# 1.0 INTRODUCTION

## 1.1 Background Leading up to the Limit State Test

Sandia National Laboratories (SNL) is conducting a research program to investigate the integrity of nuclear containment structures. This program is cosponsored by the Nuclear Power Engineering Corporation (NUPEC) of Japan and the U.S. Nuclear Regulatory Commission (NRC). As part of the program, NUPEC constructed a 1:4 scale model of the prestressed concrete containment vessel (PCCV) of a Japanese pressurized water reactor (PWR) plant at SNL's Containment Technology Test Facility in Albuquerque, NM. The model is shown in Figures 1-1 and 1-2. SNL designed and installed an extensive suite of instrumentation during and after the construction of the model and conducted a series of overpressurization model tests leading to both functional and structural failure. One of the key program objectives was to validate methods for predicting structural performance of containment vessels when subjected to beyond-design-basis loadings, such as very high internal pressurization. The NRC-sponsored analysis effort to achieve this objective included 2D and 3D nonlinear finite element modeling of the PCCV model. Such analyses were performed using the nonlinear concrete constitutive model, ANACAP-U, in conjunction with the ABAQUS general purpose finite element code [5]. The analysis effort was conducted in three phases:

1. Preliminary Analysis,
2. Pretest Prediction, and
3. Posttest Data Interpretation and Analysis.

The purpose of the preliminary analysis was to provide a basic understanding of the model response for program planning purposes and to define the scope of the pretest analysis. The preliminary analysis results were not formally documented; however, a summary paper was published [2], and the results are reflected in the pretest analysis that followed. A list of possible failure modes and locations was developed in the preliminary analysis phase prior to conducting the formal pretest analyses. Some of the potential failure modes were specifically addressed by the global analysis, while others were addressed by local models. The results of the preliminary analyses indicated that a liner tearing failure at the midheight of the cylinder near a penetration and a shear/bending failure at the base of the cylinder wall were both found to have a significant probability of occurrence. Recommendations were then made for the pretest analyses, including model refinements and the development of local models to better predict the sequence of competing failure modes were identified.

The principal objectives of the pretest analyses were to (1) exercise advanced analytical methods for predicting structural response of a prestressed concrete containment, (2) gain insight into potential structural failure modes of a prestressed concrete containment, and (3) support planning of test procedures and instrumentation. One requirement of the program was that the pretest analysis predictions be completed and published [1] prior to the high-pressure Limit State Test (LST) of the PCCV model, which was conducted in September, 2000. This meant that the pretest prediction analyses must be completed many months prior to the test. For this reason, the published pretest analysis predictions did not include certain as-built features, actual measured prestressing and associated losses, or creep and temperature effects. Prestress values, losses due to friction, anchor set, and concrete creep were approximated from the assumptions used in the PCCV model design.

In addition to a detailed axisymmetric global model, local models developed for the pretest analysis included: the Equipment Hatch (E/H) region, the Personnel Airlock (A/L) region, and the Mainsteam Penetration (M/S) region. A detailed 3D model of the entire cylinder midheight region (3DCM) was also developed to investigate tendon behavior in the cylinder and 3D effects that drive the local strain concentrations near the penetrations. A highly detailed representation of the wall-basemat juncture region was also added to the 2D axisymmetric model, making total of five pretest analysis models. The pretest analyses described herein were also the basis of the SNL/ANATECH submittal to an international Round Robin Pretest Analysis exercise [3].

The pretest analysis phase of the PCCV model test program refined and demonstrated finite element and material modeling methods and a systematic process for developing pressure response predictions from global 2D, semi-global 3D, and local 3D analysis models. Tendon modeling tasks demonstrated the utility of a new tendon modeling approach in which friction losses are explicitly represented by friction truss tie elements. Tendon stress distributions at various pressures were provided as benchmarks of expected tendon behavior. Capturing the tendon stress distributions in more detail refined the prediction of displacement response and liner strains, especially near the E/H, where this distribution is very complex. **The 3DCM model, with its detailed tendon representation, predicted the rupture of hoop tendons closest to the E/H at a model pressure of about 3.5 Pd. However, this mode was predicted to be precluded by the liner tearing and leakage failure mode.**

Using a strain-based failure criteria that considered the triaxiality of stress and a reduction of ductility in the vicinity of a weld, a liner failure strain criteria of 16% was established. The failure pressure at which a local analysis computed effective plastic strain that reached the failure strain criteria was 3.2 Pd, or 1.3MPa. The location for this liner-tearing failure was near the E/H, adjacent to a vertical liner anchor that terminated near the liner insert plate transition. Other local models showed other candidate liner tear locations, several of which were predicted to occur during the pressure range 3.2 Pd to 3.5 Pd if they were not precluded first by the growth of the first tear and subsequent depressurization of the vessel. A significant candidate tear location was also found near the 90 degree buttress where hoop strains are elevated due to circumferential bending, and weld seams with hoop stiffener "rat-holes" are coincidentally located. Failure at such locations was predicted to occur shortly after failure at the E/H location.

After publishing the pretest analysis results, a final pretest analysis was performed to refine the pretest predictions using the most current as-built model properties. This final pretest analysis was performed primarily to support test operations by providing the 'best' predictions of the model's response for real-time comparison with the actual response. This information was essential to the safe and successful conduct of the test. Since the results of this final pretest analysis were not published in the pretest analysis report [1], a summary of the results are included in Chapter 2 of this report.

## 1.2 Limit State Test and Structural Failure Mode Test Overview

The following "quick look" observations written a few days after the test by Mike Hessheimer at SNL provide a concise overview of the LST conduct and PCCV model behavior:

> The PCCV Limit State Test (LST) began at 10:00a.m., Tuesday, September 26, 2000 as scheduled. We began pressurizing in increments of 0.2 Pd, repeating the Structural Integrity Test (SIT) pressure sequence we followed on September 12. We continued pressurizing the model to 1.5 Pd, when we conducted a leak check and calculated a leak rate of approximately 0.5% mass/day after 3.5 hours. Based on our experience during the SIT/ILRT we interpreted this as indicating that there was no leakage.
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> We proceeded to pressurize in increments of 0.1 Pd until we reached 2 Pd at 22:00 Tuesday evening to conduct another leak check. Since there was no evidence of distress, we continued the leak test throughout Tuesday night and Wednesday morning and calculated at leak rate of >0.1% mass/day after holding pressure for approximately 8 hours.
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> At 07:00, Wednesday, September 28, we continued pressurizing the model in increments of 0.1 Pd until we reached 2.5 Pd around 10:00. At this point, we observed some liner strains approaching 2% and also had some evidence from the acoustic system that there might have been a liner tear. We continued with the planned leak check at this pressure and after 1-1/2 hours, calculated a fairly stable leak rate of 1.5% mass/day (+/- 0.5% mass/day). We decided that this was clear indication of a liner tear/leak and modified our test plan slightly, continuing to pressurize the model in incremental steps of 0.05 Pd, but reducing the hold time at each pressure step to less than 10 minutes.
>
> We were able to continue pressurizing the model to approximately 3 Pd, with increasing evidence of leakage and increasing liner strains. At 3 Pd, it became difficult to increase pressure so we increased the nitrogen flow rate to 3500 scfm. We were able to increase pressure to 3.1 Pd however the pressure dropped steadily after reaching this pressure. We estimated the leak rate at this point to be approximately 100% mass/day. We then increased our nitrogen flow rate to the maximum capacity of the pressurization system (5000 scfm) and were able to increase the pressure to slightly over 3.3 Pd before the leak rate exceeded our capacity to pressurize the model. Since we could no longer increase pressure and we had almost exhausted our supply of nitrogen, the decision was made to begin terminating the test. The isolation valve was closed and we allowed the model to depressurize on it's own. We estimated that the initial terminal leak rate was on the order of 900% mass/day. (The maximum flow rate of nitrogen, 5000 scfm is equivalent to 1000% mass/day.) As the model

> depressurized, we observed a steadily decreasing leak rate (initially decaying at 250% mass/day per hour). We then opened the vent valve to depressurize the model more quickly to 1.0 Pd.
>
> At 1.0 Pd, we were able to inspect the model and observe (hear and feel) nitrogen gas escaping through many small cracks in the concrete and at the tendon anchors. We suspect 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.
>
> 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 we observed large liner strains and suspect that the liner may have torn in several locations, the remainder of the structure appears 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.

Plots of the model pressurization versus time, nitrogen flow in versus time, and the flow rates versus time are shown in Figures 1-3 and 1-4. Once the model was depressurized and inspected, a total of 26 liner tears were found at 17 different locations. This observed liner tear map is shown in Figure 1-5. Every tear occurred at or near a vertical weld seam, and some of the tears grew quite large; certainly large enough to account for the depressurization of the model.

Following the LST and post-LST inspection of the model and the data, it became clear that the objectives of the test program were not fully satisfied. Other than concrete cracking, liner tearing, and leakage, the LST did not cause any significant structural damage in the model, and overall structural response (displacements, rebar and tendon strains, etc.) was only slightly beyond the elastic range. In order to provide additional structural response data to compare with inelastic response conditions, the PCCV model was resealed, filled nearly full with water, and repressurized during the Structural Failure Mode Test (SFMT). A maximum pressure of 3.6 Pd was reached when a catastrophic rupture occurred. This was preceded only briefly by tensile failure of several hoop tendons. The condition of the model immediately after the SFMT is shown in Figure 1-6.

## 1.3 Objectives of Posttest Analysis Work

The scope and objectives of the posttest analysis work are outlined below.

### 1.3.1 Final Pretest Analysis

A final pretest analysis was performed to support test operations and to account for information (such as tendon prestress levels) learned in the final months prior to the test.

### 1.3.2 Evaluation of Test Data and Comparison with Pretest Analysis Results

The published and final pretest analysis results are compared to the test data to characterize how well the pretest analyses predicted the behavior and identify areas for improvement or modification in the posttest analyses. In addition to comparing responses for specific transducers, a qualitative assessment on the overall response is also included. Also, the effect of uncontrollable external factors (e.g. variations in ambient thermal response), as well as response artifacts introduced by the instrumentation, were identified and the methods used to ‘correct’ the data for these effects were developed.

### 1.3.3 Global Posttest Analysis

The global PCCV axisymmetric model was updated to reflect actual conditions during the LST (e.g., material properties, in-situ stress conditions of concrete and tendons, etc.) and the global model was reanalyzed. The effect of soil stiffness on the basemat and the modeling of the dome tendons were also addressed.

### 1.3.4 Local Posttest Analyses

The 3DCM model, the local penetration models (E/H, A/L, and M/S), and, to address the liner failure occurrence in some unexpected location, one new model, were developed and analyzed.

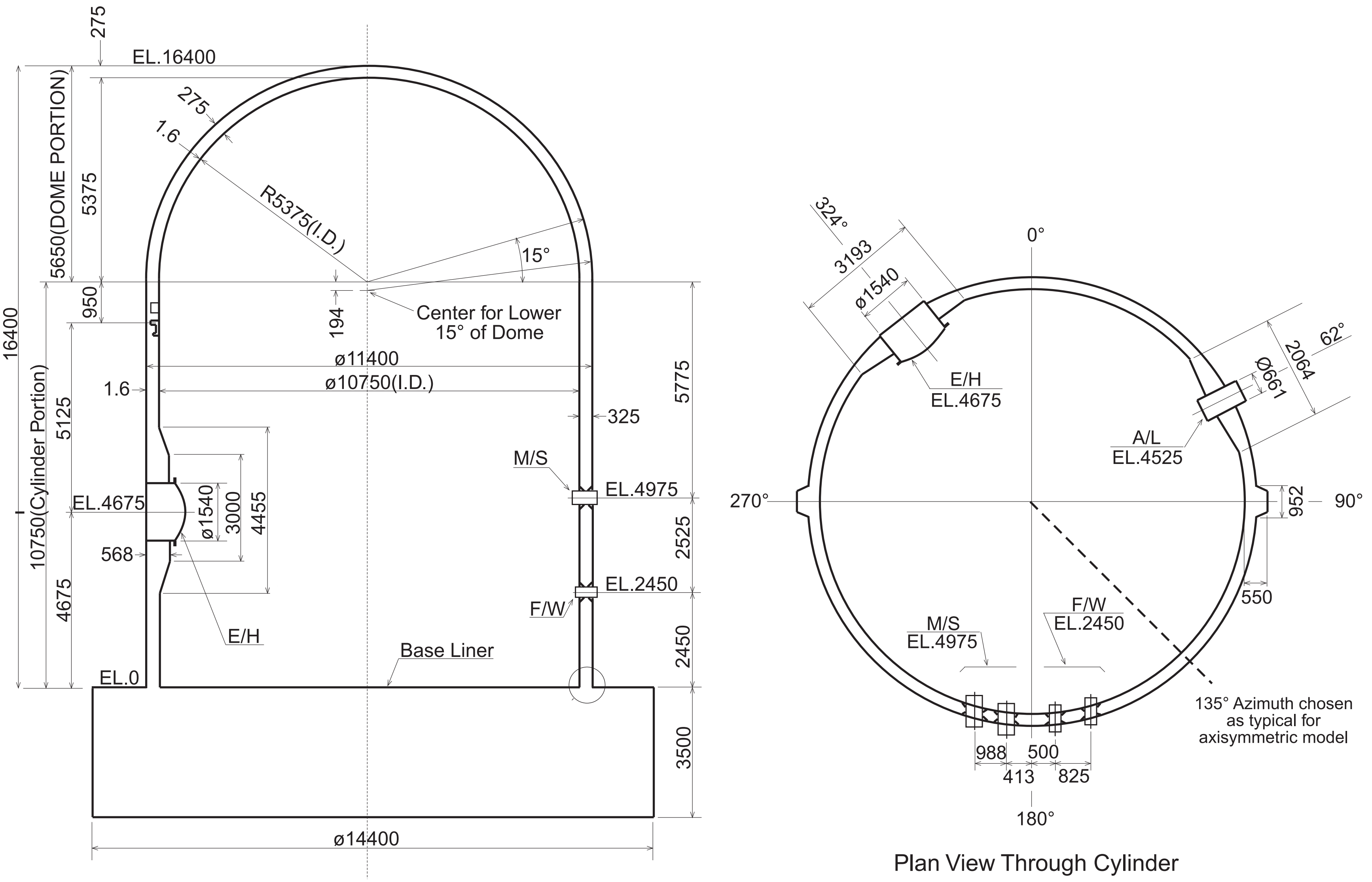
### 1.3.5 Post SFMT Analysis

Selected data from the SFMT was compared to both the pretest and posttest analyses. A simplified 3D shell model was developed to simulate and provide some insight into the sequence of events leading to the catastrophic structural failure.

### 1.3.6 Posttest Analysis Report

The results of these tasks are documented herein, including a summary of lessons learned and possible analysis methodology enhancements as a result of the PCCV analysis research program.

Figure 1-1.  NUPEC/NRC 1:4 Scale PCCV Model Built at Sandia National Laboratories



Plan View Through Cylinder

Figure 1-2. 1:4 Scale PCCV Model Geometry (dimensions in mm)

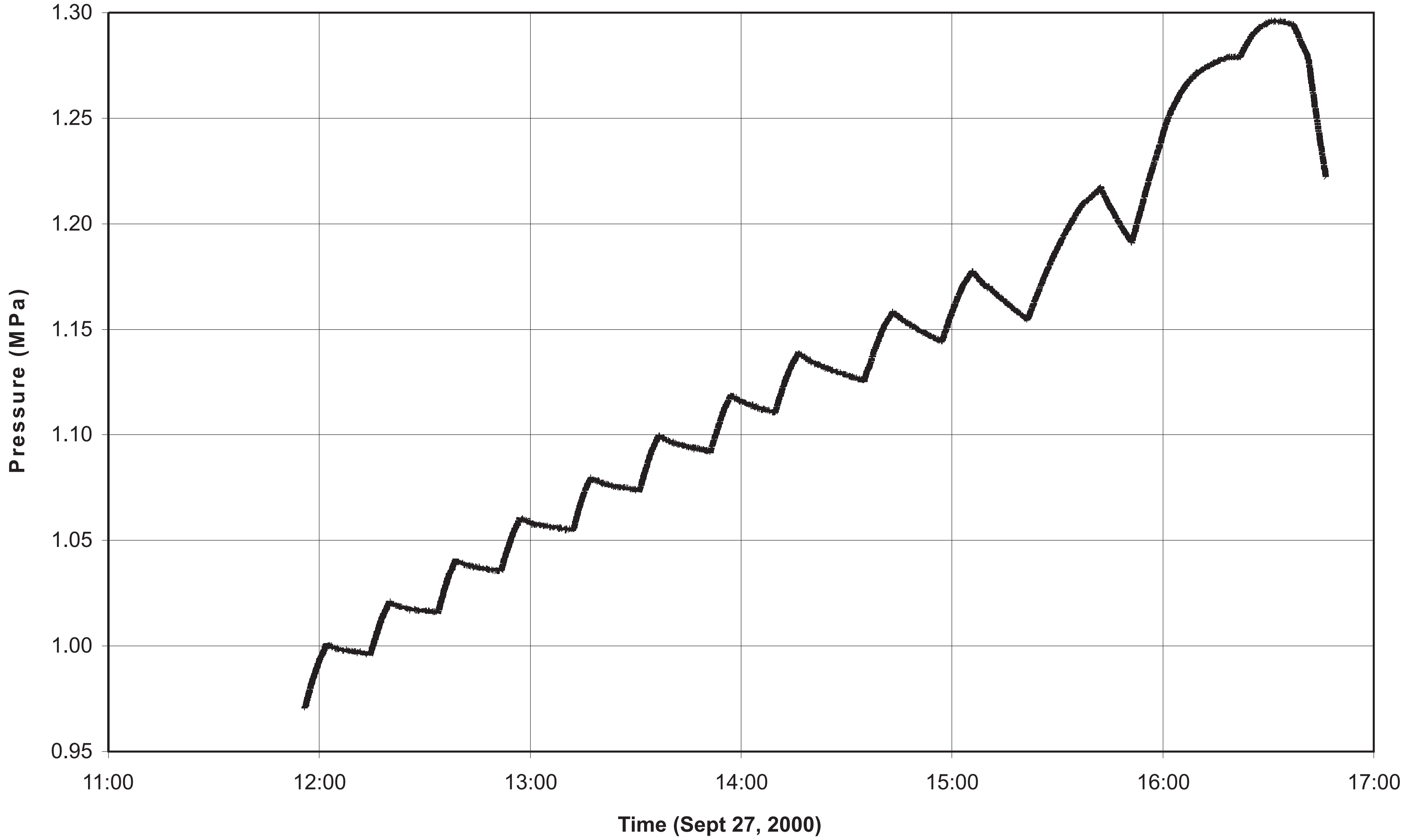


Figure 1-3. LST Pressure Time History (2.5Pd - 3.3Pd)

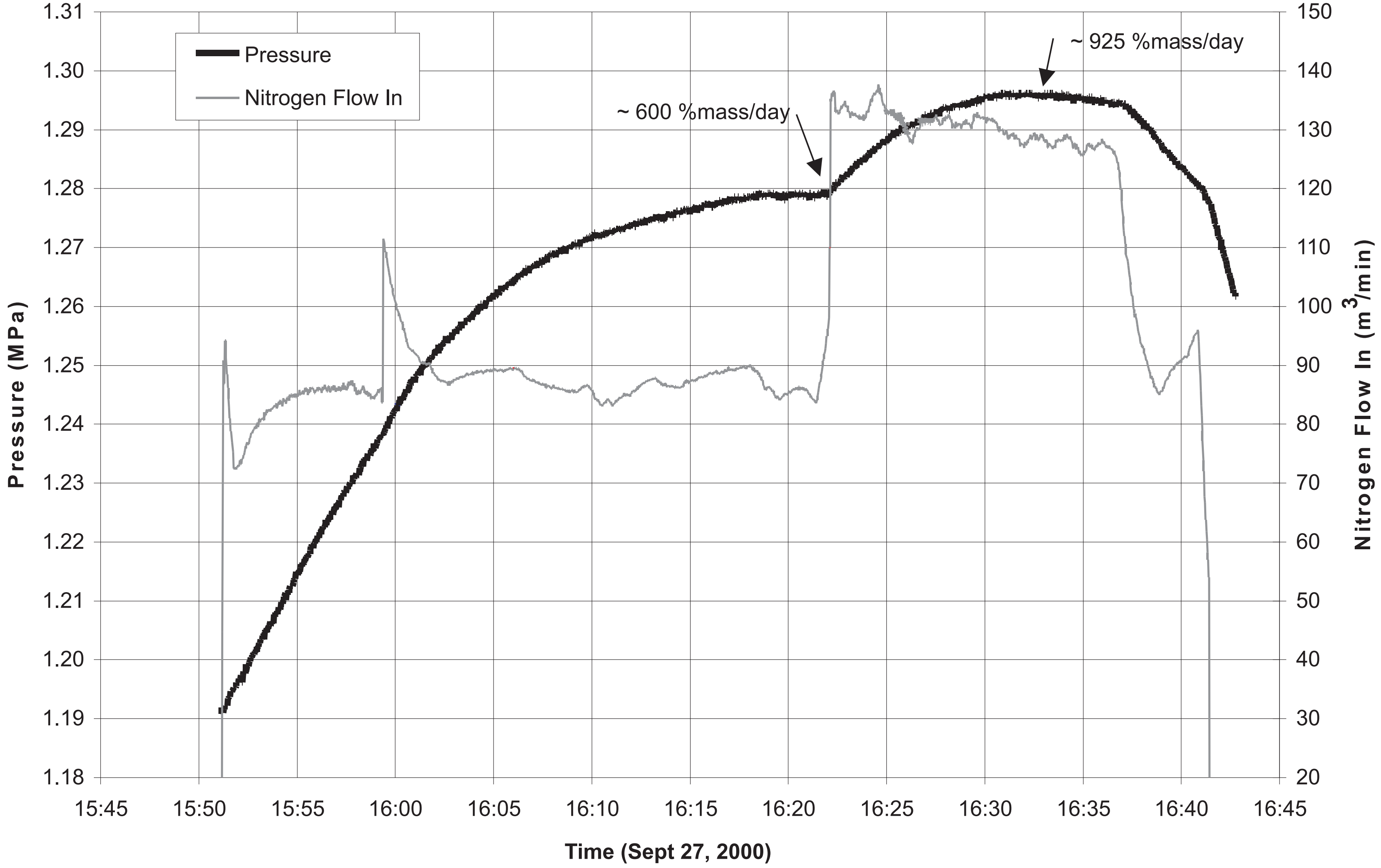


Figure 1-4. LST Pressure and Flow (Final Minutes)

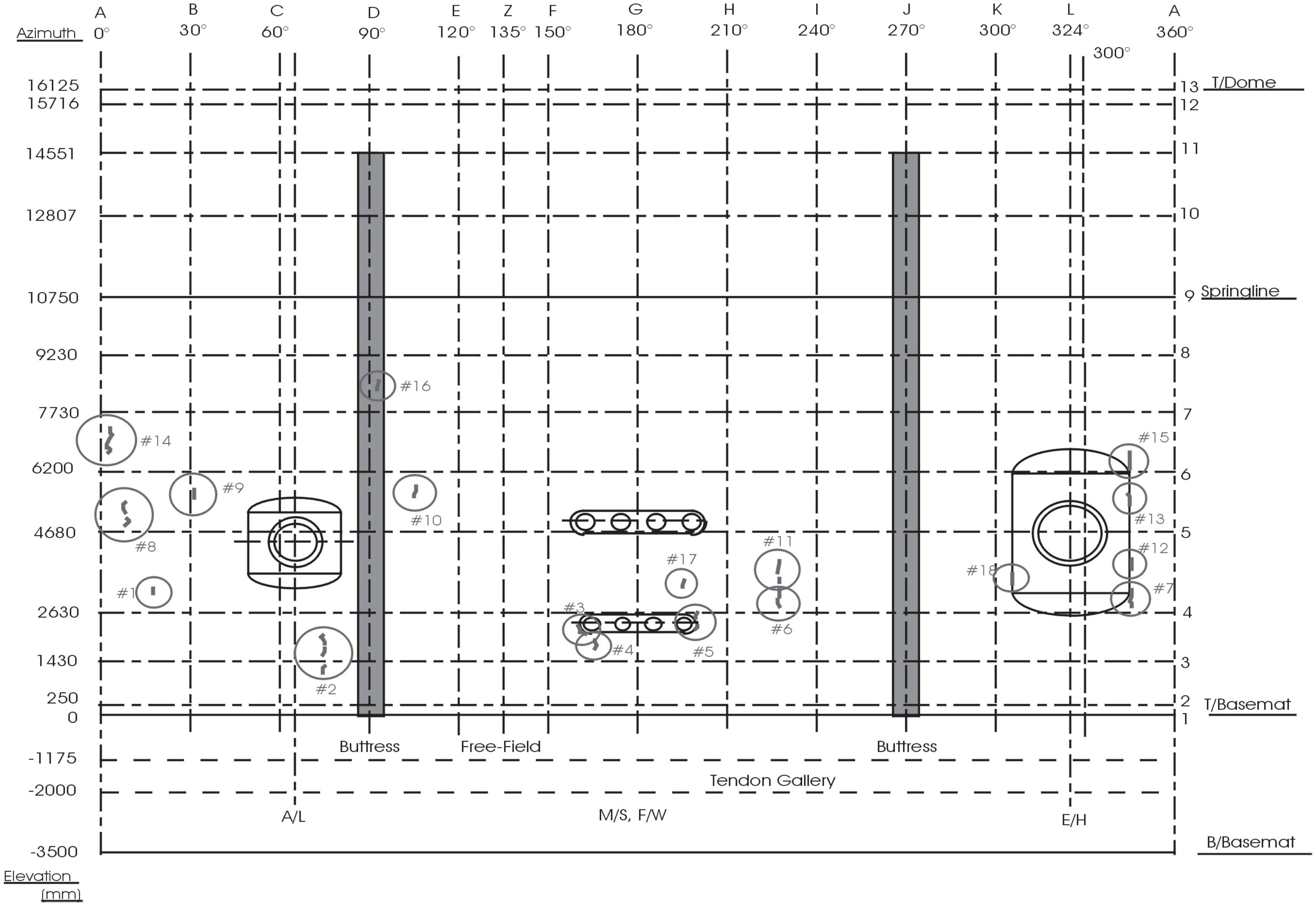


Figure 1-5. Liner Tears Observed After LST

Figure 1-6. PCCV Model after Structural Failure Mode Test