September 7, 2001

MEMORANDUM TO: Samuel J. Collins, Director
Office of Nuclear Reactor Regulation

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SUBJECT: RESULTS OF INDEPENDENT EVALUATION OF RECENT REACTOR VESSEL HEAD PENETRATION CRACKING

Per request from the Office of Nuclear Reactor Regulation (NRR), the Office of Nuclear Regulatory Research (RES) convened an independent group of experts to evaluate the recent reactor vessel head penetration (VHP) cracking observed at Oconee and Arkansas Nuclear One. The group was tasked to provide recommendations that would be relevant to: (a) issuance of a generic communication from the NRC on this issue and (b) guidance for inspection activities for Fall 2001 outages at affected plants. Given the potential safety significance of the recently observed cracking, NRR issued NRC Bulletin 2001-01, "Circumferential Cracking of Reactor Pressure Vessel Head Penetration Nozzles," on August 3, 2001. The Bulletin incorporated insights gained from the expert group review.

The members of the expert group and their respective affiliations and technical areas are:

Dr. William Shack - Argonne National Laboratory - Environmentally Assisted Cracking
Dr. Gery Wilkowski - Engineering Mechanics Corporation - Leakage modeling
Dr. Richard Bass - Oak Ridge National Laboratory - Structural Evaluation
Dr. Steven Doctor - Pacific Northwest National Laboratory - Non-destructive Inspection

Review of the groups' reports, discussions with the group members, industry and staff experts, and examination of the literature and industry submittals, supports the following perspectives on the issue. The attachment summarizes and augments these perspectives in tabular form and provides a comparison with industry perspectives and the NRC staff assessment on the issues.

1. Susceptibility Evaluation - Significant uncertainty exists in determining the susceptibility of plants to this cracking phenomenon. The current industry susceptibility model considers only time and temperature. There are other variables (material yield strength, crevice chemistry, residual stresses from fabrication processes, etc.) that can significantly influence the susceptibility to stress corrosion cracking. However, given the need for timely decisions, and the difficulty in obtaining details on the other variables, the model provides the best method for ranking plants at this time. However, the possibility of cracking at a low-ranked plant cannot be precluded and should be considered judiciously in assessing industry actions. It is noteworthy that some experts believe relatively few instances of cracking are expected at this time, even for plants as susceptible as Oconee-3. However, that does not preclude that cracking could exist and will continue to occur at future times, hence "one time" inspections will be inadequate and a program of regular inspections or monitoring should be required.

2. Crack Growth Rates - Due to the possibility of the concentration of aggressive chemical species in the annulus between the VHPs and the reactor vessel head, it is probable that crack growth rates for outer diameter (OD) cracking are higher than those expected for stress corrosion cracking (SCC) in Alloy 600. This would indicate growth rates on the order of 1 inch per year or higher for the higher temperature plants. A complicating feature is the probability of multiple crack initiation sites in the annulus around the outer diameter of the VHPs which could lead to an even faster "effective" crack growth rate until the residual stresses are sufficiently relieved that initiation of new cracks is unlikely and growth is controlled by fracture mechanics.

3. Detection and Characterization of Boric Acid Deposits from VHP leakage - Significant uncertainty exists in the determination of whether leakage through the annulus region, resulting from cracking, will be detectable as boric acid deposits on the surface of the reactor vessel head. In addition, the sensitivity and qualification of visual examination methods needs to be carefully considered in this regard. In this respect, qualified volumetric examinations are recommended as the preferred inspection method for plants which have had cracking. In addition, qualified volumetric examinations would also be the preferred method of examination for plants with a high susceptibility to the degradation. However, qualified visual examinations could be employed if the sensitivity to detection of leakage can be demonstrated on a plant-specific basis (e.g., demonstration of maintenance of a gap between the penetration and the RPV head under operating conditions coupled with an effective leak detection program).

4. Volumetric Examination - It is feasible to detect and characterize the subject degradation with ultrasonic testing (UT). Reliability and effectiveness of such inspections remain to be determined and should include use of mock-ups and performance demonstration. Automated systems for UT inspections (and repairs) are available from several domestic

and foreign industry vendors. The expert group has also considered that, given the nature of the cracking observed thus far, a limited volumetric inspection on a sampling basis would not be adequate to deal with the uncertainties. If cracking is known to exist at a plant, 100% volumetric inspection of all VHPs would be indicated in order to minimize the potential for recurrence of reactor coolant pressure boundary leakage, which could constitute non compliance with the technical specifications and Appendix B. A likely limitation for Fall/2001 would be the number of qualified systems and teams that could be fielded to cover multiple outages. Additional issues would include acceptance criteria and ALARA/labor intensiveness of inspections/repairs.

5. Structural Margin - The expert group was able to provide independent verification of the structural margin calculations performed by the industry. These calculations (both from the industry and the expert group) show that the VHPs can accommodate very large through-wall circumferential cracks (e.g., approximately 270 degrees in extent for CRDMs) while still maintaining adequate structural integrity. The largest circumferential crack discovered at Oconee (approximately 165 degrees) was well within this margin. However, large uncertainties remain regarding the time estimates required for the crack to reach the latter configuration, and for it to potentially grow further to the point of failure. Estimates of the effective crack growth rate are strongly influenced by factors such as weld residual stresses, the environment in the nozzle-head annulus, and the number of initiation sites. Until such time as these issues can be further quantified, justification for structural margin can only be approximated through application of engineering judgement (see #8).

6. Potential for On-line Monitoring for Leakage or Cracking - On-line monitoring for leakage or cracking is technically feasible. In the case of leakage monitoring, EDF has employed on-line systems for French plants which are based on detection of N-13. Sensitivities of detection to 1 liter/hour have been demonstrated. However, the total leakage from the largest through-wall crack at Oconee as determined by the amount of boric acid present was probably less than 4 liters. In the case of on-line monitoring for cracking, acoustic emission has been demonstrated to work in crack detection/propagation in a nuclear plant application, but not specifically for cracking in VHPs. The expert group considered that implementation of such technologies would require development efforts for application to U.S. PWRs that would preclude their effective use in the near-term.

7. Probabilistic Risk Assessment - Existing PRAs do not explicitly address these types of initiating events, but combine them with other possible reactor coolant system breaks of similar size. The estimation of event frequency, and the probability of recovery actions given the break location, were hampered by a lack of relevant information. Accordingly, the staff focused on the conditional core damage probability (CCDP), basically an estimate of the emergency core cooling system failure probability, given one or more CRDM failures. The major contribution to the CCDP would be from the resulting small to medium break LOCA. Additional considerations include the potential for damage of other rod assemblies, clogging the sump by dislodged insulation, and design, configuration, and alignment of engineered safety features (ESF). NRC is in need of

additional plant-specific information from the industry to enable more accurate determinations in this regard.

8. Summary - An estimate of the CCDP suggests the need for heightened attention as manifested by the issuance of NRC Bulletin 2001-01. Thus, further consideration must be given to the initiation frequency, which brings the focus to the cracking phenomenology and crack growth rates. In that regard, the appropriate technical approach would be to use probabilistic fracture mechanics (PFM). RES has initiated an effort aimed at modifying the PFM code PC-PRAISE to try to address the issue in a more quantitative manner. However, it should be re-emphasized that there are significant uncertainties in the inputs which will likely limit the usefulness of the results in a strictly quantitative sense. In addition, this effort will likely require 3-6 months to produce meaningful results.

In the interim, a cracking hypothesis can be formed that involves the following assumptions: (1) the Oconee cracking is representative of the "worst-case," in the industry, (2) cracking initiates preferentially at multiple OD locations with high residual stresses (likely 1-2 quadrants - upper and lower hillside regions); (3) cracking progresses preferentially around the circumference instead of through-wall (expectation from fracture mechanics, consistent with Oconee experience); (4) crack growth rates are approximately 1-inch/year, and (5) the progression of the cracking relieves residual stresses.

If the above assumptions hold, the crack driving force would tend to decrease as the cracking extends until it penetrates through-wall to a significant extent. At this point, the crack driving force would increase again till failure. In this case, cracking on the order of that experienced at Oconee 3 would be predicted to take in the range of 6 months to over 1 year to grow to a point where the structural margin was compromised and on the order of 15 months to several years for the crack to grow to the point where failures would occur under normal operating loads. This evaluation requires application of engineering judgement and is highly uncertain. The most difficult assumption to justify, without additional inspections, is that the Oconee crack is the "worst case" crack that exists at this time. However, even a 250° through-wall crack would probably require 6 months or more to grow to failure under pressure loads. We plan to refine our assessment and the need for additional work after reviewing the industry responses to NRC Bulletin 2001-01.

Attachment: As stated
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