Metallurgical Evaluation of a Feedwater Nozzle to Safe-End Weld from River Bend Station Unit 1

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1. Introduction

A circumferential indication was found by ultrasonic examination (UT) in the N4A-2 inlet feedwater nozzle to safe-end weld during the second refueling outage of River Bend Station Unit 1 in March 1989. The indication, approximately six inches long with a reported maximum depth of 0.2 inches, was located in the Alloy 182 weld butter on the safe-end side of the weld. The reported characteristics of the UT indication were indicative of intergranular stress corrosion cracking. This indication was re-examined during the second and third fuel cycles in March, 1990 and September, 1991, respectively, and during the third refuel outage in November, 1990. Crack growth was reported during each examination. The safe-end was replaced during the fourth refueling outage in the summer of 1992.

The U.S. Nuclear Regulatory Commission (NRC) subsequently contracted with Brookhaven National Laboratory (BNL) to conduct a confirmatory investigation verifying the failure mode and determining the root causes of cracking in the safe-end weld. Gulf States Utilities (GSU) agreed to ship the removed safe-end weld to BNL, after they completed their own non-destructive examination. BNL was to perform a metallurgical examination and failure analysis, including destructive examination of the safe-end weld.

2. Tests and Results

The feedwater nozzle safe-end assembly was labeled with the designation N4A-2. The assembly was packed in a cask for shielding purposes; maximum dose rate at the surface of the cask was 1.0 rem/hr. The N4A-2 assembly was received on September 21, 1993 and placed in a hot cell for examination, where it was unpacked, photographed, and surveyed. Contamination and dose rates are summarized in the table below.

Area	Contamination ($\beta\gamma$,dpm/100cm^2)	Dose Rates
Thermal sleeve exterior	1.1×10^7	1.1 rem/hr β 100 mrem/hr γ
Safe end exterior	2.1×10^6	20 mrem/hr γ
Thermal sleeve interior	7.1×10^5	15 mrem/hr γ

Figure 1 shows several views of the N4A-2 assembly. It was shipped with the thermal sleeve intact, and with such high levels of loose contamination, it was necessary to dedicate the hot cell as a high radiation/high contamination area. The location of the UT indication was such that cutting to remove the section of interest proved extremely difficult, primarily because the thermal sleeve was still present. An automatic feed milling machine was modified by installing a vertical cutting head, and control handle extensions were installed so that remote operations could be conducted, consistent with ALARA policies.

The UT data indicated that the circumferential crack was 8.88 inches long, and the

N4A-2 assembly had been marked with a "V" at one end of the crack, with the apex pointing in the direction of the crack. The piece cut from the N4A-2 weld is shown in Figure 2, a view of the external surface with the "V" showing. The internal surface (Figure 3) was cleaned then treated with dye penetrant (DP) to show if a crack was present. The **DP** indicated a crack 7.0 inches long, starting at a point approximately 2 inches around the circumference from the point of the "V" mark.

After the DP test, the crack was sectioned according to the scheme shown in Figure 4. The central portion of piece E, as subsectioned, was polished and etched to identify weld and base metal phases and to gather microhardness data on these phases. The polished piece was etched electrolytically in a 10% oxalic acid solution. The other part of piece E was split to expose the fracture faces for scanning electron microscope (SEM) examination.

Metallography and Microhardness Measurements

The deepest penetration by the crack, piece E, is shown in Figure 5. The initiating point for the crack is at the interface between the base metal and the weld, and penetrates directly into the weld through 84% of the safe-end/weld thickness (0.92 inches through the 1.09 inch thick wall).

Microhardness results are summarized in Table 1; the corresponding areas tested are shown in Figure 6. Each area tested was chosen because it appeared as a distinct phase after the etch. Table 1 lists the lowest and highest values found in each area, as well as the average values. If the spread in values exceeded 10% in the first three measurements, a total of five tests were made in each area. The Rockwell B and Rockwell C values listed are approximate corresponding values taken from a chart supplied by Buehler, Ltd., the manufacturer of the microhardness tester.

The "softest" areas identified by microhardness tests are Areas 1, 2, and 3, which all exhibited Knoop hardness of approximately 215, within experimental scatter. This is somewhat unexpected, since areas 2 and 3 are Inconel 182 weld material, while area 1 is the safe-end base metal, a carbon steel, ASME 508 class 1, according to the information supplied by the utility, shown here in Figure 7. Hardness values for ASME SA-508 Class 1 are not listed in the specification, but may be estimated from the tensile strength. (Ref. 1). The specification for tensile strength for SA-508 class 1 is 70 to 95 ksi, which corresponds to a Knoop hardness of 165 to 220. As-welded Inconel 82, also referred to as ERNiCr-3 has a specification of 80 ksi, which would correspond to a Knoop hardness of 185. (The conversion to a Knoop hardness may not be appropriate, since the referenced table applies only to steels.) Areas 4 and 5, on opposite sides of the crack, had slightly different hardness of 252.3 and 278.6 on the Knoop scale. Areas 6, 7, and 8 were also within this range.

Figure 7, which presumably was drawn based on the utility's UT data, shows the crack initiating in the Inconel 182 weld material. However, Figure 5 indicates that the crack initiated at the base metal-weld interface, and not in the weld metal.

Table 1
Hardness Test Results

Location (no. of points)	Knoop	Rockwell B	Rockwell C
Area 1 (5)	214.2 ± 13.3	92.6	
Lowest	199.4	89.6	
Highest	232.5	96.3	
Area 2 (3)	216.2 ± 0.8	93	
Lowest	215.3	92.8	
Highest	216.8	93.1	
Area 3 (5)	208.2 ± 14.4	91.3	
Lowest	184.5	86.1	
Highest	222.8	94.3	
Area 4 (5)	278.6 ± 11.1		25.0
Lowest	261.3		22.0
Highest	290.1		27.0
Area 5 (5)	252.3 ± 9.6		
Lowest	239.5	97.7	
Highest	265.0		22.8
Area 6 (5)	276.4 ± 22.4		24.4
Lowest	258.9		21.4
Highest	303.6		28.9
Area 7 (5)	245.4 ± 12.9		
Lowest	233.5	96.6	
Highest	267.1		23.1
Area 8 (5)	241.7 ± 9.8		
Lowest	232.5	96.3	
Highest	256.9		21.1

Scanning Electron Microscopy

The fracture faces obtained from piece E were dipped in Endox solution for 20 minutes to remove any oxide from the material. The appearance of the faces remained blackened after this treatment, so the faces were submerged in Endox in an ultrasonic bath for 3 hours. Even this treatment failed to remove the black colored corrosion product, although it did reduce the amount of loose radioactive contamination present.

Figure 8 shows a view (magnification 30X) of the fracture face. The crack is characterized by two zones of differing morphologies. At the inner surface of the safe-end

weld (the top of the photograph), there is a relatively flat zone, approximately 0.06 inches (1.6 mm) deep. The remainder of the interior of the crack exhibits a columnar morphology typical of inter-dendritic cracking (Ref. 2). Two photomicrographs in Figure 9 display the transition between the two morphologies at 100X magnification.

3. Discussion and Conclusions

Failure of nickel-based weld metal transition welds has occurred at fossil fueled plants. A literature review by Lundin [3] reported that of all utility boilers reporting, 19% had transition joint failures and of this 19% population, only 12% reported failure in nickel-based weld metal.

Ontario Hydro [4] experience with Inconel 182 weld metal has been good with no boiler failures to date; however, the reference discusses the fact that a metallographic examination of sectioned Alloy 182 welds revealed a large incidence of welding defects, typically lack of fusion or root penetration. These defects occur due to inherent problems in making dissimilar welds with these types of alloys. This type of defect is of concern since a crevice is formed at the weld root. A crevice can play a prime role in stress corrosion cracking (SCC) of austenitic stainless steels as well as the nickel-based alloys [5]. The crevice acts not only as a stress intensifier but also as a local area of potential low pH.

The predecessor of Alloy 182 electrode was Alloy 132. This alloy did not prove sufficiently crack resistant for nuclear applications so that Alloy 182 was eventually developed. Manganese appeared to have a significant part in increasing the resistance of Alloy 132 to weld metal cracking when this element was increased [5].

SCC experiments have been performed [6,7,8] on both Alloys 82 and 182 in simulated reactor environments.

In the first series of experiments [6], the susceptibility of Alloys 690, 600, 82 and 182 to intergranular SCC was ascertained in pure water at 288°C. The specimens tested were creviced and non-creviced slow strain rate test specimens, smooth sustained load test specimens and precracked fracture mechanics specimens. The uncreviced specimens were tested in water oxygen levels of either 200 ppb or 8 ppm, while the creviced specimens were tested in water having 16 ppm dissolved O_2. This set of experiments showed that in the uncreviced condition all alloys were immune to SCC, while in the creviced condition, both Alloys 600 and 182 were susceptible to intergranular SCC. The fractography of these specimens appear quite similar in nature to the River Bend cracks.

The previous investigation and literature survey have led to the following conclusions:

1. The safe-end cracking was interdendritic and progressed approximately 84% thru wall in the Inconel 182 weld metal.

2. There was no evidence of fatigue interaction in the cracking.

3. The cracking is considered to be interdendritic stress corrosion cracking of Inconel 182 weld metal which initiated at weld defect (lack of root penetration).

4. References

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