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Analyses of Core Shroud Vertical Weld Boat Samples from Nine Mile Point Unit 1

Technical Report No. 97181-TR-01
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prepared for:

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Nine Mile Point Unit 1

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Evaluation of Metallurgical Analyses of Core Shroud Vertical Weld Boat Samples from Nine Mile Point Unit 1

Overview

The following is a summary of key observations identified during a metallurgical investigation of two boat samples removed from the Nine Mile Point Unit 1 (NMP1) core shroud. The investigation was conducted by McDermott Technologies in their hot cell facilities at the Lynchburg Research Center (LRC). Results clearly indicate metallurgical evidence that is consistent with an intergranular stress corrosion cracking (IGSCC) failure mechanism. This finding confirms the analyses submitted to the Nuclear Regulatory Commission. No metallurgical evidence supporting an irradiation-assisted mechanism was observed. These findings are consistent with the mechanistic understanding of IGSCC initiation and growth processes for Boiling Water Reactor (BWR) core shrouds (BWRVIP-14).

Background

Crack-like indications were observed on the outer surface along the length of welds V-9 and V-10 using enhanced visual inspection techniques consistent with recommendations developed for the BWROG Vessel Internals Program. Visual indications were confirmed using remote ultrasonic testing methods, and crack depths were determined along the lengths of the vertical welds by measuring from the outer surface using UT sizing methods. The General Electric Company (GE) developed specific equipment for core shroud examinations including the Trimodal Core Shroud search unit, the GE Smart 2000 ultrasonic examination system, and the GE Suction Cup Scanner.

The cracks on the right side of weld V-10 (viewed with the shroud oriented vertically) are reasonably represented by a single continuous crack indication running parallel to the weld. The cracks are essentially bounded within a volume of material adjacent to the weld fusion interface known as the heat affected zone (HAZ). Crack depths typically were measured from 0.4 to 0.7 inches, although several specific locations along the length of the weld were deeper. In general the cracking was slightly deeper towards the top of the vertical weld. Eight short crack segments (parallel to the weld) were seen on the outer surface to the left side of weld V-10.

Cracking patterns are similar on the outer surface of weld V-9 except that cracking was predominantly on the left side of the weld. [Note: There were two short crack segments on the right side originating at the inner surface, and these were the only inner surface cracks associated with the vertical welds, V-9 and V-10.]

This metallurgical evaluation examined two boat samples taken from welds designated as V-9 and V-10 located in the central-mid-cylinder shell course which is located at approximately the core mid-plane. Boat sample V-10 contained a sample of the crack and was taken from the **outer surface** of weld V-10. The sample location was on the right side of the weld approximately 57.5 inches below the upper horizontal weld, H-4. Sample V-10 was used primarily to document the metallurgical features associated with the cracking of the vertical welds. This location was selected to ensure that the crack tip would be captured in the boat sample. Boat sample V-9 was not cracked, and was removed from the **inner surface**. It was located to the right of weld V-9 at an elevation approximately 25 inches below the upper horizontal weld, H-4. This latter sample represented a high fluence location and was used to determine if the accumulated fluence resulted in observable effects on material sensitization.

The cracking found on the outer surface of vertical welds V-9 and V-10 was oriented predominantly parallel to the length of the weld. The more extensive cracking on the V9 and V10 welds was biased toward the plate from which the V-10 boat sample was removed. The V-9 boat sample was taken from the other plate which makes up the central mid-cylinder section. This provided for comparison of the two heats of material in the analysis.

Analysis

A metallurgical investigation was conducted on the two boat samples removed from the NMP1 core shroud. The purposes of the investigation were to confirm that IGSCC was the mechanism for cracking, to determine if irradiation assisted stress corrosion mechanisms were involved, and to validate the crack depth measurements.
The following tasks were accomplished:

- Receipt of photographic documentation of both boat samples shipped from the site
- Sectioning the boat samples for examination of both cracked and uncracked locations,
- Documentation of microstructural features of both samples,
- Evaluation of individual cracking morphologies and patterns,
- Microhardness measurement profiles at selected locations,
- Chemical analyses of boat samples,
- Examination of oxides present on surfaces of cracks, and
- Documentation of microstructural evidence for sensitization in each sample.

Additional investigation topics will be completed and submitted by November 30, 1997 that will measure fluence associated with three different thickness locations of each sample (Fluence measurements are being conducted by Framatome Technologies Inc.), tensile properties and fracture toughness associated with the highest fluence sample, and electrochemical potentiokinetic reactivation (EPR) testing.

The following key observations are made from the results of the metallurgical investigation of the boat samples removed from the core shroud at NMP1. They include:

Nature of cracking

- All primary and secondary cracking is intergranular.
- Primary crack initiates on the surface and propagates approximately 0.4 inch in depth. This depth is consistent with ultrasonic depth measurements adjacent to the sampling location.
- Multiple primary cracks initiate on the specimen surface (likely branched from the main trunk).
- Primary crack has fractured oxides on crack faces.
- Some secondary cracks propagate approximately perpendicular to the weld fusion line and initiate subsurface.
- Secondary cracks are completely filled with oxides. This characteristic is consistent with a stationary or non-growing crack.
- Grain encirclement is observed surrounding the primary crack.
- Oxides observed near crack tip.

Microstructural Features

- Heavy grinding is present on the outer surface of sample V-10. Microhardness was measured as high as 383 HV near the surface indicating significant cold work at the surface. Microstructural evidence of cold work is seen to a depth of 6 to 7 mils. These surface conditions are favorable for crack initiation.
- Surface microhardness readings as high as 338 HV near the surface of sample V-9 provides evidence of cold work. Microstructural evidence of cold work was measured to a depth of about 2 mils.
- Classical weld sensitization (moderate) is seen in the weld HAZ of boat sample V-10 (crack location).
- Little evidence of sensitization is observed in boat sample V-10 for locations away from weld HAZ.
- The degree of sensitization in the V-9 boat sample, in the location examined, is limited. There was no discernable difference between the HAZ and the base locations based upon the optical metallography.
- It was noted that the response to etching V-9 was slower than that obtained with V-10. Different etching rates are reasonable because the samples are removed from different heats of material.

Microhardness Results

- The maximum microhardness measured near the surfaces of V-10 was 383 HV and for V-9 was 338 HV. This level of hardness at the surface is consistent with the cold worked microstructures seen on the surfaces of both samples.
- Microhardness of the base material ranged from 204 to 247 HV for both plates. These values are consistent with that expected for commercial austenitic stainless steel.

Chemical Composition

- The chemical composition measured in the two boat samples is consistent with the specification for Type 304 stainless steel and confirms the Certified Material Test Reports (CMTRs) for these materials.
- Carbon content was not measured, but CMTRs for the original plates indicated the carbon content was between 0.047 and 0.062 wt. % C.
- The only significant difference seen between the chemistries of the two samples was molybdenum. Sample V-10 had a Mo content of 0.19 wt. %, and sample V-9 had a Mo content of 0.33 wt. %. The presence of Mo tends to increase the tolerance of stainless steel to thermal sensitization, and this helps explain the differences in degree of sensitization between the locations examined for these two plates. [Note: Differences in rates of etching the microstructures were noted above.]

Scanning Electron Microscopy

- Intergranular nature of cracking is confirmed on fracture face.
- Heavy (thick) oxides on the crack faces are iron oxides, likely magnetite (Fe_2O_3).

Conclusions

Metallographic results clearly show the intergranular characteristics of the V-10 sample cracks. Cracking was initiated at a cold worked surface (ground) and propagated within the weld HAZ volume defined by thermal sensitization from welding (approximately .3 inches of the weld fusion line as measured from the V-10 sample). The increased degree of material sensitization in the volume adjacent to the weld and surrounding the crack was noted by comparing grain boundary carbide precipitation near the crack to areas away from the crack. The crack path was characterized by numerous secondary cracks propagating within the HAZ generally towards the weld. Secondary cracks were completely filled with oxides indicating inactivity. The principal crack also had oxides on the faces of the crack, but these were fractured possibly during sample removal and metallurgical sampling. Grain encirclement by corrosion characterized the initial portion of the main crack, but was not characteristic of the deeper portions of the crack.

A team composed of representatives from General Electric Company, MPM Technologies, Altran Corporation, Niagara Mohawk, Framatome Technologies Inc., and McDermott Technology Inc reviewed the metallographic results. Results obtained for these samples were compared to results obtained from boat samples removed from cracked core shroud welds at other plants. It was concluded that the cracking is consistent with IGSCC seen elsewhere. Grinding produced surface cold work which enhanced crack initiation.

The characteristics observed are consistent with the NMP1 operating history in that during the initial 5 fuel cycles the operating conductivity was typically above .3 μS/cm. The crack branching, the grain encirclement by corrosion, and the oxide filled secondary branch cracks are close to the surface supporting a chronology which indicates that the cracks initiated early in the operating history of NMP1. The oxides present in the crack and the presence of oxides near the crack tip also provide evidence supporting this chronology.

Fluence was not a factor in the cracking observed in the V-10 boat sample. [Note: Boat sample V-9 was not cracked.] This conclusion was reached based upon the absence of metallurgical features characteristic of irradiation assisted stress corrosion cracking (IASCC), and from the appearance of the main crack itself. IASCC is characterized by extensive crack tip branching, grain encirclement, and grain drop-out. The review team examined the cracking features developed in this evaluation and compared them to results obtained where IASCC was observed in the core shroud from an overseas plant. The overseas plant cracking features were different from those in the current study in which none of the features uniquely characteristic of IASCC were seen.

Second, grain encirclement was a feature of the main crack at depths near the surface, but the degree to which this feature was present diminished, as the crack grew deeper. Two key factors to consider are 1) fluence is time dependent and increases with time, and 2) the crack is propagating into material that must be at a higher fluence because it is closer to the core. Both of these factors would suggest increased grain encirclement towards the tip of the crack, grain drop-out, and increased branching. None of these characteristics were observed, and thus results suggest that irradiation was not a factor in either initiation or propagation of the vertical weld cracking.

Summary

The metallurgical results of this examination provide confirming evidence that the cracking seen is the result of intergranular stress corrosion cracking similar to that experienced in other BWR components exposed to the oxidizing environment of the BWR.

There is no substantive evidence that irradiation has degraded grain boundaries through irradiation induced chromium depletion. No metallurgical features, uniquely characteristic of IASCC, were found and it was concluded that IASCC was not a factor in the vertical weld cracking at NMP1.

Crack initiation was enhanced on the outside surfaces adjacent to the vertical welds because the surfaces were heavily ground, creating conditions favorable for crack initiation. The GE-Nuclear review of the high magnification photo micrographs concluded that the level of sensitization in the

HAZ is consistent with that expected for 304SS with these carbon levels and is conservative compared to the assumption used in the PLEDGE crack growth analysis, reference 1.

The crack depth measured in the V-10 boat sample is consistent with the ultrasonic depth measurements performed adjacent to the location from which the boat sample was removed.

These findings indicate that the assumptions regarding the level of material sensitization, initiation mechanism and crack propagation used in the analyses of the NMP1 core shroud vertical weld cracking, (reference 1, 2, and 3 and the NRC Safety Evaluation Report, reference 4), are conservative. These findings also confirm that the cracking identified in the NMP1 core shroud vertical welds is consistent with the mechanistic understanding for IGSCC initiation and growth processes for BWR core shrouds as discussed in BWRVIP-14.

References

1. General Electric Nuclear Energy (GENE), "Assessment of the Vertical Weld Cracking on the NMP1 Shroud". GENE-523-B13-01869-043.
2. MPM Technologies, "Analysis of Nine Mile Point Unit 1 Shroud Welds V9 and Weld V10 Cracking", Report No. MPM-497439, April 1997.
3. Altran Corporation, "Nine Mile Point Unit 1 Core Shroud Cracking Evaluation", letter report from Richard E. Smith to George Inch dated April 3, 1997.
4. NRC Safety Evaluation Report dated May 8, 1997, regarding the results of the reinspection of the core shroud for Nine Mile Point 1.