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Posttest Analysis of the NUPEC/NRC 1:4 Scale Prestressed Concrete Containment Vessel Model

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Sandia National Laboratories

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ABSTRACT

The Nuclear Power Engineering Corporation of Japan and the U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, are cosponsoring and jointly funding a Cooperative Containment Research Program at Sandia National Laboratories (SNL) in Albuquerque, New Mexico. As a part of the program, a prestressed concrete containment vessel (PCCV) model was subjected to a series of overpressurization tests at SNL beginning in July 2000 and culminating in a functional failure mode or Limit State Test (LST) in September 2000 and a Structural Failure Mode Test (SFMT) in November 2001. The PCCV model, uniformly scaled at 1:4, represents the containment structure of an actual Pressurized Water Reactor (PWR) plant (OHI-3) in Japan. The objectives of the internal pressurization tests were to obtain measurement data on the structural response of the model to pressure loading beyond design basis accident in order to validate analytical modeling, find pressure capacity of the model, and observe its failure mechanisms.

This report compares results of pretest analytical studies of the PCCV model to the PCCV high pressure test measurements and describes results of posttest analytical studies. These analyses were performed by ANATECH Corp. under contract with SNL. The posttest analysis represents the third phase of a comprehensive PCCV analysis effort. The first phase consisted of preliminary analyses to determine what finite element models would be necessary for the pretest prediction analyses, and the second phase consisted of the pretest prediction analyses.

The principal objectives of the posttest analyses were: (1) to provide insights to improve the analytical methods for predicting the structural response and failure modes of a prestressed concrete containment, and (2) to evaluate by analysis any phenomena or failure mode observed during the test that had not been explicitly predicted by analysis. The posttest activities documented herein also include reviewing the effects of and "correcting" the test data for external factors that were not explicitly considered in the analyses, such as ambient temperature variations and artificial response data created by the instrumentation.

In addition to documenting the comparisons between measured behavior and predicted behavior of the liner, concrete, rebar, and tendons, a variety of failure modes and locations were investigated. Global analysis helped identify possible modes; other analyses investigated localized failure modes or modes specifically associated with 3D behavior. Liner tearing failure at the midheight of the cylinder near penetrations and a shear/bending failure at the base of the cylinder wall were both found to be competing failure modes. More detailed modeling of these locations placed a higher likelihood of failure on the liner tearing mode at the cylinder midheight near a major penetration. The most likely location for the liner tearing failure was near the Equipment Hatch at the ending point of a vertical T-anchor, near where the liner is attached to the thickened liner insert plate. The pressure at which the local analysis computed liner strains that reached the failure limits (indicating tearing and leakage) was 3.2 times the design pressure (Pd) of 0.39 MPa or 1.27 MPa. During the LST, liner tearing and leakage failure was first detected at a pressure of 2.4-2.5 Pd, and subsequent increase in pressure to 3.3 Pd resulted in further tearing at many strain concentration locations and increasing leakage. This report compares measured strains near as many of these strain concentrations as possible to the predictions from the global and local penetration analyses. The report also describes reanalysis of existing models and new analysis of new models, including representation of typical liner seam details aimed at simulating some local as-built conditions that existed in the test.

The LST resulted in liner tearing and leakage, but not in a structural failure. 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 midheight 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 in-elastic response conditions, the PCCV model was resealed, filled nearly full with water, and repressurized during the SFMT to a maximum pressure of 3.6 Pd when a catastrophic rupture occurred. A comparison of pretest and post-LST analysis results to the SFMT data and additional analyses, to provide some insight into the mechanisms leading to the structural failure, are also included in this report.

The report closes with summary and conclusions on the accuracy and adequacy of the pretest prediction analysis. The summary attempts to also draw lessons learned from previous containment research and highlight the new and unique lessons learned from the 1:4 scale PCCV project, such as the modeling and behavior of prestressing and some unique liner seam details. These conclusions are then used to establish guidelines for containment analysis. The relevance of this research to U.S. plants is also discussed.

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EXECUTIVE SUMMARY

The Nuclear Power Engineering Corporation (NUPEC) of Japan and the U.S. Nuclear Regulatory Commission (NRC), Office of Nuclear Regulatory Research, are cosponsoring and jointly funding a Cooperative Containment Research Program at Sandia National Laboratories[1] (SNL) in Albuquerque, New Mexico. As a part of the program, a prestressed concrete containment vessel (PCCV) model was subjected to a series of overpressurization tests at SNL beginning in July 2000 and culminating in a functional failure mode or Limit State Test (LST) in September 2000 and a Structural Failure Mode Test (SFMT) in November 2001. The PCCV model, uniformly scaled at 1:4, represents of the containment structure of an actual Pressurized Water Reactor (PWR) plant (OHI-3) in Japan. The objectives of the internal pressurization tests were to obtain measurement data of the model's structural response to pressure loading beyond design basis accident in order to validate analytical modeling, find pressure capacity of the model, and observe its failure mechanisms. This report documents a comparison of the pre-test analyses with the test results and describes the posttest analyses performed to improve the simulation of model behavior.

The pretest and posttest analyses described herein were performed by ANATECH Corp. under contract with SNL. The current work represents the third phase of a comprehensive PCCV analysis effort. The first phase consisted of preliminary analyses to determine what finite element models would be necessary for the pretest prediction analyses, and the second phase consisted of the pretest prediction analyses. The principal objectives of the posttest analyses are: (1) to provide insights to improve the analytical methods for predicting the structural response and failure modes of a prestressed concrete containment, and (2) to evaluate by analysis any phenomena or failure mode observed during the test that was not explicitly predicted by analysis.

The first two chapters summarize the events of the high pressure LST, including the observed failure modes and corresponding pressures and a final set of analyses conducted immediately prior to the test, but after publication of the formal pretest analyses in [1] and [2]. The ABAQUS general purpose finite element program with the ANACAP-U concrete and steel constitutive modeling modules were used for the analysis. Tendons and their prestressing were modeled to replicate expected tendon stress-strain behavior and friction effects. Concrete cracking was simulated with the "smeared crack" approach, where cracking is introduced at the finite element integration points. The failure predictions consisted of liner tearing locations, all occurring near the midheight of the cylinder near penetrations and weld seams with "rat-hole" details. The most likely location for the liner tearing failure was predicted to be near the Equipment Hatch (E/H) at the ending point of a vertical T-anchor, near where the liner is attached to the thickened liner insert plate. The failure pressure was predicted to be 3.2 times the design pressure (Pd) of 0.39 MPa or 1.27 MPa. During the LST, liner tearing and leakage failure was first detected at a pressure of 2.4-2.5 Pd, and a subsequent increase in pressure to 3.3 Pd resulted in further tearing at many strain concentration locations and increased leakage. Subsequent chapters compare measured strains near as many of these strain concentrations as possible to the predictions from local analyses, and also describe reanalysis of existing models and new analyses, such as liner seam models aimed at simulating some of the model's as-built conditions.

The models that constituted the final pretest predictions were the global axisymmetric, the semi-global three-dimensional cylinder midheight (3DCM) model, and local penetration models of the E/H, Personnel Airlock (A/L), and Mainsteam (M/S) penetrations. The local failure predictions were all driven by response versus pressure histories calculated by the 3DCM model. The only changes made between the 1999 pretest predictions reported in [1] and the final (2000) pretest predictions were to material properties and prestressing levels. Because visual inspection of the model revealed the existence of micro-cracking (probably due to curing and shrinkage) throughout the cylinder, the concrete tensile strength was reduced to a cracking strain of $\varepsilon_{cr} = 40 \times 10^{-6}$, based on prior experience with similar test structures. A new suite of concrete compressive tests became available in February, 2000, so these were also incorporated into the final pretest analyses.

ANATECH was also tasked with reviewing and correcting measurements taken during the LST. This effort focused on identifying artifacts in the response data resulting from uncontrollable, external influences on the model and those that

[1] 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 multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U.S. Department of Energy under Contract Number DE-AC04-94AL85000

were a byproduct of the instrumentation. The effects and phenomena addressed in the "data correction" effort were ambient temperature variations, rigid body motion of the model, and strain localization. The details of these corrections are described in the test report; however, the phenomena and corresponding corrections are summarized in Chapter 3.

In reviewing the PCCV test data, the 55 Standard Output Locations (SOLs) used for the Round Robin prediction exercise held in 1999 were very useful comparison points. In Chapter 4, the published and final pretest analyses are compared to the test data at each SOL. All analysis data curves were "rezeroed" to the first point of the test data, i.e. the data reading occurring at the start of the test. This slightly shifted the analysis data, but it simplified the comparison of the response to internal pressure and eliminated differences in the response to dead load and prestressing and that could occur from creep or other time-dependent effects. This is justified because most of the PCCV instrumentation was initialized in March, 2000; after dead loads were applied, the model was prestressed, and subjected to six months of daily temperature cycling and low- pressure testing prior to the start of the LST (September, 2000).

The overall conclusions from the comparisons of the pretest analysis with the LST are as follows:

- Radial displacements in the cylinder wall were well predicted by global axisymmetric analysis, but dome and overall vertical displacements were significantly overpredicted.
- Wall-base juncture behavior, including many rebar and liner strain measurements, were well predicted by the detailed wall-base juncture (axisymmetric) modeling.
- Functional failure (i.e. leakage in excess of 1% mass/day) at a pressure of 2.5 Pd occurred at a liner tear in an area of high strain that was not predicted by analysis, but was probably amplified due to defects associated with weld seam repair.
- Maximum pressure, 187.9 psig (3.30 Pd), which was primarily the onset of global yielding, was closely predicted by analysis, but the predicted failure mode itself did not manifest. Note that the maximum pressure achieved during the LST was also limited by the capacity of the pressurization system to balance the increasing leak rate after functional failure occurred.
- The average radial displacement at the midheight of the cylinder of 20mm at maximum pressure, equivalent to an average hoop strain of 0.37%, is within 10% of that predicted by global analysis (21.9 mm or 0.41%).
- Maximum radial displacement at E/H = 29mm, equivalent hoop strain of 0.0054, was reasonably predicted by 3DCM model, but prediction of displacements at other azimuths–like the buttresses–were poorly predicted by 3DCM model.
- For both the hoop and vertical tendons, there was about 8% to 10% loss of stress between the initial prestressing and the start of the LST caused by long-term effects and by the SFT and SIT.
- Hoop tendon stress distribution simulated by analysis at start of LST shows fair agreement with measurements, implying that the angular friction and anchor set modeling assumptions at the start of the test were reasonable. Vertical tendon stress distribution at the start of the LST were less consistent with the initial modeling assumptions. One tendon, V85, showed significant friction losses below the springline, and the other two instrumented vertical tendons showed only about half of the friction loss in the dome than what was assumed by designers and incorporated in analysis.
- Hoop tendon stress distributions during pressurization showed poor agreement with the pretest analysis. In particular, the gages interior from the ends are underpredicted *and* the anchor forces are overpredicted.
- The cylinder hoop tendon data, in total, shows evidence of the tendons slipping during pressurization. The measurements indicate that the shape of the tendon stress profile completely changes during pressurization. Comparing the increase in the tendon strain to the cylinder hoop strain implies that portions of the tendons are slipping (i.e. tendon strain is greater than the cylinder wall strain) in order for the higher deformation at other azimuths to be accommodated.

Chapter 5 describes the global posttest analyses performed after the LST. To summarize the conclusions:

- Basemat uplift and dome displacements comparisons were significantly improved by redistributing soil basemat springs according to tributary area, improving the dome meridional tendon representation to account for the added stiffness of the overlapping tendons due to the rectilinear "hairpin" layout.
- Comparisons were also improved by using no vertical tendon friction in the cylinder.
- Analysis should not use the "Prestress Hold" option in ABAQUS.

Chapter 6 describes the posttest 3DCM analysis. In the pretest analyses, the 3DCM model was developed to investigate the non-axisymmetric behavior of the cylinder wall and provide more realistic boundary conditions for the penetration's submodels. Buttresses above and below the 3DCM model boundaries have vertical beam stiffnesses that were not accounted for in the pretest analysis. Equivalent spring properties were derived and then applied as radial spring elements. The derivation was performed by adding a 2D plane stress representation of a buttress to the axisymmetric model. The model was then cut at the appropriate 3DCM model horizontal boundary. Zero rotation boundary conditions were applied at the cut boundary and horizontal and vertical tendon prestress was maintained as in the full axisymmetric models. A horizontal displacement was then applied to the cut boundary. Separate models were analyzed with and without the buttress present and the force versus displacement results were differenced; these became the force versus deflection properties assigned to the buttress springs. The only other modeling assumption found to be at significant variance with observed test behavior was the tendon modeling, especially the representation of friction. A lengthy study and series of analyses focused on this variance. Two important observations were made about the hoop tendon measurements as pressure increases:

1. When pressure overcomes prestress, P = 0.59 MPa, tendon stress distributions change from the classical angular friction design assumption to an approximately uniform distribution; then they stay fairly uniform at most higher pressures. Toward the end of the test, some tendon interior forces slightly exceed the force at the anchor.
2. The apparent strain increases in the tendons corresponding to the force/strain gage readings are significantly larger (e.g. 0.48% versus 0.35%, for H53) than the strain that corresponds purely to radial expansion. This can only be explained by force redistribution associated with sliding. Thus the position of the tendon relative to the concrete must be allowed to change after initial prestress in order to adequately simulate tendon behavior during overpressurization.

These observations led to changes and studies of the tendon friction modeling in the 3DCM model. Because the tendon friction behavior observed in the test turned out to be quite complex, the analysis strategies investigated were chosen to at least bracket the observed LST behavior. The last three analyses presented are:

Model 6. Apply prestress. Then, by using the ABAQUS *MODEL CHANGE capability, fix the tendon nodes at their initially deformed position relative to the concrete. In other words, start from classical design prestress with friction and then grout (bond) the tendons.

Model 7. Perform run 5 (the run with only the buttress springs added) up to P = 1.5 Pd (0.59 MPa), then "MODEL CHANGE" all friction elements to non-friction elements (truss ties aligned perpendicular to the tendons. In other words, at P = 1.5 Pd, perfectly grease (unbond) the tendons).

Model 9. After prestress, keep the initial friction elements, but add a new set of friction elements in the reverse orientation so that if points on the tendon move relative to concrete in the reverse direction from that of initial prestress, they will experience reverse direction friction.

In general, the tendon friction simulation runs 6, 7, and 9 show progressively better agreement with test measurements, with run 9 showing quite good agreement at the anchors and at most points interior to the tendon ends. Based on these and the other observations, the results of run 9 were used to drive the submodels for E/H and M/S (and estimated feedwater (F/W)) penetrations posttest analysis. On tendon friction behavior, the test measurements and analytical evidence support the conclusion that tendon friction is important to the tendon behavior, but traditional friction design formulas that predict tendon stress distribution begin to break down once pressurization exceeds the pressure that overcomes prestress (in this case, roughly 1.5 Pd). The coefficient of angular friction appears to lessen, allowing sliding and force redistribution as the vessel expands, but more importantly, some parts of the tendon are forced to reverse direction of travel relative to the duct, reverse it from the direction of travel experienced during prestressing. Under this action, angular friction properties probably still hold, but the direction of friction must change sign from that assumed in a design calculation.

Chapter 7 describes the posttest analyses of the penetration submodels. Liner strains measured in the vicinity of the E/H penetration collar were much lower than predicted by pretest analysis. Since the predicted high strain locations were fundamental to the failure predictions, significant effort was spent reanalyzing the E/H model after the test. With a set of changes that included conversion of the model to the other side of the hatch (away from the buttress) and a correction to the vertical stress boundary condition, posttest E/H model's hoop expansion behavior correlated much better with measured global displacement behavior. The hoop deformation correlation-to-pressure function introduced in the pretest work was no longer needed. Two hypotheses were developed.

Hypothesis 1: The liner in the E/H area had a high degree of bond-friction with concrete, preventing slippage of the liner relative to the concrete; relative slippage is required for elevated strains to develop near local discontinuities like T-anchors and stiffeners.

Hypothesis 2: Formation of a major crack near the edge of the E/H embossment further concentrated the liner strains at the edge of the embossment.

Posttest analysis showed that by preventing relative slip between liner and concrete, the overall behavior of the system (concrete strains, tendon strains, liner strains away from the hatch) remained the same, but the elevated strains close to the collar were eliminated. In the final case, directed cracks were introduced to one row of elements, and a discrete crack was formed by adding double rows of nodes along an assumed crack line. This was found to create an elevated liner strain phenomenon. The mild strain concentration coincides, in location, with rat-hole weld seam details, and in the LST, numerous tears occurred at these details. Based on results of detailed liner rat-hole analysis (Chapter 8), the additional strain concentration associated with these details is enough to generate liner strains at the edge of the embossment in excess of the liner tearing strain criteria. This shows that with discrete crack modeling and local rat-hole modeling, a liner tear could have been predicted to occur as early as 2.8 Pd. Based on the evidence provided by liner strain gages and by acoustic monitoring, one of the tears along this embossment edge may have even occurred as early as 2.5 Pd. (Note that this posttest analysis did not attempt to include as-built liner defects, such as local thinning or residual stresses resulting from initial fabrication or subsequent repairs.) The posttest E/H study thus presents a modeling strategy with results that correlate well with the LST measurements and observations. A somewhat higher strain prediction might be possible if a discrete crack (separate rows of nodes) were propagated all the way through the concrete wall, but this would require a change in rebar modeling strategy–one that is probably not practical even for detailed analysis of containments.

The M/S and F/W penetration hot spots (both analysis and LST observations) occurred near the vertical T-anchor terminations and near the ‘equator’ of the thickened insert plate surrounding the penetration group, i.e. at the 3:00 and 9:00 positions. For the posttest analysis effort, no changes to the M/S model were necessary, other than updating the applied displacement versus pressure histories that were obtained from 3DCM posttest Model 9. After studying the F/W geometry in the posttest phase of the project, it was determined that the F/W penetration model was so similar to the M/S penetration model that it was not necessary to pursue separate analysis of the F/W model; the posttest M/S model analysis was assumed to be reasonably representative of the F/W penetrations. Several observations could be made from the well-instrumented M/S and F/W locations that are relevant to response predictions around containment penetrations.

- Many of the highest strains recorded during the LST are near the M/S and the F/W.
- There is wide variation in peak strain measurements, even at locations that are theoretically identical in geometry; factors contributing to these differences are: slight variations in liner thickness (due to manufacturing and weld repair grinding), gage position relative to the collar/weld, material properties (including welding heat effects), etc.
- The highest strain measurements can, but do not always, correspond to tear locations. Examples supporting this are: 1) a gage near the F/W tear shows evidence of rising strain prior to tear occurrence, then starting at 2.9 Pd, declining strain due to the stress relief caused by the tear; a gage located near the crack tip, on the other hand, showed quite low strain up to 3.1 Pd and then a sudden jump. This supports a hypothesis that this tear initiated at a pressure of 2.9 Pd at about the 7:30 position (midpoint of the tear) and then between 2.9 Pd and 3.1 Pd, the tear ran around the perimeter of the thickened collar and up to the 9:00 position.

Comparisons of analysis to the M/S and F/W liner strain gages show that the posttest analysis of the M/S penetrations captures the strains measured in the LST quite well for both the M/S and F/W penetrations.

Chapter 8 describes the investigation of the liner tears that occurred away from the penetrations but where welding details may have caused local liner strain concentrations. The PCCV model exhibited 16 distinct locations at which liner tears occurred. All 16 locations were near vertical weld seams, but with some variation in the presence or configuration of a horizontal stiffener or rat-hole. By comparing "before and after" photos taken by SNL and with reference to a posttest metallurgical study [7], it was observed that liner welding irregularities were present at almost all of the tear locations. These irregularities included points of extensive repair, such as grinding, points of discontinuous or missing back-up bars, or points with weld and liner seam fit-up irregular geometry. Some locations, where a seam and rat-hole existed and high strains were measured, but a tear did not occur (e.g., at Location D-7, just below where tear 16 occurred), provide additional evidence of the importance of the welding details to liner tearing. Visual observation showed extensive grinding and weld repair in the liner welds where most of the tears occurred. Ultrasonic measurements showed substantial reductions in thickness near these tears. Measurements showed ~23% thickness reduction in many locations, and more (up to 40% in a few locations). A posttest liner seam analysis study was aimed at answering questions about quantifying the effects of welding irregularities and distinguishing these from strain concentration effects solely related to geometry. A mesh-size sensitivity study was conducted. Analyses were then conducted to assess the effects of material and geometry variations. The first variation was to implement varying material properties near the weld areas. This included assignment of different material properties to the base metal, heat affected zone (HAZ), and weld fusion zone (WFZ) regions of the model. The second variation only modified the material in the WFZ. The final phase incorporated geometry modifications to the model near the weld lines. This included thinning of elements and varying the extent of thinning in the vicinity of the welds due to grinding. The geometry modifications were coupled with modified material properties ranging from uniform to including variations of base metal, HAZ, and WFZ regions. All of the material and geometry variations were based on the data contained in the SNL metallurgical analysis report [7]. The conclusions of the liner seam/rat-hole modeling study are summarized below:

- By comparison with strain gage measurements and posttest liner tear observations, some of the finite element weld seam analyses are able to generate strain fields in and around the rat-holes and liner welds which exceed the liner tearing strain criteria at locations where tears were observed.
- Because of competing mechanisms (between the weld zone and the ends of stiffeners), making yield and ultimate strength adjustments to the HAZ material properties appears to be justified and necessary to correctly predict strain concentration location and intensity.
- The models with back-up bars, nominal geometric properties, and best-estimate material properties yielded the best simulations of defect-free construction of rat-hole/weld-seam details, represented in the PCCV model at locations D7 and J5. However, even models without back-up bars also provided reasonable correlation with gages at these locations.
- A case with severe (~40%) amounts of thinning appears to provide the best simulation of the behavior of tear occurrences in which severe liner thinning (due to weld repair grinding) was reported in [7] to be present and back-up bars were absent; these conditions existed at tears 7, 8, 10, 12, 13, 14, 15, and 16.
- A case specifically representing the "tear 16" detail was performed. This case appears to provide reasonable simulation of the tears that occurred *with* back-up bars present, namely, tears 1, 2, 6, 9, 11, and 16. The severity of the strain at this case also shows that a tear ($\varepsilon_{eff} > 20\%$) at the geometry simulated would have been predicted to occur as early as 3.0 Pd.
- If a section of liner with a rat-hole/liner-seam detail, such as that at tear Locations 7, 12, 13, and 15 is subjected to additionally elevated strain (i.e. strain across the liner model that is larger than free-field global strain) a tear even earlier than 3.0 Pd can be justified. In practice, such a prediction could approximately be made using a strain concentration factor approach. The strain concentration factors (K = peak ε_{eff} divided by global ε_{hoop}) implied by this liner seam study are as follows: K = 48 (tear at stiffener end, no back-up bar); K = 45 (tear at stiffener end, with back-up bar); K = 59 (tear at HAZ, no back-up bar, and 40% thickness reduction due to grinding); K = 91 (tear at tear 16, if a short segment of horizontal weld seam back-up bar is missing)
- Using a model of the rat-hole/seam locations without defects, such as location D-7, showed that liner tears still would have developed by pressure of 3.4 Pd, so liner tearing and leakage would still have been the failure mode (for quasi-static pressurization) even in the absence of liner welding irregularities.

The LST resulted in liner tearing and leakage, but not a structural failure. 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 midheight of the cylinder only reached 0.4%, approximately twice the yield strain in steel.) In order to provide additional structural response data to compare with in-elastic response conditions, the PCCV model was resealed, filled nearly full with water, and repressurized during the SFMT to a maximum pressure of 3.6 Pd when a catastrophic rupture occurred. Chapter 9 includes a brief discussion and comparison of the pretest and post-LST analysis results to the SFMT data and presents the results of a post-SFMT analysis intended to provide some insight into the mechanisms leading to the structural failure.

The SFMT posttest analysis showed that good simulation of the PCCV global behavior through and including tendon rupture is possible with a 3D shell model. The main limitations of the shell model were a lack of local liner strain concentration prediction and a lack of accuracy in the predictions of local wall-base-juncture behavior. However, significant accuracy in global behavior prediction did not seem to be lost when a bonded tendon assumption was used.

The SFMT model provided additional insight as to how the structural failure likely developed. Near the 0 degrees - 6 degrees azimuth of the cylinder, there is a discontinuity of a step-down in inner and outer hoop rebar area of 38% (step-down from alternating D19, D16 bars to a pattern of 1D16/3D13 bars). Then at 3.49 Pd, the wall and tendon strain at the 0 degrees - 6 location is a little higher than all other azimuths, and a tendon rupture occurs. Once this occurs, the analysis shows neighboring tendons rupturing and deformations spreading quickly along this azimuth. It is interesting to note that the analysis predicts that the secondary tendon ruptures spread upward. Shortly after the first rupture at 5.4 m, analysis predicts the tendon ruptures to spread up through 6.5 m. From review of the test video, this appears to agree with observations. By 3.65 Pd, the analysis shows rupture to have spread over a vertical line spanning about 6 m. This also agrees with observations. After wall rupture, a secondary event occurred in the SFMT: through-wall failure around the circumference of the wall at about 1.5 m elevation. While it is difficult to say at what azimuth this failure initiated, it seems clear that this was a shear or combined shear/flexural failure of the wall. The plotting of analysis shear results showed that such failure may have initiated at the buttresses (evidenced by the high shear stresses predicted there) and then "unzipped." Note from the plans that at elev. 1.60 m, there is a step-down in vertical rebar from D19 to D16, which may have focused this shear failure plane. Moreover, at the buttresses, the outer vertical rebar step down occurs slightly lower: at 1.22 m there is a change from a total of nineteen D19 bars down to a total of ten D19 bars placed within the buttress. This may explain why the circumferential failure ran through the buttresses at a slightly lower elevation than the rest of the wall. As a point of comparison, the shear failure threshold calculation performed in the pretest work [1] is compared to the demand (both pretest axisymmetric and posttest SFMT) in Chapter 9. This shows that without the trigger of rupture of the vessel, the capacity (a modified compression field theory calculation) exceeds the demand throughout the pressurization. But with the triggering event of a massive wall rupture, one of two mechanisms may have caused shear demand to exceed capacity: 1) a large deformation of the wall opening, creating large rotations near the base of the wall, would crush the outer concrete of the flexural section and thereby reduce the capacity, or 2) the water jet-induced momentum imbalance would cause added shear demand; this would create tangential shear at some azimuths and would be the maximum at the buttresses; such shear acting in combination with the already high radial shear stresses could have increased shear stress demand enough to induce the shear failure.

The 1:4 scale PCCV test showed the driving response quantity that leads to the limit state of the vessel is the radial expansion of the cylinder. This aspect of response must be predicted correctly in order to reasonably predict vessel capacity and predict, at least approximately, the many other local aspects of response (local liner strains, etc.) that are driven by the cylinder expansion. With this test, as with the 1:6 scale PCCV model, many competing strain concentrations occur around the mid-height of the cylinder. Although it is difficult to predict which local liner detail will tear first, and although some particular response quantities, like basemat uplift, were not predicted exactly by the ANATECH/SNL pretest analysis of the PCCV model, the radial expansion of the cylinder was predicted very accurately. A response mechanism that also appears to have been well predicted was cylinder wall-base flexure and shear, another mechanism that, if predicted grossly incorrectly, could lead to erroneous pressure capacity/failure mode conclusions.

The minimum requirement for a containment overpressure evaluation should certainly be a robust axisymmetric analysis. Other steps, guidelines, and lessons learned are provided in the final chapter of this report. The lessons learned in the current work, which are perhaps the most novel, are those related to tendon friction behavior. As a result of this project, the best calculation methods recommended for tendon friction modeling are, in descending order of preference, 1) an advanced contact friction surface between the tendons and the concrete (not manageable for the current problem size and complexity), 2) pre-set friction ties applied in one direction during prestressing and then added in the other direction during pressurization (3DCM run 9) and 3) if neither of these methods are practical within the scope of the calculation, it is best to start with an "average" stress level (using a friction loss design formula), but assume uniform stress distribution in the tendons throughout pressurization, i.e., an unbonded tendon assumption, and finally 4) same as 3, but using a bonded tendon assumption. It should be recognized for method 4, however, that this can lead to a premature prediction of tendon rupture, because the tendon strain increments during pressurization will match the hoop strain increments of the vessel wall one-to-one, and this was not observed during the PCCV LST.

The relevance of this work to full size U.S. Containments is fundamental. All of the analysis methods tried, calibrated, and validated would be highly applicable to full-scale structures. The posttest work also provides a reasonably simple liner-only mesh approach to predicting local strains near weld seams, and the test itself underscores the need for continuous back-up bars on all liner seam welds. Such is the requirement in the current U.S. design rules.

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ABBREVIATIONS

3DCM	entire cylinder midheight region
A/L	airlock
BPS	before prestressing
CIRC	circular cross section
CTL	Construction Technology Laboratories
DOR	data of record
DYN	"dynamic" data
E/H	Equipment Hatch
F/W	Feedwater
HAZ	heat affected zone
LST	Limit State Test
M/S	Mainsteam
NRC	U.S. Nuclear Regulatory Commission
NUPEC	Nuclear Power Engineering Corporation
PCCV	prestressed concrete containment vessel
PSFT	Post System Functionality Test
SFT	System Functionality Test
SFMT	Structural Failure Mode Test
SIT	Structural Integrity Test
SNL	Sandia National Laboratories
SOL	Standard Output Locations
UTS	Ultimate Tensile Strength
WFZ	weld fusion zone