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Replacing the Recirculation Piping System at the Monticello BWR Nuclear Plant

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Abstract

Stress corrosion (IGSCC) flaws were identified in recirculation piping welds at the Monticello plant. This paper discusses the interim repairs, replacement with alternate materials, and emphasizes improvements implemented to secure additional margin of IGSCC resistance not afforded by alternate materials alone.

On September 1, 1982 the Northern States Power Company (NSP) shut down its Monticello boiling water reactor (BWR) for a routine 35 day refueling and maintenance outage. By this time, extensive intergranular stress corrosion cracking (IGSCC) had been found in the large diameter reactor recirculation system piping welds at the Nine Mile Point BWR, but the USNRC had not yet issued any new or additional requirements for inspections of similar piping welds in other US BWR's. Shortly after the Monticello shutdown, the General Electric Company advised US utilities that this might be generic to all US BWR's, because investigation at Nine Mile Point had revealed no causes of IGSCC that were uniquely attributable to that plant.

NSP then initiated a program at Monticello to obtain a comprehensive measure of any IGSCC damage in its recirculation piping system. All circumferential welds in this system were inspected with ultrasonic methods (UT). This inspection disclosed IGSCC in four 12-inch welds and one 22-inch weld. All flaws disclosed by UT were confirmed by radiographic testing (RT). The IGSCC flaws in the four 12-inch welds appeared to be short axial cracks, confined to the heat affected zone (HAZ). The flaw in the 22-inch weld was a longer axial crack that extended about one inch beyond the HAZ.

This presented a need for immediate repairs so the plant could resume operation, and a need for long term resolution of IGSCC in this system. Weld overlay was selected for the immediate repair. This appeared technically sound and conservative with respect to safety and licensing. For further margin, the weld overlays were designed to fully replace the structural capacity of the underlying pipe.

Overlay repair yielded information which influenced subsequent long term decisions. In preparing pipe surfaces for weld overlays, several small through-wall cracks were uncovered and disclosed by leakage. These were not detected by UT and could not be identified by UT after their location was known. In applying the first layer of weld overlays, additional small cracks were identified from porosity in the weld. When weld penetration reached the tip of cracks that were nearly through-wall, moisture was released to create a porosity defect in the weld metal. A hydrostatic test and inspection identified leakage from an additional 12-inch weld. This was repaired with a similar overlay. With the concurrence of the USNRC, Monticello resumed operation on December 1, 1982. The inspection and repair extended the planned outage by 66 days.

1.0 Basis of the Replacement Decision

When repairs were well under way, NSP's attention turned to longer term plans. Four decision assumptions were developed from the inspection and repair experience.

1.1 The weld overlay was regarded as an interim repair, because at the time there was neither an experience basis nor an ASME Code basis to justify for the long term performance.

1.2 UT was not adequate to detect the IGSCC flaws identified by leakage and weld porosity. Therefore, similar IGSCC flaws remain undetected in other piping welds.

1.3 Any existing, undetected IGSCC will propagate in future service conditions.

1.4 Existing IGSCC flaws, whether or not detected, are precursors to additional IGSCC in future service.

The IGSCC flaws identified were not a safety concern in the near term. However, these assumptions suggested two serious economic concerns: (a) Continued operation could encounter IGSCC flaw leakage, and require unscheduled outages for emergency repairs; and (b) Continued inspection and repair at subsequent refueling outages could accumulate large costs, and only postpone the ultimate cost of a long term solution.

These economic concerns clearly indicated to NSP that an early permanent solution was necessary for Monticello. Hydrogen addition water chemistry was considered, but regarded as unproven at that time. Induction heating stress improvement (IHSI) to remedy sound welds, supplemented by local pipe replacement to remove flawed welds was considered. This approach was unacceptably dependent on the use of UT methods to discriminate between flawed and unflawed welds. In December 1982, NSP decided to replace the recirculation piping with alternate materials at the next refueling outage. This early decision allowed a year to prepare. The first step in preparing for replacement was to consider all probable causes of experienced IGSCC.

2.0 IGSCC Experience and Causes

The predominant IGSCC in US BWR piping had been experienced near welds of Type 304 Stainless Steel systems, when the welds were not solution annealed. This IGSCC was attributed to the combination of aggressive BWR chemistry (oxygen), weld residual stress (high surface tensile stress), and sensitization (chromium carbide precipitation) from heat during welding.

Experience indicated this IGSCC was influenced by other factors, because only a small fraction of the total welds in service with these cause conditions existing, developed detectable IGSCC. In this IGSCC there were many evidences of grinding, machining marks, adverse counterbore geometry, improper weld fit up, irregular weld root geometry, or welding repairs. Some IGSCC was influenced by higher applied stress. In addition to design stress, higher applied stress near welds can be induced by cold spring to achieve fit up, and weld shrinkage combined with improper selection of system closure welds.

Although most IGSCC had been attributed to BWR chemistry, residual stress, and sensitization, there had been IGSCC in the absence of heat sensitization. This IGSCC included cause combinations of: (a) BWR chemistry, stress and crevice condition; (b) BWR chemistry, stress and surface cold work from machining or grinding; (c) Transient chemistry intrusions (halogens or sulfides) and stress.

Several cases of IGSCC were experienced in solution annealed manufacturing welds. This was a basis to suspect improper annealing and quenching practices, or crack initiation from surface attack during pickling. Also, repeated post-weld heat treatment of weld metal can reduce delta ferrite content and lower IGSCC resistance.

Type 316 Nuclear Grade Stainless Steel (Type 316NG), and similar materials, were developed to resist sensitization during welding. Type 316NG could enhance IGSCC resistance by removing sensitization from the most prevalent cause of IGSCC (BWR chemistry, residual stress and sensitization). However such alternate material, by itself, does not address the causes of IGSCC in the absence of sensitization, nor the other factors which appeared to influence initiation of IGSCC.

3.0 Replacement Philosophy and Objectives

NSP concluded that replacement with Type 316NG, as the only improvement, would still present an unacceptable risk of future IGSCC. The replacement effort then proceeded under the philosophy that "absolute immunity to IGSCC is not attainable", and the objective of achieving greater margin of IGSCC immunity through application of available technology. Further preparation efforts emphasized improvements in design, manufacture, residual stress reduction, and installation practices. With this philosophy and objective, the following improvements were conceived and implemented:

4.0 Design and Manufacturing Improvements

4.1 The total population of system welds was reduced by simplification of design configuration, bends to replace elbows, and forged fittings to replace weldments.

4.2 Installation welds were reduced to less than half those in the original system by providing preassembly spools in the largest form practical for installation.

4.3 Stress improvement was provided for all preassembly welds by solution annealing all preassemblies in their final form.

4.4 The design of inlet safe-ends was improved to eliminate creviced geometry.

4.5 All preassembly circumferential welds were provided with 2T counterbore and 1 in 4 taper transition. This improved inspectability and avoided geometric irregularities near welds.

4.6 Interior surfaces of finished and annealed preassemblies were electro-polished prior to installation. This removed all evidence of inter-granular attack during pickling. All interior surfaces were dye penetrant inspected (PT) and local surface blemishes were polished to "zero" indication.

5.0 Installation Improvements

5.1 As in preassembly, installation weld counterbores were required to have a 2T length and 1 in 4 taper transition. This again improved inspectability and avoided geometric irregularities.

5.2 All counterbore machining was finished with single-point cutting tools, rather than "form" cutters, to minimize surface cold work. All counterbores were polished to remove about .002 inch of cold worked surface after machining.

5.3 No grinding of weld counterbores was permitted before or after welding. All accessible weld roots were polished and PT inspected after welding.

5.4 Each weld fit up was held for inspection and approval by a senior NSP representative before welding could proceed, to reduce irregular root geometry or root repairs.

5.5 All welds were RT inspected after root closure before filler welding was permitted. This avoided excavation of filler material when minor root repairs were required.

5.6 The installation sequence was evaluated and prescribed, so that system induced stress from axial shrinkage of closure welds was minimized.

5.7 All installation welds were conditioned with IHSI to provide stress improvement after welding. These welds were UT inspected before and after IHSI to provide a new in service inspection baseline.

6.0 Reactor Vessel Nozzles

The existing Type 304 safe ends were replaced at the two 28 inch outlet nozzles and ten 12 inch inlet nozzles of the reactor vessel. The end and bore of these carbon steel nozzles had originally been clad with stainless steel weld metal to permit a similar metal weld to the safe ends. The vessel assembly history indicated this weld metal had experienced repeated cycles of post weld heat treatment. Additional weld metal was deposited over the existing weld metal prior to machining the weld preparation. This provided "corrosion resistant cladding" (CRC) on the nozzle. The nozzle to safe end welds were conditioned with IHSI after welding.

7.0 Additional Replacement Workscope

The original design included Type 304 stainless steel fittings welded to each of three smaller vessel nozzles, at a lower elevation on the reactor vessel. These were two jet pump instrument (JPI) nozzles, and the standby liquid control (SBLC) nozzle. IGSCC indications were found in one JPI fitting. All three fittings were replaced with fittings of Type 316NG material. Both JPI nozzles were enhanced with CRC, and the SBLC nozzle weld was enhanced with IHSI.

IGSCC indications were found near welds at two residual heat removal (RHR) system valves. These cast stainless valves were originally supplied with attached Type 304 pipe extensions, and installed into the carbon steel RHR piping system with dissimilar-metal welds. The valve extensions were removed, the mating carbon steel pipe ends were extended with stainless steel weld metal addition, and the valves installed with similar-metal welds. These welds were conditioned with IHSI.

8.0 Problems During Manufacture

Four preassemblies each included a short length of 12-inch pipe with a long radius bend. Inspection indicated surface cracking on nearly all bend surfaces. Cracking was attributed to improper control of temperature during hot bending. These pieces were scrapped and replaced with bends procured from another supplies.

Several fittings were manufactured by seam welding two hot-formed halves. Inspection indicated surface cracking near the seam welds. Extensive metallurgical examination showed exclusively a surface phenomenon. Further investigation attributed the cause to surface contamination with copper, from the copper-coated electrode used in air-arc cutting to prepare the seam-weld geometry. The surface cracks were removed by grinding, and both surfaces of the seam welds were PT inspected to "zero" indication.

A number of ends of rolled and welded pipe sections did not conform to specification tolerances for ovality and diameter. Corrections were made with special mandrels to mechanically re-size these end sections.

9.0 Type 316NG Pipe Installation Welds with GTAW

Welding tests were conducted using planned weld joint geometry, welding procedures, Type 316NG pipe, and gas tungsten arc welding (GTAW) machines. These tests resulted in two changes to installation practices.

Grain boundary surface tearing near the weld root was indicated. Further testing related this tearing, to surface cold work from machining the weld counterbore. Procedures were developed demonstrated to eliminate this phenomenon by removing the first .002 inch of cold worked surface material with polishing methods. All installation weld counterbores were polished with this procedure before welding.

IHSI methods were originally developed as an IGSCC resistant remedy for SMAW welded Type 304 pipe in operating plants. The welding tests showed about 30% higher residual stress near the root and a broader residual stress field in the Type 316NG pipe GTAW welds, than observed in Type 304 pipe SMAW welds. IHSI tests resulted in a need for refinement of the IHSI procedures to produce the desired stress improvement in the Type 316NG welds.

10.0 Conclusions

The piping replacement effort at Monticello required nearly one year of plant shutdown to complete the work. The improvements beyond the use of alternate materials addressed every cause of IGSCC in these systems that experience could identify. NSP is confident that the risk of future IGSCC has now been reduced to an acceptable level.

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