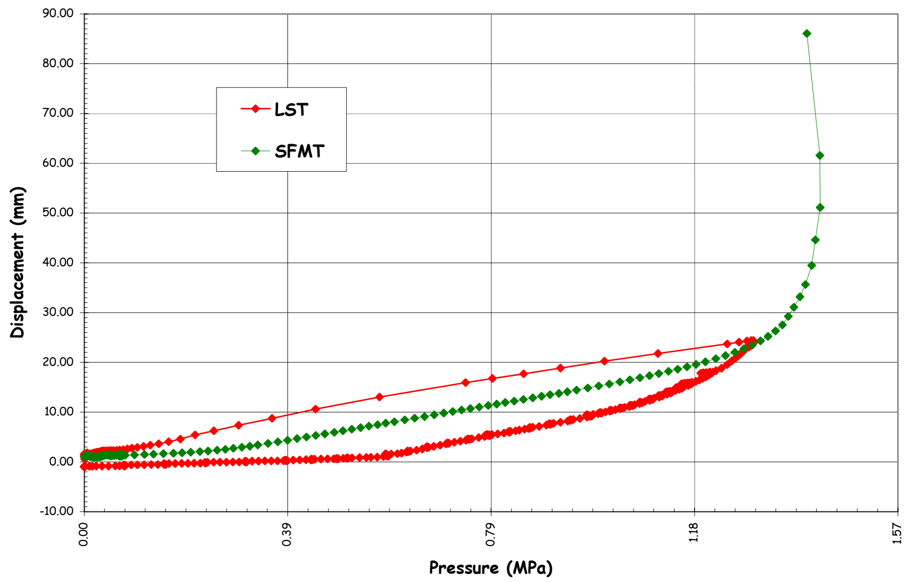



**Figure 5 SFMT – Radial Displacement at Az. 135º, El. 6200**

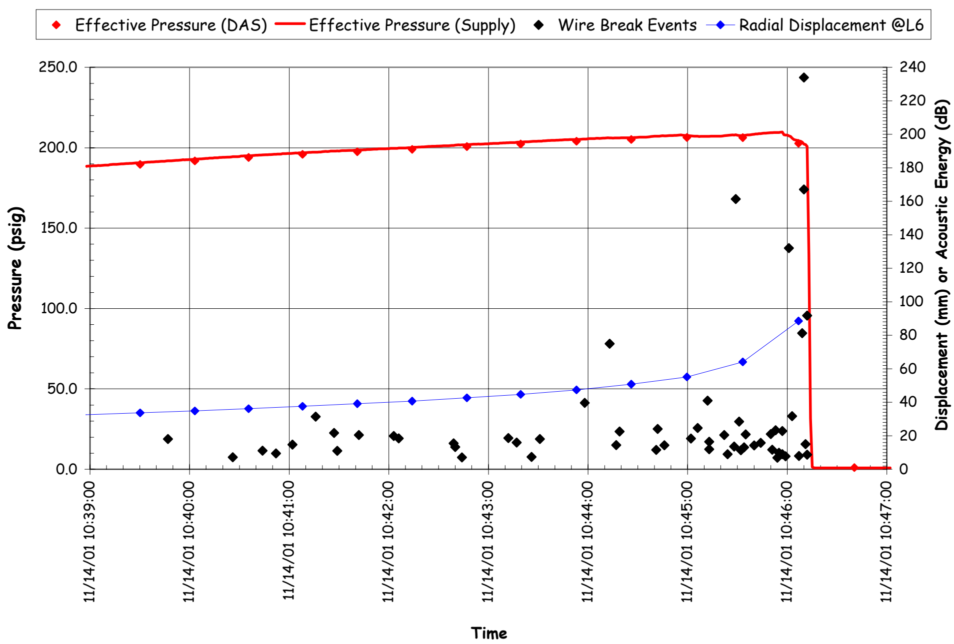
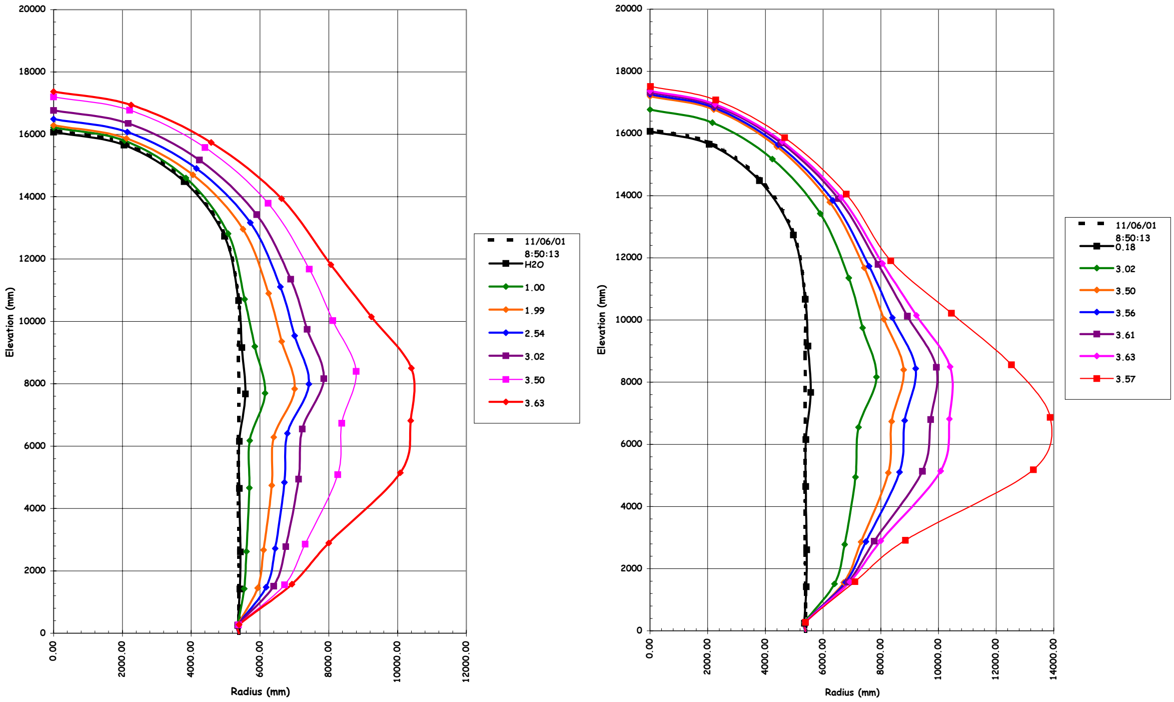
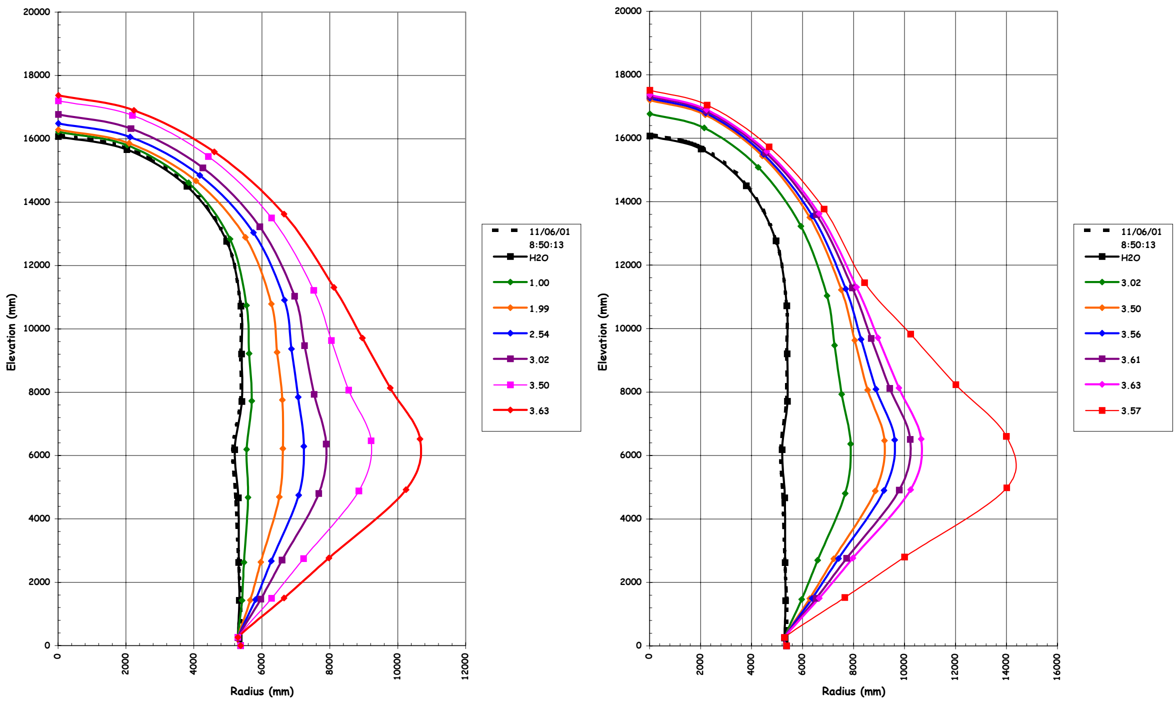



**Figure 6 SFMT Wire Break Events vs. Pressure vs. Displacement**




(a) $0P_d$ to$3.63P_d$ (b) $3.0P_d$ to$3.63P_d$

**Figure 7 SFMT - Deformation @ Az.135º (Z) x 100**




(a) $0P_d$ to$3.63P_d$ (b) $3.0P_d$ to$3.63P_d$

**Figure 8 SFMT - Deformation @ Az. 324º (L) x 100**