December 20, 2001

MEMORANDUM TO: William H. Bateman, Chief
Materials and Chemical Engineering Branch
Division of Engineering

FROM: Jacob I. Zimmerman, Project Manager ***/ra/***
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SUBJECT: SUMMARY OF NOVEMBER 8, 2001, MEETING WITH NUCLEAR ENERGY INSTITUTE, MATERIAL RELIABILITY PROGRAM, AND OPERATING PRESSURIZED WATER REACTOR LICENSEE'S ON BULLETIN 2001-01, "CIRCUMFERENTIAL CRACKING OF REACTOR PRESSURE VESSEL HEAD PENETRATION NOZZLES" (TAC NO.: MB2060)

On November 8, 2001, members of the U.S. Nuclear Regulatory Commission (NRC) staff participated in a public meeting held at the NRC offices in Rockville, Maryland, with representatives from the Nuclear Energy Institute (NEI), Material Reliability Program, various operating nuclear reactor licensees, and members of the public. In addition, the NRC established a telephone conference bridge number, to allow interested individuals to participate in the meeting via telephone. The bridge number was made available prior to the meeting in the meeting notice issued on November 1, 2001. Attachment 1 is the meeting agenda, Attachment 2 provides the meeting slides, and Attachment 3 lists the meeting attendees and those participating via telephone.

The purpose of the meeting was to discuss NRC staff's preliminary technical assessment for vessel head penetration nozzle cracking associated with NRC Bulletin 2001-01, "Circumferential Cracking of Reactor Pressure Vessel Head Penetration Nozzles."

Jack Strosnider, Director, Division of Engineering in the NRC's Office of Nuclear Reactor Regulation (NRR), informed those in attendance that the technical assessment was preliminary and he welcomed any feedback or new information based on external stakeholder review. In addition, Mr. Strosnider stated that the preliminary technical assessment is generic, and that licensees should contact their project managers if they wish to discuss plant-specific issues.

Allen Hiser, lead technical reviewer, with the Materials and Chemical Engineering Branch of the Division of Engineering, presented an overview of the Bulletin, and included a summary of the plants that have conducted bare metal visual examinations. This summary listed the total number of cracked or leaking CRDM nozzles, the number of circumferential nozzle cracks, and the number repaired for each plant that has been inspected.

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Dr. William Shack of Argonne National Laboratory presented his results regarding crack growth rate (CGR), crevice chemistry (environment in the CRDM annulus region), and probabilistic models for crack initiation. Dr. Shack showed a plot of crack growth rate as a function of stress intensity factor (K). The data were from heat 69, which is highly susceptible to primary water stress corrosion cracking (PWSCC). The CGR equation used was the modified Scott correlation: $da/dt = A(K\text{-}9)^{1.16}$ with an A value equal to $5.5\text{x } 10^{-12}$. The overall data set was limited, however, weighting the data by heat provided a better picture of CGRs and dependence on K and temperature. **<u>Action Item</u>:** Dr. Peter Scott, Framatome ANP, suggested that the staff go back to the CGR equation that was developed for steam generators since it involves a larger data set. Dr. Scott did not see product form as an issue, but stated that the degree of cold work is an issue. He also suggested that more data are available on heat 69 from three additional laboratories. With regard to crevice chemistry. Dr. Shack concluded that once a significant through wall crack has formed, the crevice has good communication with the bulk and the water chemistry is more likely to be close to primary water (i.e., not expected to be highly aggressive) and, more importantly, the crack growth rate is likely to be affected by less than a factor of two. For the probabilistic crack initiation model, Dr. Shack concluded that operating experience of leaking nozzles appears to be well modeled by the Weibull analysis with a slope b=1.5, however, new information from the industry will continue to be assessed. **<u>Action Item</u>:** Dr. Peter Scott suggested that the staff use a 3 parameter Weibull equation. Dr. Scott also suggested that it may be possible to benchmark the equation using French data.

Dr. Gery Wilkowski from Engineering Mechanics Corporation of Columbus, Ohio, presented his results on critical crack size, stress analysis, crack-driving force, and leak rate analysis. In order to determine critical crack size, Dr. Wilkowski used a restrained-bending limit load solution with a definition of flow stress equal to yield plus ultimate stress divided by 2.4, which comes from pipe tests with similar loading. The resulting throughwall critical crack size with a safety margin of three on pressure is 270°. The critical size for nozzle failure and possible ejection is 324°. For stress analysis and crack-driving force, a single estimate for K as a function of circumferential crack length was provided, with a value of 66 MPA√m (60 ksi √in.) due to residual stresses for a crack angle of 90°. Dr. Wilkowski also had some suggested improvements to the stress analysis. For example, weld sequencing effects may have an impact on crack-driving force since high stress spots can exist at the 0° and 180° locations. Steve Fyfitch from Framatome stated that exploring weld sequencing is a "lost cause" since welding of CRDMs was a manual process where welders started and stopped at their own discretion. **<u>Action Item</u>:** Mr. Fyfitch mentioned an Electric Power Research Institute (EPRI) stress analysis workshop in the early 1990's which is documented in a report. The staff requested an exact reference for this report. In response to a question from the phone bridge, Dr. Scott stated that thermal fatigue inside the reactor vessel head had been investigated and the effect of small cyclic stressed on PWSCC is minimal compared to other factors. Cyclic stresses have more of an effect on crack initiation than on crack growth.

Allen Hiser presented the staff's preliminary deterministic and probabilistic assessment. Mr. Hiser first summarized staff conclusions on annulus environment, crack initiation, crack growth rate, stress analysis and crack-driving force, and critical crack size as discussed in Dr. Shack's and Dr. Wilkowski's presentations. Mr. Hiser then outlined the deterministic assessment and the base case assumptions. The critical flaw size is 270° with a safety margin of 3 on pressure. The critical size for nozzle failure and possible ejection is 324°. The 95/50 statistical bound was used for 318°C (605°F), and the resultant A value for the Scott model is 1.303×10^{-11} .

The initial flaw size is unknown, but was used as a parameter in sensitivity studies. Specifically, the sensitivities studies focused on different statistical bounds (mean, 95/50, and 95/95 curves), effects of temperature on CGR, and initial flaw size. The estimated K for a CRDM nozzle based on Structural Integrity Associates (SIA) and Oak Ridge National Laboratory (ORNL) results is 60 ksi √in. for 90° (45° crack half angle as shown in Figure 15 of the meeting slides). The presentation included a summary of outer diameter circumferential flaws identified at Oconee Units 2 and 3 and Crystal River Unit 3 during spring and fall 2001 outages. The evaluation of operating time to reach critical flaw sizes at 3 times design pressure and at nozzle failure/ejection after development of a 165° long circumferential through wall flaw is approximately 30 months (three times design pressure) and 42 months (nozzle failure/ejection).

Figure 23 of the presentation showed a crack growth analysis using various CGR assumptions with an initial flaw size of 165° (the largest circumferential flaw reported to date). Decreasing the temperature has some effect on CGR, but the most significant increase in failure times occurs with the mean crack growth curve instead of the 95/50 curve. Figure 24 compares the time to reach the flaw size representing 3 times the design pressure for a variety of CGRs as a function of initial flaw size. Figure 25 compares the time to reach the flaw size representing nozzle failure/ejection for a variety of CGRs as a function of initial flaw size. The 95/95 curve is the most restrictive when compared to the 95/50 and high mean curves. For the deterministic evaluation, Mr. Hiser concluded that the results are sensitive to initial flaw size, the statistical bound (95/95, 95/50, or high mean), and the temperature. He stated that due to the lack of industry data, use of the 95/95 or 95/50 curves is not unreasonable. He also reiterated Mr. Strosnider's point at the beginning of the presentation that traditional safety margins may not be sufficient to account for large variability in CGRs for Alloy 600 in PWSCC conditions.

With regard to the probabilistic assessment, Mr. Hiser stated that it is in progress, however, a complete model would require a better understanding of the complete cracking process and data to characterize the means and statistical bounds critical parameters.

Mr. Hiser stated that eight out of nine of the high susceptibility plants have identified cracking, and that effective visual examinations will provide additional data for the moderate susceptibility plants. The high susceptibility plants that have performed effective inspections can use Figures 24 and 25 to determine adequate inspection timing based on an assumed initial flaw size, however, new circumferential cracking can initiate. High susceptibility plants that have not performed effective inspections need to perform a baseline inspection to provide a basis for their evaluation. The qualified visual examination, as discussed in Bulletin 2001-01 is appropriate as well as additional surface or volumetric examinations (e.g., eddy current or ultrasonic examinations). The inspection scope must include the entire surface or metal volume of interest of 100 percent of nozzles. The "wetted surface" includes the J-groove weld, the nozzle outer diameter (below the weld), and the nozzle inner diameter to a location above the weld. For volumetric examination, the critical location is the outer diameter of the nozzle above the J-groove. The visual qualification analysis (plant-specific) can occur after the inspection.

Mr. Hiser concluded his presentation with future staff plans and industry interactions. The staff plans to continue development of probabilistic modeling, complete the review of the Bulletin 2001-01 supplemental responses, assemble findings from inservice inspections, issue a NUREG report, and engage licensees on long-term inspection plans. Additional industry and staff interaction, which includes refined deterministic and probabilistic analyses, determination of inspection methods and findings, and destructive confirmations (e.g. flaw sizes, annular conditions) is necessary to further understand this phenomenom.

Mr. Strosnider concluded by stating that this preliminary technical assessment is generic, and licensees need to look at past inspections for plant-specific assessments. Mr. Strosnider stressed that Bulletin 2001-01 was a one-time action, and that industry needs to address long term actions. Mr. Strosnider indicated that the NRC eventually wants to develop the information that we have into a Regulatory Guide 1.174 framework, however, additional industry data is needed.

The staff will schedule further meetings with industry, as necessary, to facilitate the timely exchange of technical information and to assure that stakeholders are kept informed of the status of the issue in the regulatory process.

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