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SUBJECT: Status of EPRI Materials Reliability Project's Industry Program on Alloy 600 Reactor Vessel Closure Head Penetrations

PROJECT NUMBER: 689

This letter provides an update of the EPRI Materials Reliability Program (MRP) CRDM / Alloy 600 Issue Task Group (ITG) activities. This status may be of interest to the NRC since most licensees referenced the ITG integrated Alloy 600 closure head program in the response to Generic Letter (GL) 97-01, *Degradation of Control Rod Drive Mechanism Nozzle and Other Vessel Closure Head Penetrations*. The letter reviews recent and current projects and discusses the status of the industry's Alloy 600 head penetration inspection program.

Enclosure 1 provides the status of the ITG tasks related to the vessel closure head penetrations.

Enclosure 2 provides a summary of the head penetration inspections that have occurred since the ITG last briefed the NRC staff in February 1999. A review of the results concluded that no changes to the predictive model were warranted. The results from those recent inspections were consistent with the existing model predictions.

Recently, the MRP revised the susceptibility histogram to better support license renewal activities. Using the original susceptibility calculations, the revised histogram subdivides the original *greater than 15 effective full power years* category into five new subdivisions. This will better support plant management decisions relative to units that are predicted to exceed the acceptance criteria during the license renewal period.

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The MRP has tabled an earlier plan to consolidate the two predictive models into one. This change occurred because the current system of normalizing the two models to the results at D.C. Cook 2 is working well, and the benefits of merging the two independent models do not outweigh the corresponding cost.

Four additional inspections of reactor closure head penetrations are planned as part of the integrated industry inspection program. These inspections are at:

- Crystal River 3 (B&W design),
- Diablo Canyon 2 (Westinghouse design),
- Farley 2 (Westinghouse design), and
- San Onofre 3 (CE design).

Additional plants may perform reactor closure head penetration inspections in the future, consistent with any commitments made during the review of license renewal applications. The MRP will evaluate the results of all inspections as they occur.

By the end of 2001 the remaining CRDM / Alloy 600 Issue Task Group activities will be transferred to the MRP Technical Support Subcommittee (TSS). This change reflects the completion or near completion of the ITG tasks. The TSS is the MRP group that provides management oversight of material-related tasks with a level of effort not warranting a separate ITG. The MRP will keep the NRC staff informed of future significant head penetration activities and conclusions.

The MRP and industry remain committed to managing the potential for Primary Water Stress Corrosion Cracking of reactor closure head penetrations and the broader issue of Alloy 600's aging management.

Please direct questions regarding the MRP efforts to Kurt Cozens (202 739-8085, koc@nei.org).

Sincerely,

David J. Modeen

KOC/maa
Enclosures

c: Mr. Bill Bateman, U. S. Nuclear Regulatory Commission
Mr. Jim Medoff, U. S. Nuclear Regulatory Commission
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Enclosure 1

STATUS OF THE CRDM / ALLOY 600 ITG TASKS

ACTIVE TASKS

- ***Alloy 600 PWSCC Crack Initiation Mitigation Testing:*** This project includes the following activities:

  - Evaluation of the relative effectiveness of a number of surface modification techniques to extend PWSCC crack initiation time in reactor vessel head (RVH) penetrations,
  - Demonstration of the effectiveness of a weld repair technique for reactor vessel head penetration PWSCC, and
  - Benchmarking of test data with previously established test and field data.

  The candidate mitigation techniques being tested are:

  - Electroless nickel plating
  - Shot peening
  - Gas tungsten arc welding (GTAW) excavation weld repair
  - Electro-mechanical brush plating
  - Laser cladding
  - Waterjet surface treatment
  - Electrical discharge machining (EDM) skim cut
  - Flapper wheel surface polishing
  - Two laser weld repair techniques
  - A review of other research regarding zinc addition

  Each technique was tested using two to three material heats. Similar techniques sponsored by different vendors were tested using the same heat in order to facilitate appropriate comparisons. The ring specimens for the tests were fabricated from archived B&W Tubular Products materials and actual nozzle materials cut from the Ringhals 2 (Sweden) and Jamesport reactor closure heads.

  The program consisted of a matrix of accelerated crack initiation autoclave tests performed by Westinghouse using high-stress ring specimens of representative nozzle materials in a doped steam environment. The ring specimens used for the testing were developed specially for the mitigation testing program (four ovalization cycles were used, machining was performed to reduce stiffness, and an ovalization fixture was used to retain stresses). Dye penetrant testing of the specimens was performed periodically (and captured digitally) to detect crack initiation during the testing.

Testing was initiated in April 2000. Westinghouse will analyze the test data in Fall 2000 to rank the effectiveness of the remedial techniques. A final EPRI technical report will be issued by mid-2001.

- ***Survey Report of Alloy 600 PWSCC Experience:*** This project will produce a comprehensive summary of domestic Alloy 600 degradation experience in PWR primary systems (not including steam generator tubing). The survey report will serve as an authoritative, organized reference for plant engineers, bringing together in one place the practical plant experience regarding PWSCC into one place. The report will include how each occurrence of PWSCC was identified, the extent of the degradation (e.g., number of flaws, flaw geometry and morphology), and the repair/remedial approaches taken. Additional available information such as properties of the affected material and relevant fabrication information will be included as appropriate.

  The survey report will be published by EPRI in the first half of 2001.

- ***Inspection and Evaluation (I&E) Guidelines for PWSCC of Reactor Closure Head Nozzles:*** The objective of this project is to provide utilities with voluntary guidance for the management of PWSCC of reactor vessel closure head penetration nozzles, including available inspection techniques, evaluation of inspection results, and disposition of indications. For example, appropriate crack growth rate experience will be provided in the guidelines to provide utilities a basis for dispositioning any detected cracks.

  The guidelines will take into account appropriate domestic and international industry and laboratory experience and will support license renewal efforts.

  A focus group within the CRDM/Alloy 600 Issues Task Group will oversee the development of the guidelines, which are planned for release in 2001.

- ***EDF Testing Program for Crack Growth in Alloy 182 Weld Metal:*** The MRP is evaluating the recent results of a large Electricite de France (EDF) laboratory program to obtain Alloy 182 PWR primary water crack growth data. Laboratory testing was performed by EDF and two other European laboratories. The study also included crack growth data available in the literature.

  The EDF study evaluated the effects of the main engineering parameters on the crack growth rate including temperature, stress intensity factor, heat treatment, cold work, chemical composition, and orientation of the dendrites. The EDF study proposes a model of propagation in Alloy 182 that incorporates the influence of all the parameters of the study. The model conservatively fits the experimental data within a factor of two to three. The investigators found similar crack growth behavior for Alloy 182 weld metal compared to Alloy 600 with regard to temperature, stress intensity factor, cold work, and cyclic loading.

In addition, EDF demonstrated a beneficial effect of stress relief and significant effects of dendrite orientation and heat-to-heat variation on crack growth rate for Alloy 182. The crack growth rate parallel to dendrites was found to be up to five times that across dendrites. Finally, the investigators also examined tests performed by ETH using Alloy 82-weld metal, but no crack propagation was observed in these tests.

The plan is to publish this work in an ERPI report by mid 2001.

COMPLETED TASKS

- ***2000 EPRI Workshop on PWSCC of Alloy 600 in PWRs:*** In February 2000, EPRI held an industry conference on Alloy 600 PWSCC in reactor coolant system components, other than steam generator tubing. This was the fifth EPRI PWSCC workshop at which experience and technology within the domestic and international industries was shared. Presentations were given regarding recent industry experience, as well as new developments in inspection, repair and remedial measures, crack initiation and growth testing and modeling, and strategic planning. PWSCC experience regarding small-bore Alloy 600 penetrations in pressurizers and reactor coolant system piping was discussed in addition to experience regarding reactor closure head nozzles.

  The workshop proceedings will be published at the end of 2000 as EPRI TR-1000873, *Proceedings: 2000 EPRI Workshop on PWSCC of Alloy 600 in PWRs.*

- ***Alloy 600 PWSCC Crack Initiation Testing Program:*** A cracking susceptibility test program was performed to characterize the relative susceptibility to crack initiation of Alloy 600 reactor vessel head (RVH) penetration material heats, and to correlate behavior with material type and microstructure.

  Ten Alloy 600 heats (multiple B&W Tubular Products, Huntington Alloys, and Schneider-Creusot heats) and one Alloy 690 heat were tested. Ring specimens were sectioned from archived RVH penetration materials and then ovalized to simulate residual nozzle stresses. Autoclave tests were performed for 750 hours in 400°C doped steam (30 ppm chloride, fluoride, and sulfate) and hydrogen to produce accelerated PWSCC. Intermittent dye penetrant testing was performed to detect SCC initiation.

  Materials with higher grain boundary carbide (GBC) coverage and relatively large grain size distribution generally showed lower susceptibility to SCC. In addition, the Weibull test data exhibited a crack initiation slope that was lower than anticipated. Consequently, quantitative comparisons between materials were difficult. However, results of this study were adequate to establish groupings of relative susceptibility. In addition, cracks did not initiate in the Alloy 690 material during the tests.

The results are documented in EPRI Technical Report TR-108970, *Evaluation of Crack Initiation in Alloy 600 Reactor Vessel Head Penetration Materials.*

- ***Alloy 600 PWSCC Crack Growth Rate Testing Program:*** In 1997, Westinghouse completed a study on crack growth and microstructure in Alloy 600 PWR vessel head penetration materials. This study, which began in 1992, used a large number of samples fabricated from archived heats corresponding to actual reactor vessel head penetrations. The crack growth rate tests were performed using a reverse DC potential difference crack monitoring method on 1/2T compact tension (CT) samples tested at 290–330°C in water with 1200 ppm boron, 2 ppm lithium, and 25 cc/kg hydrogen.

  Results were reported to be consistent with the Scott correlation of crack growth rate versus stress intensity, although enhanced growth rates were observed in two material heats that exhibited low grain boundary carbide coverage.

  The results are documented in EPRI Technical Report TR-109136, *Crack Growth and Microstructural Characterization of Alloy 600 Vessel Head Penetration Materials.*

- ***EDF Plant Measurements of Crack Growth in Alloy 600 CRDM Nozzles:*** The MRP is evaluating results from a large EDF program that measured growth rates of CRDM nozzle service cracks. A total of 180 cracks (in 27 nozzles on 15 vessel heads) were monitored via successive ultrasonic inspections performed during two or three refueling outages. The maximum depth propagation rate observed over a single operating cycle was 0.46 μm/hr (3.5 millimeters during a 7660 hour operating cycle). The average of the maximum depth propagation rate for each nozzle in one cycle was 0.18 μm/hr. The average depth propagation rate for all cracks (92 pairs of depth measurements) was 0.12 μm/hr (with a standard deviation of 0.1 m/hr).

  To compare the EDF data to domestic laboratory measurements, the MRP has evaluated the EDF data in terms of stress intensity factors. This comparison has shown the EDF crack growth experience to be generally consistent with the domestic crack growth laboratory testing.

  A final report for this task was published EPRI Technical Report TR-114757, *Cracking in Vessel Head Adaptors: Analysis of Crack Growth Rate Reports (PWRMRP-12).*

- ***Alloy 182 Weld Metal PWSCC Crack Growth Rate Testing:*** This study examined the effects of temperature, stress intensity factor, material heat, and weld dendrite orientation on the crack growth rate in Alloy 182 weld metal.

  Westinghouse tested weldments prepared with standard materials and procedures used to construct pressure vessels. Results for 17 specimens from

three heats were reported. Compact tension specimens were machined from weldments in several orientations, pre-cracked, and tested in an autoclave in PWR water under active loading. Crack growth was measured on-line during the tests, and crack extension was measured with a scanning electronic microscope (SEM) at the conclusion of the tests. The SEM was also used to characterize crack morphology.

The main testing conclusions were:

- Interdendritic crack growth was observed in all specimens.
- Crack fronts were uneven on all Alloy 182 specimens and—in contrast to previous tests with Alloy 600—were non-planar in some cases.
- Alloy 182 crack growth rates were up to a factor of five higher than the crack growth rate in Alloy 600.
- The effects of temperature and stress intensity factor on Alloy 182 crack growth rate were similar to those on Alloy 600.
- A significant effect of crack orientation relative to weld dendrite orientation was observed: the growth rate parallel to weld dendrites was five to ten times higher than the growth rate around dendrites.

The results were published as EPRI Technical Report TR-1000037, *Crack Growth of Alloy 182 Weld Metal in PWR Environments (PWRMRP-21).*

- ***Susceptibility Models for PWSCC of Reactor Closure Head Nozzles:*** Two computational tools—the EPRI and Westinghouse models—were developed to perform plant-specific, probabilistic assessments of the susceptibility to SCC of reactor closure head nozzles. These models were used to rank plant susceptibility in support of the industry response to Generic Letter (GL) 97-01 and are being used to evaluate the results of industry inspections. The results of such evaluations will be used to determine whether changes to the models or their assumptions are warranted in the future.

  The EPRI model was incorporated into a module of the EPRI CHECWORKS software suite. This software allows individual plants to evaluate various reactor closure head nozzle inspection and repair strategies based on the predicted probability of deep cracking and net present value cost analysis.

Inspection Results

Licensee responses to GL 97-01 included consideration of the ITG's industry-wide histogram of plant susceptibility to reactor closure head nozzle PWSCC. The histogram, developed in 1998, was based on the predictive models developed by EPRI and Westinghouse. Its purpose is to provide a relative ranking of the domestic PWR units in order to prioritize inspections. Since the original histogram development, additional head penetration inspections have been performed: an initial CRDM nozzle full inspection at one U. S. plant and a follow-up inspection at another.

The following inspections were recently performed:

Plant	Penetrations Inspected	Findings	Year of Inspection
Ginna (Westinghouse design)	38	Found indications in a single penetration located in the second nozzle row from the outside. The indications were too shallow (less than 2 millimeters deep) to be sized by ultrasonic testing (UT)	1999
Oconee 2 (B&W design)	Nozzles No. 23 and No. 63 (contained previously identified shallow indications) plus 6 other penetrations	No indication growth since 1994 was detected in penetrations 23 and 63. This reconfirmed the finding of the first re-inspection of these nozzles performed in 1996. The other six penetrations had NDE responses similar to that observed in 1994.	1999