In-Service Cracking Experience with Nickel Chromium Iron Alloy 182 at Pilgrim Nuclear Station

E.F. Kearney
Boston Edison Company, 800 Boylston Street, Boston, Massachusetts 02199, U.S.A.

Abstract
During safe end replacement work at the Pilgrim Nuclear Power Plant, axially-oriented intergranular stress corrosion cracking was found in the Nickel-Chromium-Iron Alloy 182 weld materials which join the stainless steel safe ends to the low alloy steel reactor vessel recirculation system nozzles. This paper describes the results of metallurgical examinations performed to determine the cause of cracking. A brief discussion of the structural integrity aspects of the cracking is also provided.

1. INTRODUCTION AND BACKGROUND
The Pilgrim Nuclear Power Plant is a single cycle, forced circulation, Boiling Water Reactor producing steam for direct use in the steam turbine. The plant is located in the town of Plymouth, Massachusetts, U.S.A. and is wholly owned by the Boston Edison Company.

The Pilgrim reactor vessel is fabricated from low alloy steel and is clad internally with stainless steel. The vessel is designed to Section III of the ASME Boiler and Pressure Vessel Code for a pressure of 1250 psig and temperature of 550°F.

One of the activities scheduled during the recent refueling and maintenance outage was the replacement of the Type 304 stainless steel recirculation inlet and outlet safe ends with low carbon 316 Nuclear Grade stainless steel safe ends. Safe ends provide a transition on the reactor vessel nozzle so the piping can be connected without postweld heat treatment. Weld material used as a transition between a nozzle or safe end and a connecting butt weld is commonly referred to as "butter".

A cross-section view of the 12-inch recirculation inlet nozzle is shown in Figure 1. (The configuration of the 28-inch outlet nozzle is identical except that the thermal sleeve is absent). The safe ends are attached to the nozzle using nickel base alloy welding materials -- Nickel-Chromium-Iron Alloy 182 and Nickel-Chromium Alloy 82. The typical compositions applied at this plant are shown in Table 1. Alloy 182 material is a covered electrode applied with the Shielded-Metal Arc process, and Alloy 82 is a bare rod normally applied with the Gas-Tungsten Arc welding process.
**Figure 1.** Recirculation Inlet Nozzle Configuration Including Nozzle, Safe End and Thermal Sleeve. (Recirculation Outlet Nozzle Identical Except Thermal Sleeve is Absent).

<table>
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<th>Alloy</th>
<th>C</th>
<th>Ni</th>
<th>Cr</th>
<th>Mn</th>
<th>Fe</th>
<th>S</th>
<th>P</th>
<th>Nb+Ta</th>
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<th>Si</th>
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<td>7</td>
<td>8</td>
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<tr>
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<td>75</td>
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<td>3</td>
<td>0.5</td>
<td>0.005</td>
<td>0.005</td>
<td>2.5</td>
<td>0.38</td>
<td>0.2</td>
</tr>
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</table>

During replacement of the 12-inch recirculation inlet safe ends, liquid penetrant (PT) examination of the machined weld preparation surfaces on one nozzle revealed 5 axial cracks in the Alloy 82 butter. PT examination during subsequent weld preparation machining on the remaining inlet nozzles revealed two additional nozzles with crack indications in the weld material (approximately 12 cracks per nozzle). Cracking typically extended 20-30% radially through the wall, up to a maximum depth of about 70%.

Liquid penetrant examination of the inside weld surfaces of the 28-inch recirculation outlet safe ends revealed multiple (33) axial cracks in one of the two nozzles. The cracks were confined to the Alloy 82 weld butter on both the safe end and nozzle side of the weld with the exception of minor crack extension into the stainless steel safe end base material observed at a few locations.

2. **RESULTS AND DISCUSSION**

Metallographic examination of boat samples taken from the outlet nozzle weld region confirmed that the cracking was Intergranular Stress Corrosion Cracking (IGSCC). A total of four boat samples were taken from recirculation outlet nozzle NI-8, three of which were examined at the General Electric Company Vailecitos Nuclear Center. The fourth sample was given to the Nuclear Regulatory Commission (NRC) for an independent analysis.
2.1 Boat Sample No. 1 and 2

The locations for removal of boat sample No. 1 and 2 are shown in Figure 2. Sample No. 1 was removed from azimuth location 180° (0° is top dead center) to include an axial crack in the Alloy 182 butter which had also extended into the safe end. Sample No. 2 was removed from azimuth location 30° to include a short circumferential crack on the safe end side and a connected axial crack. Figure 2 also shows the complex metallurgical condition which exists in the nozzle to safe end weld joint.

![Diagram of boat samples with cracks and labels: No. 1 boat sample with axial crack, No. 2 boat sample with short circumferential crack, Alloy 82 root passes, 308 stainless steel cladding, nozzle (low alloy steel), Safe-end 304 SS, 182 weld butt, etc.]

Figure 2. LOCATIONS FOR REMOVAL OF BOAT SAMPLE NO. 1 AND 2. ALSO NOTE COMPLEX METALLURGICAL CONDITION OF NOZZLE TO SAFE END WELD JOINT.

Boat sample No. 1 was mounted on its exposed (I.D.) surface in order to examine the nature of the cracking in both the 182 butter and the safe end. Optical metallography results are shown in Figure 3. On close examination, one can see a change in structure in the Alloy 182 weld butter. The material closest to the weld interface (a diluted zone) has retained its original dendritic solidification structure. Further from the interface, the weld metal dendritic structure is not visible. The material in this area shows distinct grain boundaries. This structure results from subsequent weld pass heating, or from the solution heat treatment (1950°F, water quench) performed on the safe end following application of the weld butter.
As shown in Figure 3, the cracking is interdendritic and intergranular in the Alloy 182 butter, and the extension of the crack into the safe end is intergranular. This mode of cracking in this material is characteristic of stress corrosion cracking.

Boat sample No. 2 contains a short (less than 1" long) circumferential crack near the butter/safe end interface and a connected axial crack. Optical metallography and Scanning Electron Microscopy (SEM) confirmed that both cracks were intergranular and that the circumferential crack followed the butter/stainless safe end interface. The cracking at this location is not typical of the other cracks found in the NI-8, or the cracks found in the N2 (inlet) nozzles. Crack initiation would not be expected in the stainless steel safe end (since the safe ends were solution heat treated following weld buttering). At this particular location, it appears that the circumferential crack is a branch of an axial crack which initiated in the weld butter.

2.2 Boat Sample No. 3 and 4

The locations for removal of boat sample No. 3 and 4 are shown in Figure 4. Sample No. 3 and 4 were removed from azimuth locations 185° and 195°, respectively. Both included two axial cracks in the butter material on the safe end side and a portion of the Alloy 82 root pass material. Sample No. 3 was examined by General Electric, and sample No. 4 was sent to the NRC for independent analysis.
After sample No. 3 was removed, an axially oriented subsurface crack was discovered between the two other surface cracks in the weld butter, as shown in Figure 5. Since the tip of this crack was not open to the surface anywhere on the safe end side of the weld, it would appear that this is the extension of an axial crack found in the butter on the nozzle side of the weld. This crack must have originated in the nozzle side butter and "tunneled" around the Alloy 82 root pass toward the safe end. (Figure 4 shows an axial crack on the nozzle side that is the likely origin of this subsurface crack.)
In order to examine the behavior of the subsurface crack in the vicinity of the Alloy 82 weld root pass, sample No. 3 was removed from its mount and separated at the location of the subsurface crack. One side of the sample was mounted and polished for optical metallography and the second side was submitted for SEM examination of the fracture face. Optical metallography results are shown in Figure 6. Branches of the subsurface crack are seen to have extended up to the weld interface and into the transition zone of the root pass, but not beyond. This behavior is consistent with General Electric's understanding of Alloy 182 and 82 weld metals. Laboratory data has shown that Alloy 182 has a greater IGSCC susceptibility than Alloy 82 in high temperature water environments.

Scanning Electron Microscopy of the Alloy 182 portions of the fracture surface confirmed optical metallographic results showing interdendritic/intergranular crack morphology which is characteristic of stress corrosion cracking.

![Figure 6. OPTICAL METALLOGRAPHY OF CROSS-SECTION PLANE AT SUBSURFACE CRACK ON BOAT SAMPLE NO. 3. NOTE CRACK ARREST IN ALLOY 82 ROOT PASS MATERIAL. (250X)](image)

2.3 Other Evaluations

The cracking observed in the recirculation system safe ends confirmed the in-service susceptibility of Alloy 182 material to Intergranular/Interdendritic Stress Corrosion Cracking in high temperature oxygenated water environments. An extensive review of the fabrication and construction records did not identify any correlation between the weld material compositions or fabrication procedures and the location or frequency of the cracking.
Finite element residual stress analyses were performed for the safe end to nozzle weld region using the applicable joint/butter geometries and material properties. Results showed that the predominate residual stress in the butters is due to the safe end to nozzle weld, and is oriented in the hoop or circumferential direction. Hoop residual stress combined with applied pressure stresses would explain the observed axial cracking pattern.

Analysis was also performed to determine structural integrity of the recirculation safe end/nozzle weld joint with the axial cracking. A through-wall crack was conservatively evaluated assuming both linear elastic fracture mechanics and limit load failure mechanisms. For the more conservative of the two calculated failure mechanisms, the critical crack length for an axial, through-wall crack in the 12-inch nozzle is 22 inches, and for the 28-inch nozzle is 38 inches. The corresponding values for the stainless safe ends are higher. Since the observed cracking is axially oriented with a length of approximately 0.5 inch, significant structural margin is maintained for the nozzle safe end weld region.

3. SUMMARY

It was found, by the examination performed, that the cracking in the Alloy 182 weld metal was due to interdendritic (intergranular) stress corrosion cracking. Since the majority of the cracking was confined to the Alloy 182 material, it is apparent that the cracking initiated in the Alloy 182. Propagation in the Alloy 82 material was not observed, and subsequent removal and repair of the cracking confirmed that cracking did not propagate into the low alloy steel nozzle material.

Residual stress analyses explained the axial orientation of the cracking since the predominate weld residual stress for this complex joint configuration was in the hoop or circumferential direction. The structural integrity of the component was also demonstrated using fracture mechanics analysis.

The experience at this plant confirmed the in-service susceptibility of Alloy 182 material to IGSCC in oxygenated high temperature water. The higher resistance of Alloy 82 to crack initiation and growth was also demonstrated. Although the weld materials or fabrication history did not provide a plant-unique explanation for the observed cracking, a significant generic cracking problem may not be present based on Alloy 182 examination results during safe end replacement at other operating plants with comparable years of service.