April 30, 2004

MEMORANDUM TO: William D. Travers
Executive Director for Operations

FROM: Ashok C. Thadani, Director ***/RA/***
Office of Nuclear Regulatory Research

SUBJECT: UPDATE ON STRUCTURAL INTEGRITY ASSESSMENT OF DAVIS-BESSE REACTOR PRESSURE VESSEL HEAD WITH CORROSION WASTAGE CAVITY

My memorandum to you dated January 8, 2003, summarized RES activities related to the degradation of vessel head penetration nozzles in pressurized water reactors, including estimates of the pressure necessary to fail the Davis-Besse RPV head in the as-found condition on February 16, 2002, and how long Davis-Besse could have operated before the cladding failed. My memorandum noted several uncertainties in the analyses, including those related to cracks found in the cladding. The attachment to the memorandum stated that the licensee would determine the depth of the cracks in the cladding and that the presence of cracks might necessitate a revision of the calculations and could possibly reduce the pressure margin identified in the original calculations.

This memorandum updates the January 8, 2003, memorandum, specifically addressing the influence of the cracks on the pressure necessary to fail the cladding and how long Davis-Besse could have operated before the cladding failed. Since the original calculations, additional work has been done in the following areas:

- Clad disk tests of samples with simple cavity and clad crack geometries,
- Characterization of cracks in the Davis-Besse cladding,
- Fracture toughness characterization of the Davis-Besse cladding,
- Development of a detailed finite element model of the Davis-Besse wastage cavity and cladding as they were on February 16, 2002, and
- Peer review by an independent external panel to review the experimental activities and the approach for the analytical work.

Our analyses of the pressure necessary to fail the cladding used two representations of the cladding cracks to provide understanding of the sensitivity to crack size. For the longer and deeper of these two crack representations (with length of 2 inches and depth 0.1 inches, consistent with an ASME Code representation for the multiple cracks in the cladding), estimates of the pressure necessary to fail the cladding range from 2700 to 3300 psi (at the 5^{th} and 95^{th} percentiles, respectively), with a median pressure of 3000 psi. For a shorter (0.66 inches) and shallower (0.065 inches) representation, estimates of the pressure necessary to fail the cladding range from 3900 to 6550 psi (at the 5^{th} and 95^{th} percentiles, respectively), with a median pressure of 5250 psi.

Considering the uncertainties in predicting the failure pressure for multiple flaws, in our engineering judgment the ASME Code representation of the cladding cracks is the more appropriate model. Thus, our judgment is that the margin against failure ranges from a factor of 1.2 to 1.5 of the operating pressure, with a median value of 1.4. These estimates are in agreement with the forensic evidence that the operating pressure of 2165 psi was insufficient to produce crack initiation. The margin against failure at the relief valve setpoint (2500 psi) ranges from a factor of 1.1 to 1.3 of the setpoint pressure, with a median value of 1.2.

Finally, we used a simplified model of the cavity geometry in Davis-Besse to estimate how long after February 16, 2002, Davis-Besse could have operated without failure of the stainless steel cladding. For the ASME Code representation of the cladding cracks, this model predicts an operating time of 2 to 13 months (at the 5^{th} and 95^{th} percentiles, respectively), with a median estimate of 5 months. For the shallower depth crack of 0.065 inches (and length of 2 inches), estimates of the operating time range from 3 to 13 months (at the 5^{th} and 95^{th} percentiles, respectively), with a median estimate of 8 months. There are significant uncertainties regarding the rate and direction of cavity expansion (for example, was the cavity continuing to grow? - our analysis assumes that the cavity was growing) and the rate of stress corrosion crack growth in the cladding. With our engineering judgment that the ASME Code representation of the cladding cracks is the more appropriate model, it is our conclusion that Davis-Besse could have operated for 2 to 13 months without failure of the cladding, with a median value of 5 months.

A more complete description of the experimental and analytical work performed is attached to this memorandum. At present we are preparing input for an Accident Sequence Precursor (ASP) analysis of Davis-Besse and finalizing the detailed documentation of this work, including the experimental testing, characterization of the cracks in the Davis-Besse cladding, the analytical modeling efforts, and the external panel review. In accordance with normal Agency process to evaluate the risk significance of operating conditions at nuclear power plants, the ASP analysis will evaluate the risk from the degradation of the reactor vessel head at Davis-Besse. A final engineering and analysis report will be issued when we report on the preliminary results and findings of the ASP analyses in early summer.

Attachment: As stated

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ATTACHMENT

STRUCTURAL INTEGRITY ASSESSMENT OF DAVIS-BESSE REACTOR PRESSURE VESSEL HEAD WITH CORROSION WASTAGE CAVITY

A memorandum from A. Thadani (RES) to W. Travers (EDO) dated January 8, 2003, summarized RES activities related to the degradation of vessel head penetration nozzles in pressurized water reactors, including estimates of the pressure necessary to fail the Davis-Besse RPV head in the as-found condition on February 16, 2002, and how long Davis-Besse could have operated before the cladding failed. The memorandum noted several uncertainties in the analyses, including cracks found in the cladding. The attachment to the memorandum stated that the licensee would determine the depth of the cracks in the cladding and that the presence of cracks might necessitate a revision of the calculations and a possible reduction in the pressure margin identified in the original calculations.

Since the original calculations, additional work has been done in the following areas:

- Clad disk tests of samples with simple cavity and clad crack geometries,
- Characterization of cracks in the Davis-Besse cladding,
- Fracture toughness characterization of the Davis-Besse cladding,
- Development of a geometrically accurate finite element model of the Davis-Besse wastage cavity and cladding as they existed on February 16, 2002, and
- Peer review by an independent external panel to review the experimental activities and the approach for the analytical work.

This additional work is described below, along with an update to the calculations using the best available information and modeling available to the staff.

Clad Disk Tests

The failure calculations reported in the January 8, 2003, memorandum were based on a failure model which depended only on the strength of the cladding material, and is characterized as a net-section collapse model. It was chosen based on limited failure testing of thin plate specimens performed by EPRI well before the discovery of the Davis-Besse RPV head degradation. Initial testing was performed at Oak Ridge National Laboratory (ORNL) to confirm that this model was appropriate for cladding material, and in particular for cladding material containing cracks. The initial test results clearly indicated that the failures were dependent on the fracture toughness of the cladding and not just its strength properties. Additional testing was performed to validate this finding. ORNL performed a total of 11 tests of clad disk specimens machined from the pressure vessel of a canceled plant (note this was *not* cladding from the Davis-Besse RPV head). The geometry of these tests was simplified, with a circular 6-inch diameter "cavity" machined through the ferritic steel to provide an exposed cladding surface as the test piece. The circular cavity in these samples was similar in overall size to the cavity at Davis-Besse, but the surface area of exposed cladding in the tests (~ 28.3 square inches) was greater than at Davis-Besse (~16.5 square inches). The difference between the test configuration and the Davis-Besse condition is due to the J-groove weld in the Davis-Besse RPV head, which could not be incorporated into the ORNL tests. However, since the tests were designed to validate the failure model, this difference was not significant. Three of these tests were performed with no cracks in the cladding. The remaining tests had flaws machined into the cladding with a 2-inch length and depths ranging from 10% to 85% of the clad thickness. These tests demonstrated that, in the presence of cracks in the cladding, failure would occur consistent with a ductile tearing fracture mechanics model rather than the net-section collapse model used in the earlier analyses. Therefore, the failure model was revised and additional material property testing was initiated to provide appropriate properties for the Davis-Besse cladding.

Cladding Cracks

Based on work at BWXT Service (initially funded by FirstEnergy and then continued by RES funding), the Davis-Besse cladding was found to contain a complex network of stress corrosion cracks having a total extent on the surface (length) of ~2 inches. The longest contiguous portion of these cracks (0.66 inches in length) was in the central portion of the cracking coincident with the deepest cracking. However, the shorter crack segments were close to this longest segment but slightly offset from the axis of the crack. A maximum depth of 0.1 inch (40% of the cladding thickness) and an average depth of 0.065-in. (26% of the cladding thickness) were measured in this region. The maximum flaw depth occurred in small “fingers” that are characteristic of stress corrosion cracking. The 0.1 inch deep fingers were identified over ~20% of the central 0.66 inch of the crack network.

An additional, and very important, finding of the forensic examination is that the stress corrosion cracks in the Davis-Besse cladding showed no evidence of ductile tearing at the operating pressure (2165 psi), a necessary precursor to cladding failure. This finding provides a reality benchmark for our analysis of pressure margins reported below: a realistic model of the Davis-Besse as-found condition will not predict initiation of a ductile crack at the operating pressure for the conditions that existed on February 16, 2002.

Geometrically Accurate Model

A finite element model was developed that provides a geometrically accurate representation of the as-found Davis-Besse configuration, including the size and shape of the exposed cladding surface, the J-groove weld, and the control rod drive mechanism (CRDM) nozzles in the RPV head. Based on the flaw size information described above, two crack configurations were incorporated in the finite element model. A crack 2 inches long and 0.1 inch deep was adopted to represent the network of flaws in the cladding (essentially an envelope around the cladding cracks) since the shorter crack segments were close to the longest contiguous segment. This characterization of the crack network in the Davis-Besse cladding is consistent with American Society of Mechanical Engineers (ASME) Code rules regarding modeling of multiple cracks and with traditional fracture assessments of cracked components. A separate analysis included a crack 0.66 inch long and 0.065 inch deep based on the dominant crack in the cladding, as described previously. These two characterizations of the cracks were used to address the uncertainty in the failure pressure predictions caused by the multiple cracks. The 2 inch long crack provides a traditional prediction while the 0.66 inch long crack provides a more optimistic prediction.

External Review Panel

To provide an independent perspective on the experimental and analytical work, an external review panel, composed of the following individuals, was formed:

- Dr. William Shack of Argonne National Laboratory and the ACRS. Dr. Shack has expertise in materials analysis and corrosion.

- Dr. Gery Wilkowski of the Engineering Mechanics Corporation of Columbus. Dr. Wilkowski has expertise in fracture testing of both laboratory test specimens and large structural components and in fracture analysis of structural components.
- Professor James Joyce of the United States Naval Academy. Professor Joyce has expertise in fracture analysis and testing.

The review panel met with the staff and ORNL in early December 2003 and had several discussions with the staff after that time. Each reviewer submitted an independent letter to the staff (ADAMS accession ML041030107 and ML041110832), but all reviewers raised the following themes:

- While the clad disk tests provide useful information on the failure characteristics of the cladding, they should not be taken to represent the conditions that existed at Davis-Besse. Estimates of the Davis-Besse structural integrity should be based on a finite element analysis that represents much more closely the geometric conditions that existed at Davis-Besse on February 16, 2002, combined with laboratory data on the strength, toughness, and failure characteristics of the stainless steel cladding.
- The clad disk tests should have additional instrumentation to permit differentiation of crack initiation and failure.
- A better characterization of the crack network that existed in the Davis-Besse cladding is needed to support a realistic assessment of the as-found condition.
- Evidence on the fracture morphology of the cladding cracks does not suggest that failure was imminent on February 16, 2002.

These suggestions were incorporated in the final clad disk tests and analyses described previously.

<u>Updated Estimates of Davis-Besse Failure Conditions</u>

As-Found Condition on February 16, 2003

Ductile tearing fracture analyses were completed for the two crack characterizations, using the geometrically accurate finite element analysis of the cavity. This analysis accounted for the variability in strength and toughness properties of the stainless steel cladding. The variability in material property data was obtained directly from measurements on the Davis-Besse cladding. The strength and fracture toughness properties of the Davis-Besse cladding determined from the testing performed under this program were compared to values obtained for the cladding tested in the clad disk tests and to values previously obtained for archival cladding material. This comparison revealed that the Davis-Besse cladding has similar strength to the archival cladding material and the cladding from the clad disk tests, with the fracture toughness for the Davis-Besse cladding lower than that for the clad disk tests and higher than that for the archival cladding material.

For the ASME Code representation of the cladding cracks, estimates of the pressure necessary to fail the cladding range from 2700 to 3300 psi (at the 5^{th} and 95^{th} percentiles, respectively), with a median pressure of 3000 psi. For the shorter and shallower crack, estimates of the pressure necessary to fail the cladding range from 3900 to 6550 psi (at the 5^{th} and 95^{th} percentiles, respectively), with a median pressure of 5250 psi. Considering the uncertainties in predicting the failure pressure for multiple flaws, in our engineering judgement the ASME Code representation of the cladding cracks is the more appropriate model. Thus, our judgement is that the margin against failure ranges from a factor of 1.2 to 1.5 of the operating pressure, with a median value of 1.4. These estimates are in agreement with the forensic evidence that the operating pressure of 2165 psi was inadequate to produce crack initiation. The margin against failure at the relief valve setpoint (2500 psi) ranges from a factor of 1.1 to 1.3 of the setpoint pressure, with a median value of 1.2.

To provide an independent check on the ORNL analyses, the staff had one of the peer review panel members develop an estimate of the failure pressure. The panel member used an empirical approach that relies heavily on structural integrity assessment procedures developed and validated for ductile fracture by the gas transmission pipeline industry. Those estimates of failure pressures are consistent with the estimates developed by ORNL and reported above.

Continued Operation Beyond February 16, 2002

This analysis accounted for the variability in both the rate of cavity enlargement (assuming that the cavity was continuing to grow) and the rate of stress corrosion crack growth due to the concentrated boric acid solution inside the wastage cavity. To overcome the lack of empirical evidence on the cavity and crack growth rates, expert opinion was used to estimate these parameters and their variability. For the ASME Code representation of the cladding cracks, this model predicts that Davis-Besse could have operated for 2 to 13 month (at the 5^{th} and 95^{th} percentiles, respectively) without failure of the cladding, with a median estimate of 5 months. For a crack with a shallower depth of 0.065 inches (and length of 2 inches), estimates of the operating time range from 3 to 13 months (at the 5^{th} and 95^{th} percentiles, respectively), with a median estimate of 8 months. There are significant uncertainties regarding the rate and direction of cavity expansion (for example, was the cavity continuing to grow? - our analysis assumes that the cavity was growing) and the rate of stress corrosion crack growth in the cladding. With our engineering judgement that the ASME Code representation of the cladding cracks is the more appropriate model, it is our conclusion that Davis-Besse could have operated for 2 to 13 months without failure of the cladding, with a median value of 5 months.

Future Activities

Detailed documentation of this work is under preparation, including the experimental testing, characterization of the cracks in the Davis-Besse cladding, the analytical modeling efforts, and the external panel review. A final engineering and analysis report will be issued in conjunction with the report on the preliminary results and findings of the Accident Sequence Precursor (ASP) analysis in early summer.