Emc²

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Dr. William Shack
Chairman
Subcommittee on Material, Metallurgy & Reactor Fuels
ACRS U.S. Nuclear Regulatory Commission
Washington, D.C. 20555-0001

Dear Dr. Shack:

Final Report on Review of Oyster Creek Generation Station 3-D Drywell Confirmatory Analyses

The following letter report documents our findings in the review of the various Oyster Creek Generation Station 3-D Drywell Confirmatory analyses. Two CDs have been received with various documents as well as other files transmitted by e-mail. Of these, the ones we have had time to focus on to date are:

- SIA report dated January 2009 – Report # 0006004.403
- NRC-NRR staff "Assessment of the Oyster Creek 3-D Finite Element Analysis of the Drywell Shell", dated May 12, 2009.
- Exelon letter on "Updated Information Regarding the Results of the Structural Analysis of the Oyster Creek Drywell Shell, Performed in Support of License Renewal", dated September 9, 2009.
- "Applicability of ASME Code Case N-284-1 to Buckling Analysis of Drywell Shell" by Clarence D. Miller – June 15, 2006.
- State of New Jersey independent analysis by Becht Nuclear Services cover letter dated April 7, 2009.
- Viewgraphs from various presentations
    - AmGen October 3, 2006
    - AmGen January 18, 2007
    - NRC staff presentation September 23, 2009
    - AmGen presentation September 23, 2009
    - EELC "Oyster Creek Drywell Modeling Issues" September 23, 2009 by Richard Webster

During this review, it was found that ***there has been an extraordinary amount of analysis conducted for this evaluation***, which included;

- GE finite element analysis (1992 analysis of record, but not reviewed by us),
- Sandia National Lab finite element analysis (conducted in 2007 but not available for review),
- Structural Integrity Associates more detailed finite element analysis (January and September 2009),
- Becht Nuclear Services review analyses,
- NRC-NRR assessments of the analyses,
- Brookhaven National Lab review of modified Capacity Reduction Factors (not available for our review),
- Professor Hutchinson assessment of buckling capacity reduction, and
- Engineering Mechanics Corporation of Columbus review as per this letter report.

Objective of Emc^2 Review

The objective of this review by Emc^2 (by Dr. Gery Wilkowski with input from Dr. Frederick Brust) was to focus on the adequacy of the SIA 3D finite element stress analysis. Our evaluation involved consideration of the fidelity of the finite element model, loads, material property input, and boundary conditions. We did not focus on the buckling Capacity Reduction Factors (CRF) or ASME Code margins, although we added some additional comments as a result of information learned at the September 23, 2009 review meeting. Also, we did not look at the corrosion data or corrosion mitigation aspects in detail other than at the September 23rd review meeting, and have only minor comments on those aspects.

Overview

As a general overview statement, we believe the SIA analysis is extremely thorough. They have a highly defined FE model, and conducted numerous sensitivity studies on mesh refinement and corrosion depth, and modified versus unmodified capacity reduction factors. We had this opinion prior to seeing other reviewers' comments and we are in agreement with them.

General Comments

The main objective of this analysis was to determine whether material loss from corrosion near the bottom of the drywell shell can lead to buckling problems. The corrosion occurred over a decade ago, and thickness measurements show the corrosion has been mitigated by thorough cleaning and epoxy coating. During this time period (since ~1992) the drywell has performed adequately under the service conditions experienced. Since there were probably only normal operating conditions with large margins, that is not surprising, but it is at least a necessary condition.

The SAI analysis was very carefully performed and appeared to have the type of nuclear quality assurance standards applied to the analysis process necessary for such a critical model. A full three-dimensional shell analysis which includes all necessary components of the drywell shell and supports was included. However, the concrete which surrounds the exterior of the shell over most of the top 90% of the structure and the concrete that embeds the shell at the bottom are not explicitly modeled. The concrete above the floor has a 3-inch gap with the steel liner and should not be included in the modeling. The embedded concrete at the bottom is accounted for by imposing boundary conditions on the steel shell that are meant to account for the shell taking compressive support from the concrete. This is done by assuming there are no radial displacements of the shell in the concrete, although no shear stress between the concrete and the steel liner are assumed. The skirt that holds up the drywell and is embedded in the concrete under the vessel is pinned to the drywell vessel. There is concrete on the inside (floor) that is above the outside sandbag region that would prevent inward buckling deflections, but that restraint was not modeled. That was a conservative assumption.

The original January 2009 model was well-refined with 406,000 elements, and that mesh was further refined in the September 2009 sensitivity study to 1,000,000 elements. The entire drywell shell with many penetrations and reinforcing pad locations was modeled using ANSYS Shell63 thin-shell elements. The mean radius of the shell elements followed the original theoretical drywell curvature. When the thickness was reduced, the mean radius was kept constant so that the thickness was centered on the original mean radius (i.e., the classical mid-surface definition of the shells did not change – only the thickness was modified)[1]. For the corroded areas, the mean radius was used for the reduced thickness regions. That allows the R/t of the corroded shell to be very closely modeled, the membrane stresses to be correct, but the bending from the eccentricity of the external corrosion imperfection must be accounted for by the Capacity Reduction Factor. The Capacity Reduction Factor has to account for deviations in the out-of-roundness imperfections of the shell from the true theoretical form. The tolerance for this deviation is given in Article NE-4221.2 of ASME Section III Division 1 – NE. In this article, Figure NE-4221.2-1 determines the deviation (e) relative to the shell thickness (t) as a function of the outside diameter/thickness (D_o/t) of the shell and the design length between the stiffener-to-outside diameter (L/D_o) ratios.

For the sandbag region, the arc length between stiffeners was 235 inches as per VG 77 of the September 23rd Exelon presentation, the shell diameter at the floor level is 35 feet or 420 inches, and the nominal initial thickness was 1.154 inches. This gives a D_o/t of 364, an L/D_o of 0.56, and from Figure NE-4221.2-1 the "e" value (imperfection from theoretical shape) is ~0.9t for the initial fabrication guidelines for this drywell shell. The corrosion reduces the "e" value that is available to account for general fabrication imperfections. For the general thinning down to 0.826 inch (thickness loss of ~28%), the "e" value is reduced by about 1/3 leaving 2/3 for other fabrication flaw imperfections. For the larger area, local thinning down to 0.696 inch (thickness loss of ~40% of thickness), the "e" value is reduced by about 45% leaving 55% for other fabrication flaw imperfections. Since the corrosion imperfection is a large percentage of the design imperfections, some conservatism is needed in maintaining the CRFs used. However, an

[1] EMC^2 staff use ABAQUS for most finite element analyses. ABAQUS permits off-center shell mid-surface definitions and unbalanced Gauss point definitions. We are not sure if ANSYS permits this.

encouraging aspect was some limited sphere test data by Odland that was cited by Dr. Miller on VG 65 of the Exelon Sept 23, 2009 presentation. That data showed that with "e"/t = 1.8 the buckling failure stresses were higher than the Code values. This is double the "e" values for the drywell design requirement, making the concern of the loss in the CRF from the corrosion less significant.

Additionally, the CRF comes from experimental bounding to test data. Such data are subject to significant scatter, and perhaps the fabrication of the drywell shell was actually better than the bounding case, and may have more margin than by bounding calculations. Exelon might want to use curvature template measurements of the eccentricity from the perfect shell design on the ID of the drywell relative to the design guidelines in Article NE-4221.2 of ASME Section III Division 1 – NE using the arc length guidelines in Figure NE-4221.2-2.

A full finite element model was developed of the drywell, vent tubing, toroidal pressure suppression chamber, upper supporting trusses, lower cement supports, and downcomers, with great detail to penetrations through the drywell, welding pads and support plates on the main drywell vessel. However, there is one aspect that remains unclear. The ends of the downcomer pipes were said to be supported, and there were bellows between the vent pipes and the toroidal suppression chamber. There seemed to be conflicting comments about how the bellows was modeled, i.e., either the reduced stiffness of the bellows not modeled and loads are transferred between the toroidal suppression chamber and the drywell, or the bellows was given zero stiffness, in which case there are no loads between the drywell and the toroidal shell. With no loads between the two, none of the toroidal and piping beyond the bellows needs to be modeled, other than giving a "gee-whiz that looks cool impression", where perhaps 100,000 of the elements in the model might be useless. The real behavior might be closer to zero stiffness than totally neglecting the bellows and assuming only solid pipe in the FE model, the impact of that change on the final load transfer to the drywell shell is unknown. Any forces from the vent pipe may enhance or reduce buckling depending on the direction of those forces relative to the buckling deformation mode shape.

Because a full finite element model of the entire drywell shell was developed and modeled, buckling concerns of the entire shell (not just the corroded areas) were considered. However, many of the 200 buckling modes were in areas of the model that did not have degradation and there were low load participation factors. Exelon also said that not all of the loads in the toroidal area and vent lines were included in the model, so buckling modes in those areas are not relevant. It would have been of great assistance to have some comments added to the buckling mode tables (8-2 and 8-3 in SIA January 2009 report) that noted where the buckling occurred, or elimination of non-relevant buckling modes. Furthermore knowing the shape of the buckling modes of primary concern is quite helpful in understanding the thickness sensitivity studies. Having a copy of the pertinent buckling shapes from the SIA work is desirable. (Those mode shape figures were passed around at the September 29th meeting to the ACRS staff and G. Wilkowski, and Figure 1 is an attempt to illustrate the buckling mode shape of interest.)

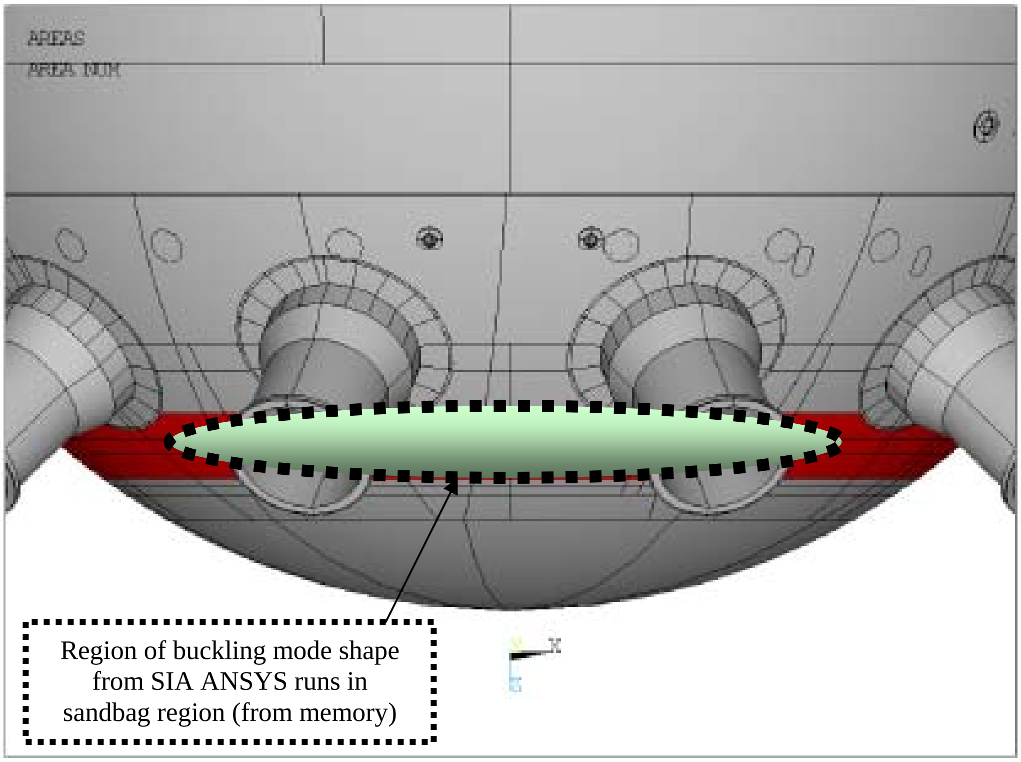
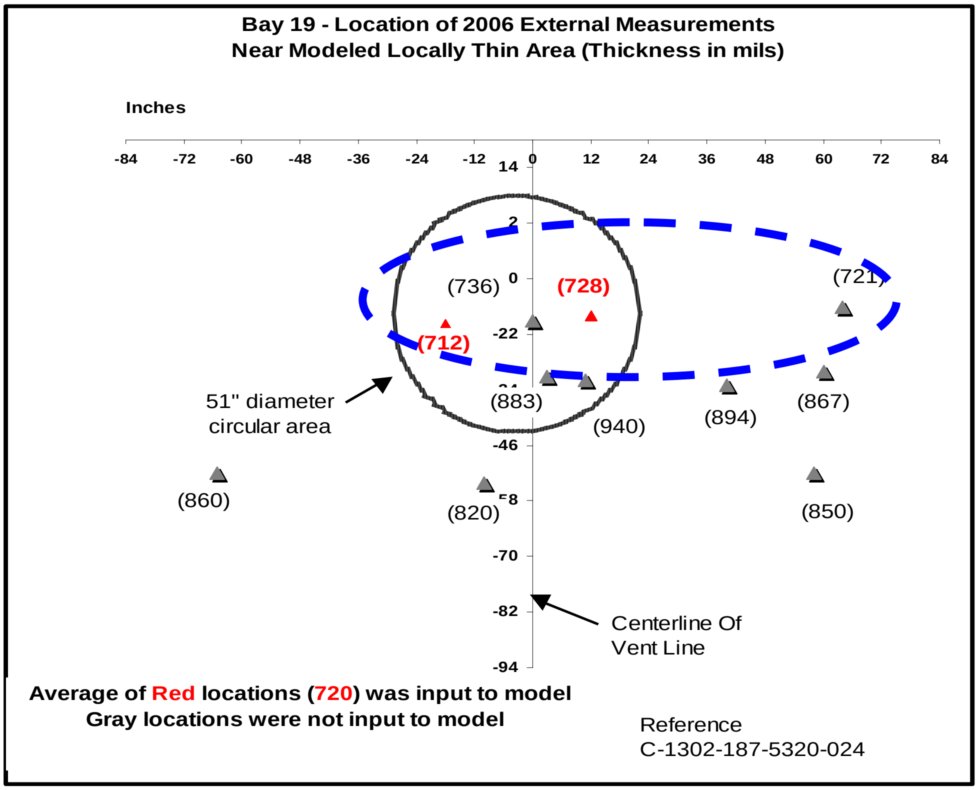


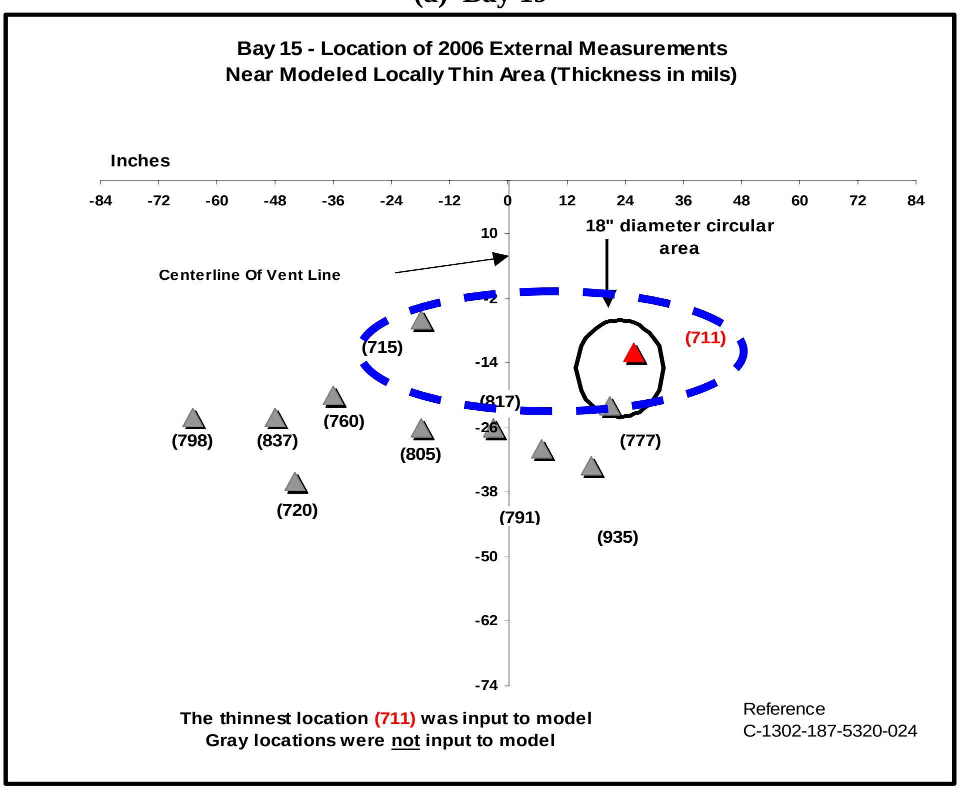
Figure 1 Approximation of buckling mode shape

The sensitivity studies conducted were quite impressive from the refinement of the FE mesh. They involved general thinning of a whole bay, or increased thinning of a local area. There was negligible difference in the buckling margins between the original and refined meshes as reported in the September 23, 2009 Exelon presentation. However, a quick glance at the relevant buckling mode figure for the sandbag area showed that the buckling deformation would have to extend over about 2 bays (~20% of the circumference). Hence, if the general thinning sensitivity study was conducted over a circumferential length corresponding to the buckling mode shape, the results might be different. As Dr. Miller pointed out, having even a 6-inch diameter hole (100% loss of thickness) in this shell would not change the initial buckling margin (6" hole corresponds to 1.4% of the circumferential in the sandbag region). Since the height of the corrosion is limited to the relatively narrow sandbag region, the only other dimension that can affect the buckling behavior is the circumferential extent *relative to the shape of the buckling mode of concern*.

In regards to the thickness measurements and how they were modeled, at the September 23, 2009 meeting several of the ACRS staff members and the EECL presenter noted (as I did) that some of the thickness measurement plots in the Exelon presentation suggested that the thinned region might be more elliptical in shape (longer in the circumferential/horizontal direction) than the circular areas used in the SIA FE model. In particular this could be seen for Bay 19 (VG 26) and Bay 15 (VG 29). These longer elliptical shapes (illustrated in my Figure 2) would be in the same direction as the buckling mode shape in the sandbag region.



(a) Bay 19



(b) Bay 15

Figure 2 Thickness reduction measurements, SIA idealized circular reduced thickness areas, and blue dashed ellipses suggesting larger local thinned regions

In regards to the loading conditions in the FE analyses, the flooding condition gives the lowest buckling margin. The load-combination for this case includes the postulated accidental flooding induced stresses (a very low probability event not experienced to date) and then a safe-seismic event (SSE) loading occurring at the same time that the full flooding condition is reached (another low probability event not experienced to date). For the Oyster Creek plant, the SSE design peak-ground acceleration (PGA) values have been found to correspond to a mean probability of occurrence of ~1.4 E-4, or one event every 14,000 years[(2)]. This is another very low probability event at the same time as the flooding. The two events occurring at the same time might have a probability well below 10E-6, unless they were somehow connected. Logically a possible connection is if the SSE loading caused the flooding to occur; however, the SSE loading (duration of ~10 to 25 seconds) would be over well before the drywell could be flooded to the 72-foot level in the analyses. The most severe logical load-combination condition might be that an aftershock from the main SSE event might occur while the drywell is flooded, which probably would have a peak-ground-acceleration value less than an operating basis earthquake (OBE). (The OBE PGA is typically about ½ of SSE peak-ground-acceleration value.) Hence the full flooding loads simultaneous with the SSE load combination for the drywell is overly conservative from a realistic viewpoint, which is a comforting aspect even if that load combination cannot be relaxed from the design basis.

One very minor point (especially in light of the above discussion on SSE loading) is that to include the SAM loads in the SAI report, three different approaches were noted. Approach II was the maximum relative displacements, and Approach III was time-history analyses to get the relative displacements. It was noted in the report that Approach III was the most accurate and gave the largest SAM movement. I would have thought using the maximum relative displacements would have to give the same or larger displacements than any relative displacements during a time-history analyses.

It would have been prudent to perform a full buckling analysis for some of the worst cases by performing a full time-domain large-deformation solution (or Riks analysis) to determine the margins on the buckling loads. I didn’t explicitly ask if such an analysis was attempted or completed, but I know my staff would have been working weekends out of personal curiosity to see what would happen in such an analysis. This could have been done for just the worst case loading (according to the simpler eigenvalue analysis). Time-history large deformation analyses are quite accurate today and are superior to eigenvalue-based solutions with modern finite element codes <u>*as long as the imperfections are properly included*</u>. At the reduced thickness corrosion areas, the corrosion imperfections are present, but they are centered on the theoretical mean radius of the uncorroded shell. That aspect would have to be corrected to use this model to analytically predict what the CRF might be. One should also include the fabrication induced deviations to the uncorroded shell (see above discussion about taking shell shape measurements on the ID surface), and then induce the corrosion thinning properly on the OD surface. They were very close to being able to do this type of analysis.

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(2) From - Sobel, P., NUREG-1488 “Revised Livermore Seismic Hazard Estimates for 69 Nuclear Power Plant Sites East of the Rocky Mountains,” October 1993.

Finally, it should also be noted that buckling of the drywell shell is not by itself a disastrous mechanism, since the material being used is quite ductile. In all likelihood there would be a buckle, but no cracking in the buckle. Cracking of the buckled region would require large displacement cyclic stresses of the buckled mode shape. For instance, it is well known in the oil and gas industries that thin-wall transmission pipe can tolerate large buckles and dents up to 40 percent of their diameter without cracks developing. Below is a figure of a buckle in a pipe that still maintained pressure (I have seen many such pictures of the years). Prior to 1950, field bends in pipes were made by intentionally wrinkling the pipe (wrinkle bends) which performed adequately unless there were a lot of axial cyclic loads over decades of use. Hence the intended service of the drywell shell (to contain the flooded water in the event of a rare accident) could still be met even if a buckle existed.

Figure 3 Example of a buckle in pipe that still held high pressure

Summary

The procedure for assessing buckling of the drywell shell is described in Section 8 of the SAI report. The process is:

1. An eigenvalue buckling finite element analysis was performed for all load cases. This provides the theoretical buckling stress for each mode shape. Two hundred modes (from the entire model) were considered for each load case – a very thorough analysis, although it is difficult to determine which of these mode shapes are important for the corrosion in the sandbag region without seeing the plots of the mode shapes. (We recognize that putting in 200 plots of mode shapes is a daunting task, but a few of the key ones would be helpful.)
2. Due to geometric and material imperfections, the theoretical buckling stress is never realized in practice. The ASME code prescribes capacity reduction factors (CRF) to reduce the theoretical buckling stress at the location of interest. Recently, ASME has

relaxed the CRF to increase the CRF if tensile stresses occur in the other directions at the location of buckling (Miller correction). A safety factor is also applied.

3. All critical locations in the drywell shell, including the locally corroded areas, were assessed for buckling in this way. This is a valid approach.

It is noted that other industries use similar capacity reduction factors since buckling of shells is complex since the geometric imperfections can be quite complicated. For instance, NASA developed ‘knock down’ factors for shell buckling during the 1960’s when some of the early rocket designs in the Mercury and Gemini programs buckled and failed during testing. These “knock down” factors are currently being modified (relaxed) under a program at NASA Langley using full-scale nonlinear finite element modeling along with new test data.

In summary, we saw a few areas that would be helpful in better understanding the buckling margins. There were some weaknesses in the analysis, but there were many more conservative aspects. The analysis appears to be well done and appears to validate the claim that buckling is not a concern for even the worst load case considered.

Sincerely,

Gary M. Wilkowski

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President
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