Preliminary Results of a 1:4-Scale Prestressed Concrete Containment Vessel Model Test[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. A series of overpressurization tests were conducted on the model beginning in July, 2000, concluding with a limit state test in September. This paper describes the preliminary results of this test.

INTRODUCTION

Sandia National Laboratories (SNL) is conducting a Cooperative Containment Research Program that is 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 is 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 is accomplished by conducting static, pneumatic overpressurization tests of scale models at ambient temperature. This research program consists 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.[b]

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. Details of the instrumentation were provided in [1]. 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.

Construction and instrumentation of the PCCV model was completed on June 25, 2001. 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 final overpressurization test.

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[a] *This work is jointly sponsored by the Nuclear Power Engineering Corporation and the U.S. Nuclear Regulatory Commission. The work of the Nuclear Power Engineering Corporation is performed under the auspices of the Ministry of Economy, Trade and Industry, Japan. Sandia is a multi program laboratrory operated buy Sandia Corporation, a Lockheed Martin Company, for the U.S. Department of Energy under Contract Number DE-AC04-94AL85000.*

[b] *Hessheimer, M. F. "Overpressurization Test of a Prestressed Concrete Containment Vessel Model. To be published.*

Prestressing

Prestressing levels for the model tendons were selected so that the net anchor forces (considering all losses due to anchor seating, elastic deformation, creep, shrinkage and relaxation) at the time of the Limit State Test matched those expected in the prototype after 40 years of service. One further adjustment was made by increasing the vertical tendon stress level to account for the additional gravity load in the prototype, which is lost in the geometric scaling. Eight instrumented tendons and load cells at the ends of $1/6^{th}$ of the model tendons were monitored continuously during prestressing. Figure 2 compares the force distribution in one of the instrumented vertical tendons during prestressing with the design force distribution. Unfortunately over half of the strain gages installed on the tendons were damaged during prestressing operations, nevertheless, enough survived to provide useful data on the tendon response during prestressing and pressurization tests.

Since all model sensors were scanned during and after prestressing, the overall response of the model to prestressing forces as well as ambient thermal response and time dependent effects was also recorded. Figure 3 shows the vertical displacement history at the springline during prestressing and prior to initial pressure testing.

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 0.5Pd 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 1.25Pd on September 12, 2000 and after holding pressure for approximately 1 hour, the model was depressurized to 0.9 Pd 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.

The Limit State Test (LST), conducted on September 26 & 27, 2000, fulfilled 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. Figure 4 shows the average temperature and pressure time history inside the model during the LST. As the model was pressurized, periodic leak checks were conducted by holding pressure and monitoring pressure and temperature and calculating the apparent leak rate. Figure 5 shows the calculated leak rates at 1.5, 2.0 and 2.5 Pd. At 2.5 Pd a calculated leak rate of 1.6% mass/day gave the first evidence that the pressure boundary had been breached and subsequent analysis of the acoustic data indicated that a leak in the liner had occurred during pressurization from 2.4 to 2.5 Pd. At this time, the data showed high strains (> 2%) in the liner at the edge of the equipment hatch embossment.

At this point, the model was pressurized in rapid incremental steps to approximately 3Pd, with increasing evidence of leakage and increasing liner strains. At 3Pd, it became difficult to increase pressure so the nitrogen flow rate was increased to 3500 scfm. The pressure was increased to 3.1Pd however, the pressure dropped steadily after reaching this level. The leak rate at this point was estimated to be approximately 100% mass/day. The nitrogen flow rate was then increased to the maximum capacity of the pressurization system (142 std m^3/min) and the pressure was increased to slightly over 3.3Pd before the leak rate exceeded the capacity to pressurize the model. Since the pressure could no longer be increased and the supply of nitrogen was exhausted, the decision was made to begin terminating the test. The isolation valve was closed and the model was allowed to depressurize on it's own. The initial terminal leak rate was estimated to be on the order of 900% mass/day. (The maximum flow rate of nitrogen, 142 std m^3/min is equivalent to 1000% mass/day.) As the model depressurized, a steadily decreasing leak rate was observed (initially decaying at 250% mass/day per hour).

After the model depressurized to 1.0 Pd, the model was inspected close-up and nitrogen gas was observed (hear and feel) escaping through many small cracks in the concrete and at the tendon anchors. It is suspected that the liner acted as a leak chase, allowing nitrogen gas escaping through a tear or tears in the liner to travel between the liner and the concrete until it found an exit path through a crack in the concrete or a conduit in the tendon duct. (Note that the tendon ducts were not grouted or filled with grease.)

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%. Figure 6 shows the history of radial displacements at various elevations at Azimuth 324, the centerline of the equipment hatch. Figure 7 shows the history of the radial displacement at the mid-height of the cylinder wall at various azimuths. While large liner strains were observed and it was speculated that the liner may have 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%.

POSTTEST INSPECTION

After the PCCV model was depressurized and the pure nitrogen atmosphere was purged with fresh air, the equipment hatch cover was removed to allow personnel to enter the model and inspect the interior surface of the liner. After a thorough visual inspection, a total of 24 distinct tears at 17 different locations were discovered. (A few locations that appeared to have a tear were checked by local vacuum box testing.) Figure 8 is a developed elevation of the PCCV model showing the location of the liner tears. All of the liner tears run more or less vertically (i.e. driven by the hoop strain) appear to associated with a field weld, i.e. none of the tears occurred in the main body of the individual liner panels. A series of acoustic events, keyed to the pressure levels at which they were observed are also shown in the figure. The acoustic data, along with the liner strain data, strongly suggests that the liner first tore at the edge of the equipment hatch embossment at approximately 2.5Pd, while the tears at either end of the Feedwater penetration insert plate occurred very near the end of the LST around 3.0Pd.

While the tears at these locations appear to be associated with major geometric discontinuities, the remainder of the tears appear to be randomly distributed around the middle of the cylinder wall where, as noted previously, the global hoop strains were only on the order of 0.4%. Figure 9 shows a tear at the edge of the equipment hatch embossment (#15) and at the edge of the feedwater penetration insert plate (#3). Figure 10 shows a typical 'free-field' liner tear (#2). Further investigation gives evidence that every tear location was also subject to some post-weld repair work, i.e. that the weld was ground or that the initial weld was removed and replaced. This suggests that local geometric discontinuities associated with the repair of the weld, such as local thinning or removal/replacement of the back-up bars, may have made a significant contribution to the initiation of any specific liner tear. Further metallographic examination of individual tears may provide further insight into the mechanism(s) that led to the formation of the liner tears.

There was also a fairly uniform pattern of liner buckling between the vertical T-anchors, as shown in Figure 11. It is believed that this buckling occurred during depressurization as the liner, which was strained beyond yield, was unable to match the elastic recovery of the concrete wall. There is some displacement data to suggest, however, that local buckling may also have occurred during the pressurization phase.

SUMMARY

In conclusion, this test program was generally successful in meeting the program objective of providing a significant amount of data on the response of a prestressed concrete containment vessel model to static overpressurization. Unfortunately, the fact that the liner tore at 2.5Pd may be an artifact of the model. It is not clear that, due to the difficulties of welding the very thin (1.6 mm) liner and non-representative details (single-sided welding with back-up bars vs. double-sided welding), the extensive liner tearing exhibited by the PCCV model is representative of the response of a full size containment. If the liner had not torn, it is possible that model would have been capable of resisting higher pressures and may have exhibited more damage to the structural elements (i.e. reinforcing steel and tendons).

Furthermore, analysis of the data indicates that, except for the liner, the model essentially remained elastic. Since one of the objectives of the test program was to provide a benchmark for calculations of structural response 'well into the in-elastic regime', it is not clear that the test has provided adequate data to support this objective.

REFERENCES

1. Hessheimer, M. F., D.W. Pace, E.W. Klamerus, T. Matsumoto and J.F. Costello, "Instrumentation and Testing of a Prestressed Concrete Containment Vessel Model", *Proceedings of the 14th International Conference on Structural Mechanics in Reactor Technology (SMiRT 14), Lyon, France, August 17-22, 1997*

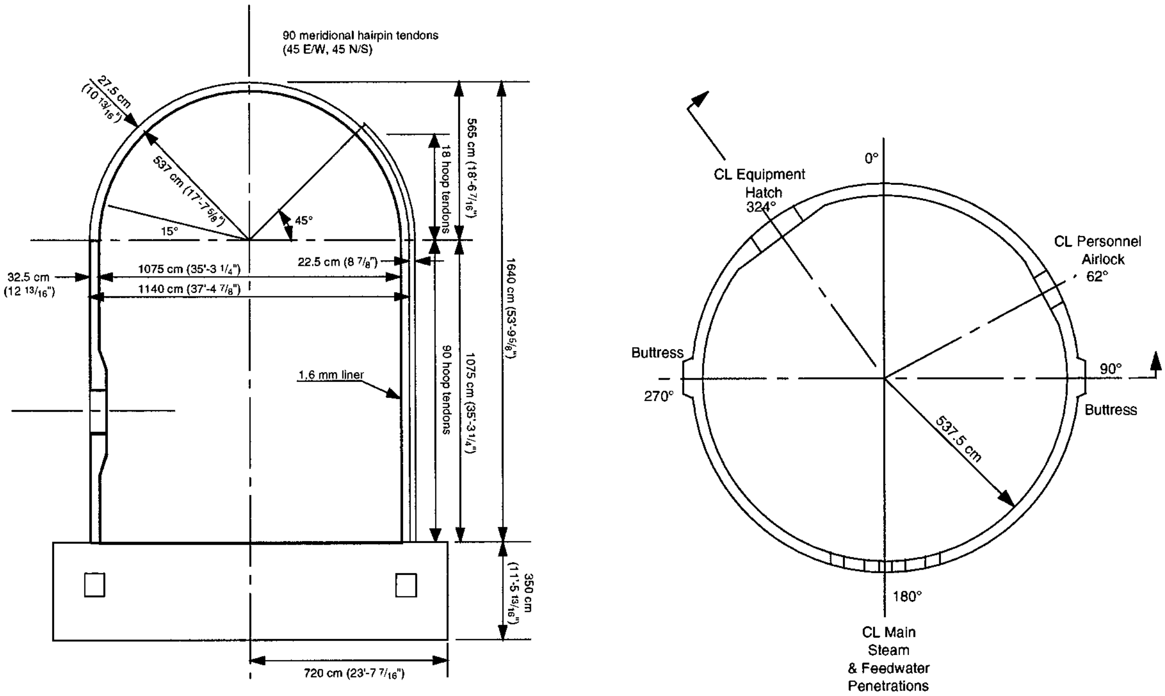

Figure 1 **Prestressed Concrete Containment Vessel (PCCV) Model Geometry**

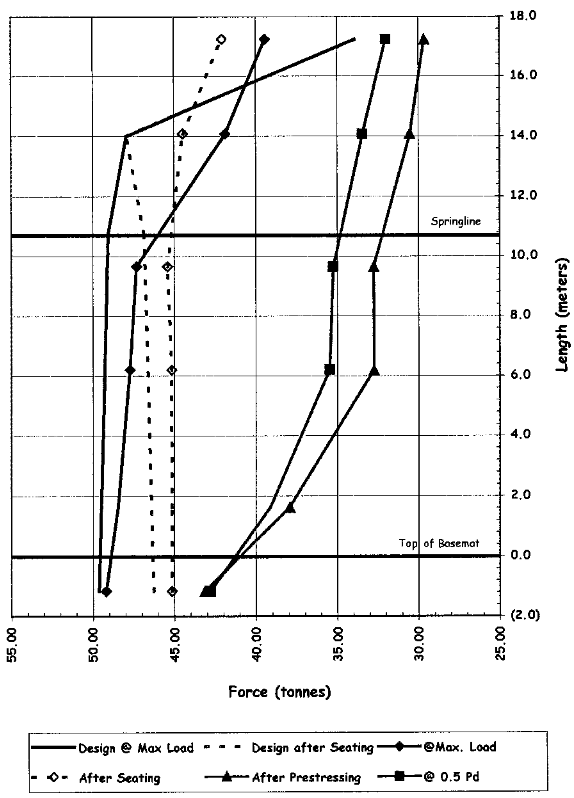

Figure 2 **Force Distribution in Vertical Tendon (V47) During and After Tensioning**

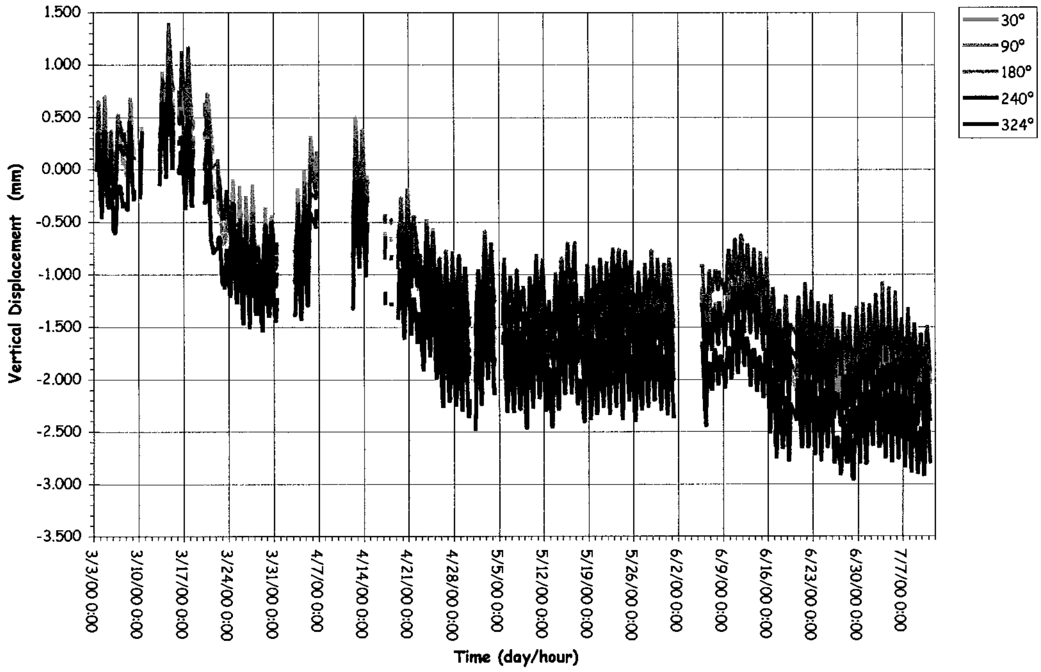

Figure 3 Vertical Displacement History @ Springline (Elev. 10750)

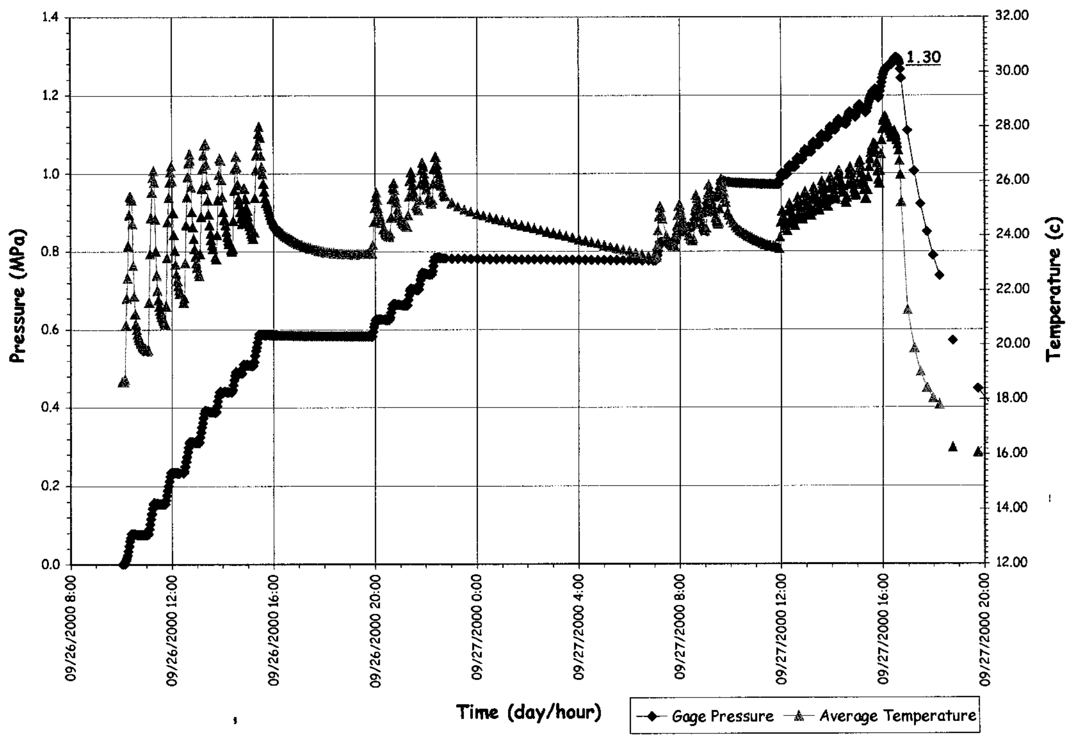

Figure 4 Limit State Test Pressure and Temperature Time History

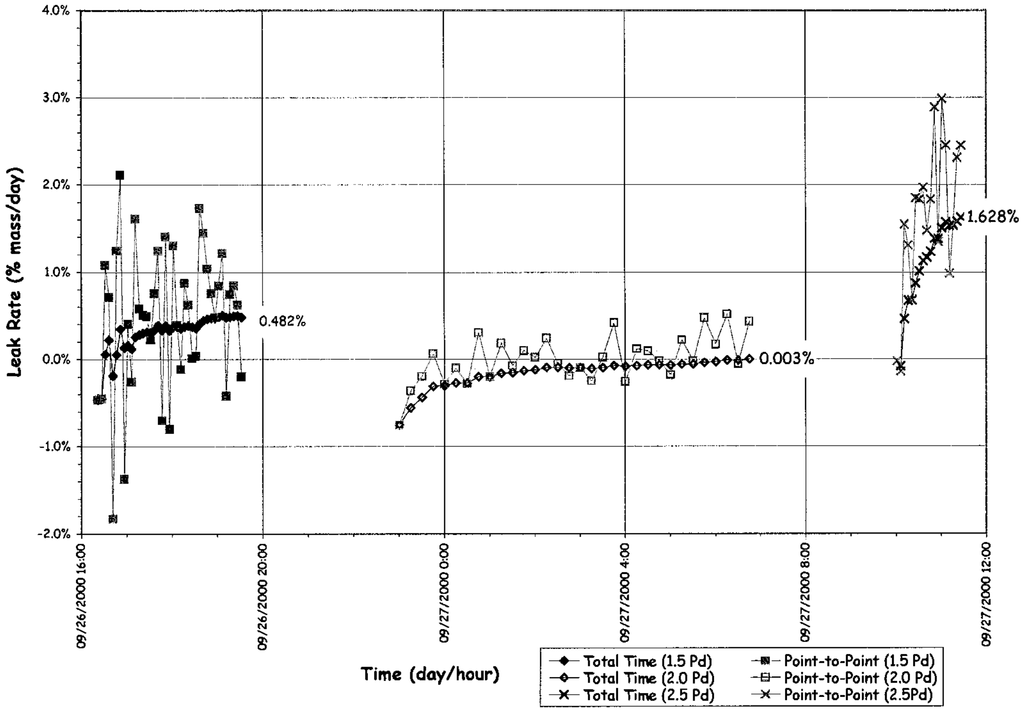

Figure 5 Limit State Test Calculated Leak Rates

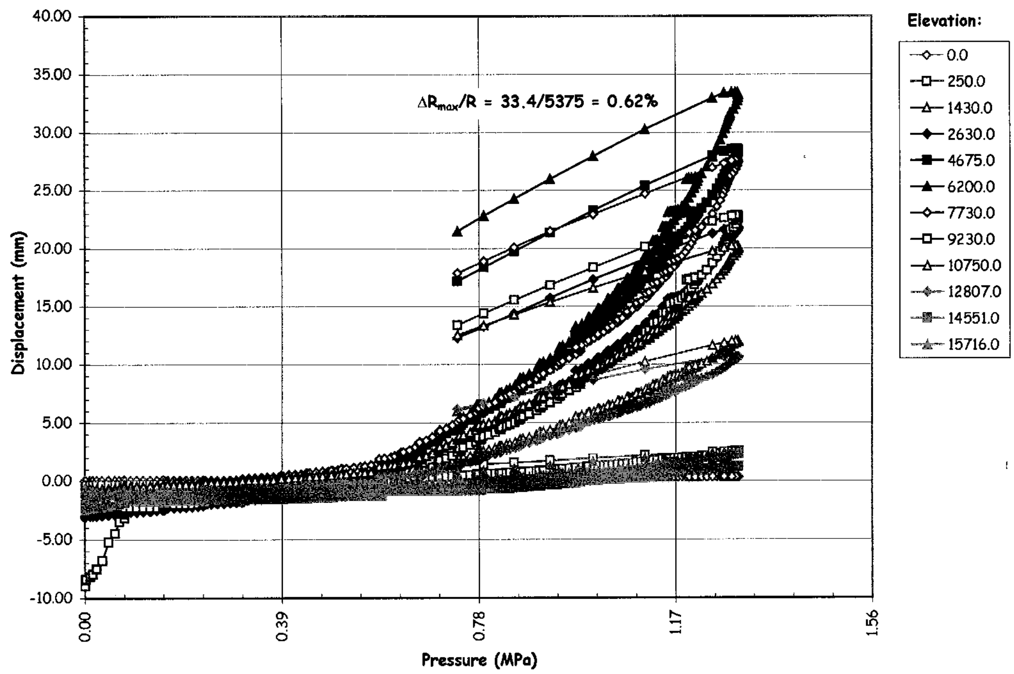

Figure 6 Radial Displacement along Azimuth 324 during LST

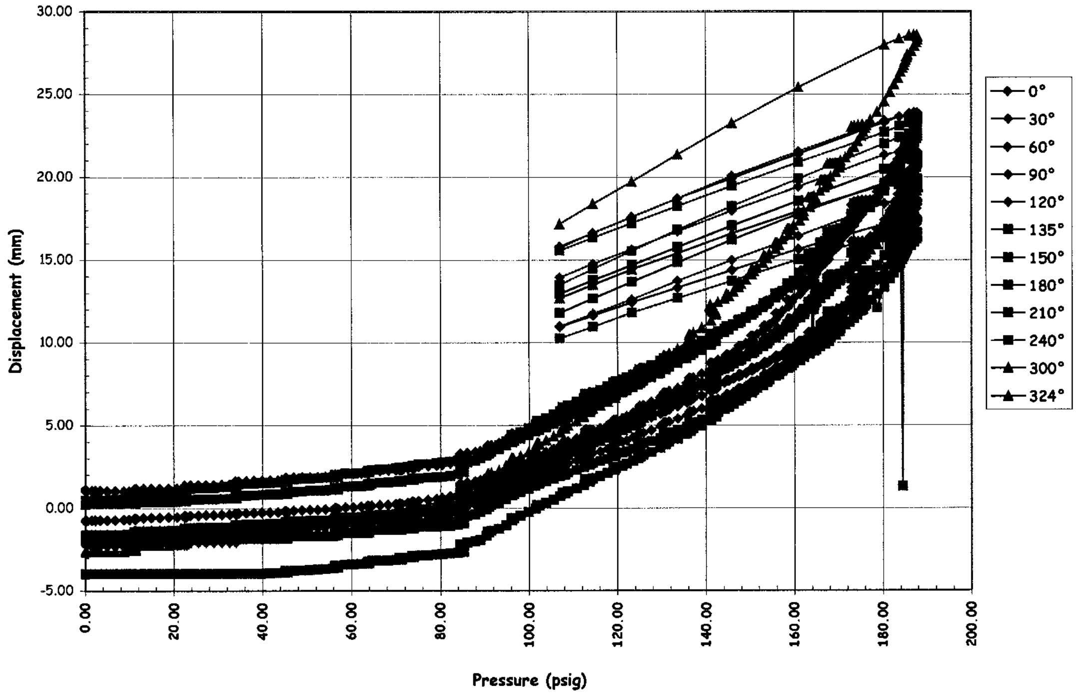

Figure 7 Radial Displacement @ Mid-height of Cylinder Wall during LST

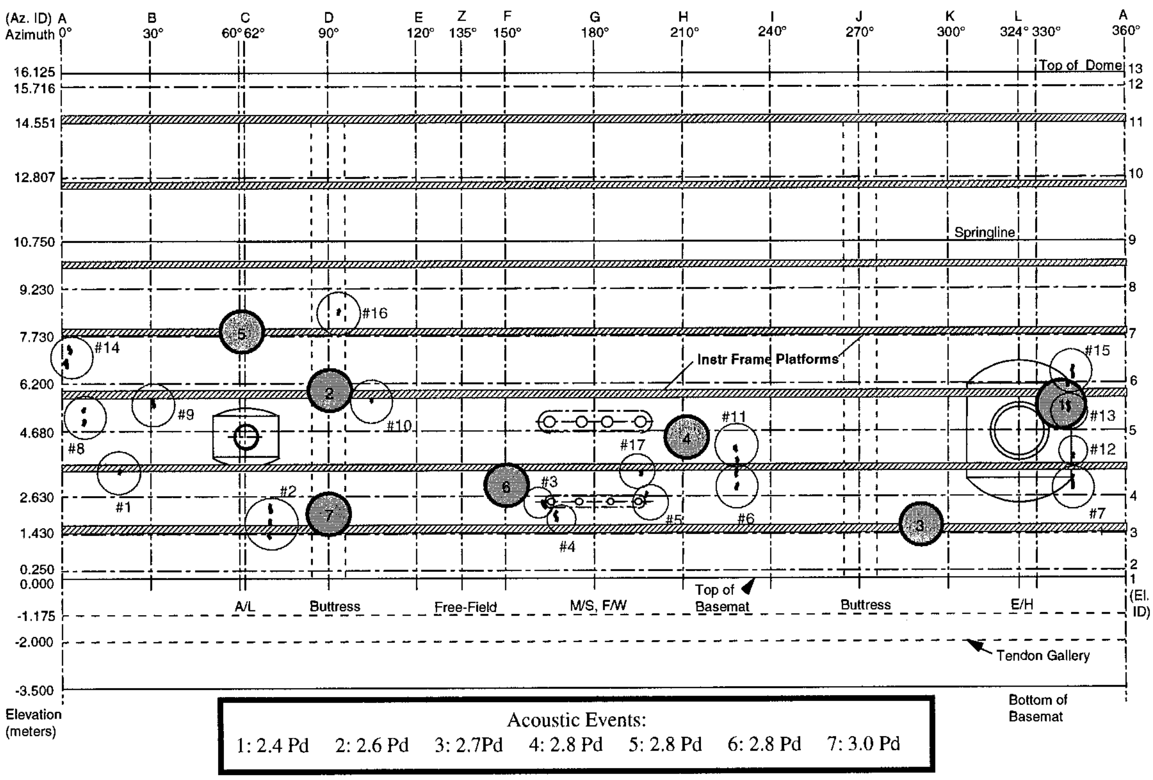

Figure 8 Location of Liner Tears and Acoustic Events

Figure 9 Liner Tear at Locations 15 (Equipment Hatch) and 3 (Feedwater Penetration)

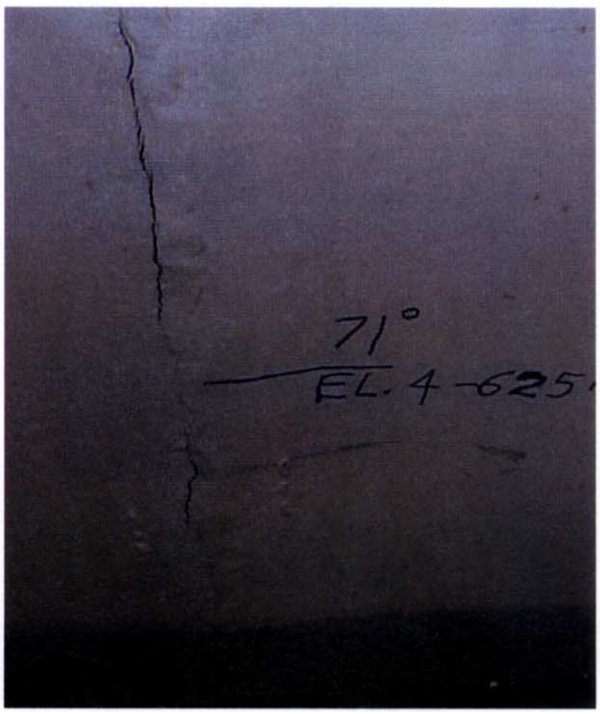

Figure 10 Liner Tear #2

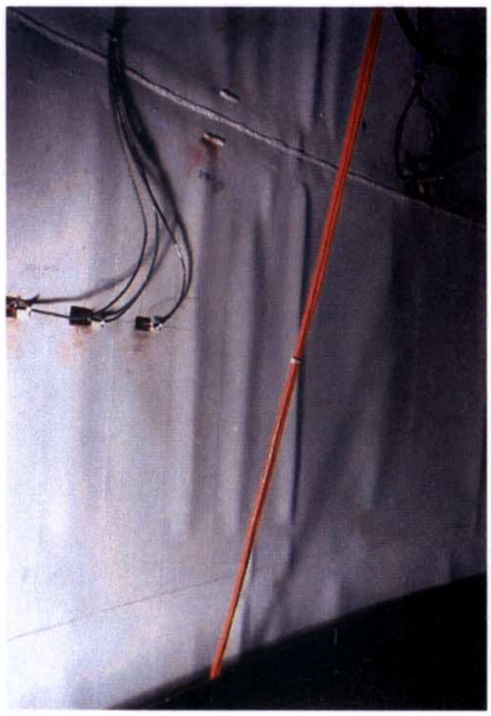

Figure 11 Liner Buckling