UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C 20555-0001

September 7, 2001

MEMORANDUM TO: Samuel J. Collins, Director
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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

B-26

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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ATTACHMENT

TABULAR SUMMARY OF PERSPECTIVES AND COMPARISON WITH INDUSTRY POSITIONS

Issue	Industry Position	Experts Opinion	Staff Assessment
1. CRDM Critical Circumferential Through-Wall Crack Length	273 degrees around the circumference at 3 times the operating pressure.	271 to 277 degrees at 3 times operating pressure. 225 to 90 degrees for combined through-wall and surface flaw geometries. Further work is needed to evaluate time estimates for single or linked flaws to reach a critical length in the environment of the annular gap.	Based on the information presented by the industry and the independent experts opinion on issues 1- 5, the staff believes that: • Detectable leakage can occur at crack lengths smaller than a critical crack length. • The average time between plant outages is potentially less than the time required for a crack to reach a critical size. • The remaining lifetime of a 165° through-wall crack ranges between 1.5 - 6 years • Additional confirmatory work will be needed.
2. Crack Growth Rate	Relief of residual stress due to opening of the crack retards or terminate further crack growth. 6 years is required for crack to grow through wall. A circumferential crack is unlikely to propagate through the wall and grow along the nozzle-weld contour.	Restrained bending condition limits crack growth. Weld residual stresses will be the primary driving force. Rates of residual stress relaxation expected to accompany crack growth are unknown. The CGR can be accelerated in acidic or basic solution, and presence of sufficient stress. Above certain crack opening, the environment seen by the crack would be controlled by the primary coolant chemistry. Simple fracture mechanics models may underestimate crack growth if multiple cracks initiate and link.	

Issue	Industry Position	Experts Opinion	Staff Assessment
3. **Susceptibility Ranking and Activation Energies**	Primarily based on time and temperature. The activation energy (Kcal/mole °C) crack initiation ~ 40 - 50 crack growth ~ 30 -35	The proposed ranking in terms of susceptibility based on operating temperature is reasonable. Activation energy is appropriate.	
4. **CRDM Crack Leakage**	Annular average interference gap will contribute to leakage if the crack length in the tube is greater than some value.	Leak rate analyses, which consider crack-opening displacement, surface roughness, number of turns, and actual flow path to thickness length indicate that a detectable leakage would occur from the crack. Thermal expansion between the penetration and the RPV head creates an annular gap for leakage. Ovalization of the nozzle head penetration will affect the dimensions of this gap. An interference fit may occur at operating temperature, hence significantly blocking leakage; but could provide detachment restraint.	

Issue	Industry Position	Experts Opinion	Staff Assessment
5. **Plugging of Leakage Path**	Boric acid plugging the crack is unlikely. System pressure will sweep out deposited boric acid.	For a 180-degree crack, and for water quality < 100%, boric acid stays in solution. No concern of boric acid plugging the crack. Plugging from other corrosion products needs to be evaluated.	
6. **Adequacy of Visual Inspection to Detect CRDM Cracking**	VT-2 can distinguish between boron deposits from CRDM cracks and other non-relevant deposits.	Boric acid deposits from prior leaks from other sources could challenge the ability to detect leaks from the VHP crevice if the vessel head has not been cleaned. Requires adequate access to inner rows of CRDMs and good illumination. If only a small amount of leakage escapes the crevice there is less confidence in the visual examination.	NRC Bulletin 2001-01 indicates the need for use of qualified inspection techniques for certain categories of plants.

Issue	Industry Position	Experts Opinion	Staff Assessment
7. **CRDM Crack Detection (Eddy Current , Ultrasonic, and Penetrant Testings)**		ET is adequate for detecting and length sizing through-wall cracking initiated from the ID of the nozzle. UT can be used to confirm length measurements and provide depth estimates. Adaptive scanning is needed to accommodate the complex shape of *J*-groove. UT using time-of-flight diffraction should work for OD PWSCC.	
8. **Can OD PWSCC in CRDM Nozzle Grow Through-Wall without Leaking?**	System pressure will prevent blockage of the crevice	Requires blockage of the crevice immediately after sufficient concentration of lithium hydroxide and boric acid is formed and enough steam or water is also trapped to provide the environment in which cracking can occur in the outer surface of the CRDM nozzle.	Expert analyses and opinions suggest that the concentration mechanism for boric acid is not probable and boric acid should remain in solution in the crack plane. However, the possibility of prohibiting leakage still exists due to potential for interference fits at temperature and the possibility of plugging from other corrosion products (see Issue 5).

Issue	Industry Position	Experts Opinion	Staff Assessment
9. **CRDM Sampling Inspection**	Being evaluated	Considerations include: • Technical and statistical basis for the sampling plan • Residual stresses and weld repair effects (e.g highest residual stresses are associated with the outermost penetrations.) • Sporadic instances of cracking can be expected to occur.	Recognizing the risk perspective (Issue 11), and the required time to inspect ~ 70 CRDMs per plant, a sampling inspection would be considered. However, statistical analysis and operating experience do not support sampling inspection.
10. **Leak Detection Equipment**	Industry is looking into availability and efficacy of several detection technology.	Equipment capable of detecting small leakage are available • 0.5 gpm-acoustic emission • <0.2 gpm visual • 0.026 gpm humidity • 0.0044 gpm N_2-13	Techniques are available, but not for near term implementation. Potential implementation would be driven by the need for qualification and the associated costs to the industry.

Issue	Industry Position	Experts Opinion	Staff Assessment
11. Risk Implications	Under development	Existing PRAs do not explicitly address these types of initiating events, but combine them with other possible RCS 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 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.	Staff concurs with expert group evaluation. NRC is in need of additional plant-specific information from the industry to enable more accurate determinations in this regard.