Evaluation of the Transgranular Cracking Phenomenon on the Indian Point #3 Steam Generator Vessels

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Abstract

A metallurgical investigation was performed on specimens from the shell of steam generators #31 and 32 of the Indian Point-3 Power Plant. The shell material exhibited high values in hardness which was indicative that relatively high residual stresses may have been present. All observed cracks were transgranular in appearance and were associated with pits on the vessels' inside surfaces. Both stress relieved and non-stress relieved specimens of SA302 Grade B material were tested in a constant extension rate apparatus in various environments in order to reproduce the transgranular cracking at Indian Point #3. The paper concludes that SA302 Grade B material is susceptible to transgranular stress corrosion cracking (SCC) in constant extension rate testing (CERT) with as little as 1 ppm chloride (as $CuCl_2$) in 268°C H_2O.

1. Introduction

Indian Point-3 is a 925 MWe pressurized water reactor (PWR) with four Westinghouse Model 44 steam generators (vertical U-tube design). The unit has had approximately three years of effective full power operation since its commercial starting date in 1976.

On March 27, 1982, during a refueling outage (with the reactor in a cold shutdown condition), a small leak was detected on the shell side of steam generator #32. Further examination of steam generator #32 disclosed that the detected leak originated in the circumferential weld joining the transition cone to the upper shell (closure weld) of the steam generator (Figure 1). Closer examination of the area of the leak disclosed a hole on the outer surface of steam generator #32 approximately 16 mm long by 5 mm wide. Further inspections disclosed that the closure weld on each of the steam generators had in excess of 100 cracks associated with them, although the only through-crack was the "leaker" in steam generator #32. A significant amount of pitting was also associated with the closure welds of the steam generator inside surfaces.

The actual path of the through wall "leaker" seemingly followed the weld heat affected zone and is defined in Figure 2. The broadening of the crack near the outside surface of the steam generator is most probably the result of a steam channel erosion effect after the crack had breached the outer surface.

The steam generator shell is constructed of SA302 Grade B material of 4" approximate thickness. The original closure weld had a nominal 45° included angle weld preparation and was welded from the outside surface of the vessel by the submerged arc process with backing. The spacer strip was then back-gouged and the weld completed by welding from the inside surface with the shielded metal arc (SMAW) process using E8018-C3 electrode. The weld was then continuously stress relieved at 1000°F minimum for three hours/inch of thickness (12 hours total soak time).

2. Hardness Measurements

A cross section of a 6" plug weld section from steam generator #32 was polished and etched and then microhardness measurements were performed on the specimen "as received." Additionally, Rockwell measurements were performed for comparison of the weldments' bulk properties. The plug section was then subjected to two differing heat treatments:

a) 1000°F for 3 hours/inch of thickness with a cooling rate not exceeding 100°F/hour until 600°F, then furnace-cooled.

b) 1125°F for 1 hour/inch of thickness with a cooling rate not exceeding 100°F/hour until 600°F, then furnace-cooled.

Hardness measurements (both Knoop and Rockwell) were taken after each heat treatment and values recorded for the base metal, weld metal and heat affected areas. It was observed that each of the heat treatments reduced not only the maximum hardness values, but also the average hardness values recorded.

These results indicate that this particular section of the plug weld had received a heat treatment of less than 1000°F in the location of the hardness measurements.

3. Optical Microscopy

Various pits on the inside surface of steam generator #32 were examined by optical microscopy after etching with a 10% Nital solution.

Some shallow pits had cracks associated with them (Figure 3). The cracks were tight and transgranular in nature, emanating at the bottom of the shallow pits. These cracks were continuous with virtually no branching evident. Other pits had shallow, opened-mouthed cracks associated with them. These cracks had the appearance of having a more active corrosion process associated with them than the predominantly transgranular ones.

4. Scanning Electron Microscopy (SEM)/Energy Dispersive Spectroscopy (EDS)

Various fracture faces from both steam generator 31 and 32 were examined, in the hope of characterizing the failure mode. Additionally, fracture faces and various pits were examined by EDS in an attempt to determine if corrosive constituents were present.

The first specimen examined was from the area of the through hole "leaker." Salient features of the surface were virtually non-existent due to the erosive environment of the leaking secondary fluid. This particular specimen had visible copper colored deposits in evidence after electrolytic cleaning. These deposits were confirmed by EDS as copper, with zinc also in evidence.

The next specimen examined exhibited a transgranular fracture face with the "wood-like" appearance normally associated with progressive or fatigue-type fractures. Higher magnification scrutiny of the fracture face disclosed an area of possible fatigue interaction (Figure 4).

All of the fracture faces examined displayed characteristics of fatigue fractures. Each of the fractures exhibited transgranular features with wood-like characteristics and all of the fractures initiated at pits (Figures 5 and 6). EDS scans of the area of initiation on the fractures indicated Fe, Cr, Ni, Si, S, Cu and Zn as typical constituents.

The failure analysis portion of the investigation generally concluded that low cycle corrosion fatigue was the primary cause of degradation although the relative importance of corrosion in the crack initiation propagation process was not fully understood.

5. <u>Test Program</u>

Since part of the Brookhaven National Laboratory (BNL) program with the U. S. Nuclear Regulatory Commisison encompasses failure prevention, in addition to investigation of failures, a test program was devised in order to simulate the cracking phenomenon of the steam generator vessels (in the laboratory). This program was primarily aimed at determining if SCC could be a contributing cause in the steam generator vessels' failure.

The materials used for this program consisted of 1" thick normalized ASME SA302 Grade B plate (welded with E8018 C-3 welding electrode. Two 6" x 12" pieces of A302 Grade B plate were chamfered to a 45° nominal angle and welded. After welding, the plate was cut in half. One half of the plate was left in the "as welded" condition, while the other half was furnace stress relieved for three hours/inch of thickness at 1000°F; cooled at the rate of 100°F/hour until 600°F was reached and then still air cooled. Hardness readings were taken of the base metal prior to welding; and of the weld, base metal and heat affected zone of the welded plate both in the "as welded" and stress relieved condition. This heat treatment lowered the average hardness of both the weld metal and the heat affected zone from the "as welded" values. These plates were then machined into flat CERT specimens. For purposes of this investigation, a total of 23 CERT were performed. After the completion of the tests, the specimens' fracture faces were examined by SEM and cross sections were mounted, polished and etched for microscopic examination.

For all tests, demineralized/deionized water was used (with or without additives). The specimens were loaded in a Hastelloy C autoclave and no attempt was made to control the oxygen. Since the system was static for these tests, it was assumed that most of the oxygen would be consumed during the test and that this oxygen level would be reasonably consistent from test to test.

Three tests were performed in air in order to obtain base line data. The first test performed was on base material (no weld) at room temperature. This specimen obtained a tensile value of 585 MN/m^2 with an elongation of 3.18 mm. The next two air tests were performed on welded specimens, one specimen in the "as welded" condition and the other specimen tested after the 1000°F stress relieving treatment. They obtained values of 488 MN/m^2 (3.56 mm elongation) and 470 MN/m^2 (3.12 mm elongation) respectively. The fracture faces on all three specimens showed necking and ductility.

Five tests were done in H_2O only. One test was scrapped due to recorder problems. Of the five tests performed, two were done on base material (no weld). The first test was done at 30°C and obtained a tensile value of 596 MN/m^2 with 2.92 mm elongation. The second base metal test was performed at 268°C (secondary side operating temperature) and failed at 736 MN/m^2 with 3.3 mm of elongation. Two tests were performed on welded specimens; one stress relieved and one "as welded." These obtained tensile values of 543 MN/m^2 (3.71 mm elongation) and 591 MN/m^2 (3.35 mm elongation), respectively. All of the fracture faces had a dimpled ruptured appearance with "necking" of the specimens.

The next three tests were base metal and welded specimens tested at different concentrations of sodium chloride at different temperatures. Chloride additions were used due to the fact that in January 1981, the unit suffered a turbine blade failure which damaged approximately 50 condenser tubes and allowed chloride into the steam generators with recorded levels of up to 325 parts per million (ppm).

The first specimen was a base metal specimen tested in 325 ppm chloride (as NaCl) at 30°C. This specimen had a tensile strength of 582 MN/m^2 and an elongation of 3.02 mm. The next two specimens tested were both welded specimens one stress relieved and the other "as welded" and both tests were run at 268°C. The first stress relieved specimen was tested in 25 ppm chloride (as NaCl) and attained a tensile value of 504 MN/m^2 with 3.68 mm elongation while the next non-stress relieved specimen was tested in 325 ppm chloride and attained a tensile strength of 565 MN/m^2 but only had an elongation of 2.39 mm. The fracture faces of the first two specimens were ductile (Figure 7) while the 325 ppm test at 268°C had a more brittle appearance near the edges with no visible necking.

Since Indian Point-3 had significant amounts of copper in the system, as evidenced by copper deposition on the "through wall leaker," some tests were performed to determine if copper could have a complementary effect with chloride on cracking. The next twelve tests all contained varying chloride levels (as $CuCl_2$) at differing temperatures.

These tests were performed at chloride levels ranging from 325 ppm down to 1 ppm (chloride as $CuCl_2$) and with the exception of one test at 30°C all of the tests were performed at 268°C.

In all cases, there was a reduction of elongation (with no specimen necking) and transgranular features on the fracture surfaces. The lowest concentration tested was 1 ppm chloride (as $CuCl_2$). The fracture face of the stress relieved specimen tested at this concentration (Figure 8) showed very little necking with areas of transgranular cracking along its edges. A higher magnification SEM photo (Figure 9) shows that the initiation point of the transgranular area is at pits and that the same wood-like structure and half moon shape as the actual steam generator cracks (Figure 6) is evident. There is even the intimation of beach marks on the fracture. The amount of transgranularity was greater on the "as welded" specimens than on the stress relieved ones which indicate the potential benefit of an adequate stress relief.

The fact that steam generator components (e.g. feedwater nozzles) have suffered thermal fatigue failures in the past and that beach marks and possible fatigue striations were found during the investigation, led to the original conclusion that the Indian Point-3 steam generators had suffered a corrosion fatigue phenomenon. The only questions unanswered at the time were: a) whether the fatigue phenomenon or the corrosion phenomenon was the controlling factor in the cracking; b) whether the utility's countermeasures of rewelding the vessel and re-stress relieving the welds would be sufficient to effectively mitigate the future occurrence of this cracking phenomenon. The attempt to answer these questions by possibly duplicating the cracking phenomenon in the laboratory was the primary goal of this investigation.

Choi, et al. [1] has shown that A508 Cl. 2 steel (a similar vessel steel) is susceptible to a transgranular SCC failure mode in oxygenated water and Weinstein [2] has associated oxygen in water to the environmental assisted cracking in carbon steels; it is reasonable to assume that the presence of oxygen would be the controlling factor in any SCC or low cycle corrosion fatigue failure of this material. In either case, the oxygen would aid in pit formation which would form potential crack sites for either failure mechanism. The detrimental effect of too much oxygen has a direct bearing on Indian Point-3 due to the fact that for environmental reasons, hydrazine levels had been kept low allowing a higher than normally expected oxygen level in the steam generator operation.

These higher than normal oxygen levels coupled with available copper in the system and a massive chloride intrusion could easily have caused cracking in a weld where a complete stress relief had not been accomplished.

6. Conclusions

The following conclusions may be drawn from the test program:

a) This particular alloy (A302 Grade B) is susceptible to a transgranular SCC attack in CERT with as low as 1 ppm chloride (as $CuCl_2$) at 268°C. It must be remembered, however, that no attempt was made to either measure or control the oxygen levels during the test.

b) At lower concentrations of $CuCl_2$ (5 ppm and 1 ppm chloride) there is a beneficial effect of stress relief on weldments in minimizing this kind of attack. Although stress relief may be of some benefit, the cracking of the base metal specimen in $CuCl_2$ solutions indicates that the material itself may be susceptible to SCC in this environment.

c) In order to mitigate the possibility of additional cracking occurring in the field, the environment should be maintained low in oxygen and chloride, and copper ions in solution should be minimized or eliminated. Implementation of these precautions, coupled with a thorough stress relief of the pressure vessel, should dramatically reduce the propensity for cracking.

7. Acknowledgements

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8. References

1. Choi, H., Beck, F. H., Szklarska-Smialowska, F. and MacDonald, D. D., Corrosion, 38, No. 3, (March 1982).

2. Weinstein, D., EPRI NP-2406, Project 1248-1, Final Report, (May 1982).

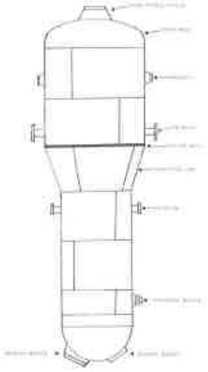

Figure 1 Schematic depicting the closure weld location on the steam generator.

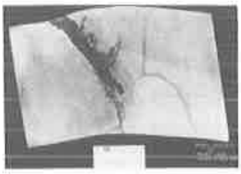

Figure 2 Photograph of 6" plug cross section showing the leak path's relation to the weld.

Figure 3 Photomicrograph of a transgranular crack propagating from a shallow pit.

Figure 4 Fractograph showing possible fatigue striations (boxed area).

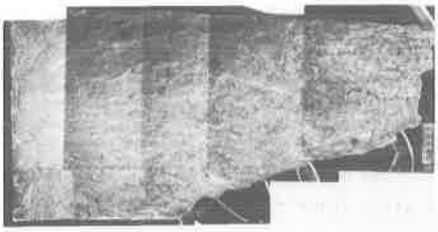

Figure 5 SEM photo of a typically observed fracture originating at pits.

Figure 6 A second fractograph showing the "wood-like" characteristics of fatigue-type fractures.

Figure 7 Low magnification SEM photo of specimen tested in 268°C water with 25 ppm chloride (as NaCl).

Figure 8 SEM photo of the fracture face of specimen tested in 1 ppm chloride (as $CuCl_2$) at 268°C.

Figure 9 Higher magnification fractograph (of area of Figure 8) showing the "wood-like" characteristics of the crack. This crack propagates from pits.