CORROSION TEST OF STEAM GENERATOR TUBES WITH ALLOY 800 MECHANICAL SLEEVES

REPORT NO. 98-FSW-021 REV. 00
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SECTION 1

INTRODUCTION

The Alloy 600 heat transfer tubes in many PWRs have experienced degradation which has required removal of the tubes from service by plugging or the installation of sleeves which span the degraded areas and permit continued use of the tubes. Most of the sleeves installed in the US have been welded at one or both ends to insure that the sleeves are leak tight. Welded sleeves have performed well but their installation rate is relatively slow because of the need to clean the ID of the tubes prior to sleeve installation, to inspect, and to post-weld heat treat to lower residual stresses. Mechanical sleeves, which have been installed in some steam generators, have a higher installation rate but in some plants, some sleeved tubes have developed flaws, apparently related to the relatively large amounts of deformation of the Alloy 600 tubes caused by the installation procedure. ABB Reaktor (ABB R) has developed a mechanical sleeve which uses the difference in thermal expansion between the Alloy 600 tubes and an Alloy 800 sleeve to provide a leak limiting sleeve which can be installed with only small deformations of the Alloy 600 tubes. Mock-ups of Alloy 600 steam generator tubes with Alloy 800 mechanical sleeves have been tested by ABB Combustion Engineering Nuclear Power (ABB CENP) in an aggressive environment. This report documents the results of that testing and compares the results with prior service experience and laboratory test results.

SECTION 2

MATERIALS AND SPECIMENS

ABB CENP provided ABB R 28 inch long sections of 3/4 inch (nominal) OD by 0.048 inch (nominal) wall thickness NiCrFe Alloy 600 for the fabrication of the sleeved mock-ups. The Alloy 600 tubes were from heat number 752677, which had a yield strength of 49,000 psig. The specified yield strength for tubes in ABB CE supplied steam generators is 35,000 - 55,000 psig. Thus, this heat had mechanical properties typical of installed tubes in CE plants.

ABB R fabricated the seven mock-ups used for corrosion testing including welding of the Alloy 600 tubes to the simulated tubesheet assembly and installing the Alloy 800 sleeves into the mock-ups. The mock-ups were uniquely identified by numbers engraved on the simulated tubesheets. Figure 1 is a schematic drawing of the mock-ups. Mock-up numbers and the amount of Alloy 600 tube deformation resulting from the hydraulic expansion used to install the sleeves were

NUMBER	DEFORMATION, %
P54-16	0.168
P54-19	0.255
P54-20	0.453
P54-21	0.499
P54-22	0.455
P54-23	0.376
P54-24	0.244

After receipt of the mock-ups from ABB R, ABB CENP welded end fittings to each to permit pressurization during the autoclave tests.

ABB CENP included in the test Alloy 600 bolt loaded (stressed) C-ring specimens fabricated from heat number 752677 (3/4 inch OD by 0.048 inch wall). These were fabricated and loaded in accordance with ASTM G38-73 (re-approved in 1990), "Standard Practice for Making and Using C-Ring Stress Corrosion Test Specimens". Deflections were selected to yield final strain levels of 0.3%, 0.5% and 1.5%. Triplicate specimens of each strain level were tested. In addition, another set of C-Ring specimens were tested that had the same final strains but which were initially loaded to 0.2% strain above the target value and then relaxed to the target value (0.3, 0.5 or 1.5% strain). Table 1 provides identification numbers, initial and final strain levels and results of post-test examinations (see Section 4) of the C-Ring specimens.

SECTION 3

TEST CONDITIONS AND OPERATIONS

The environment used to induce stress corrosion cracks in the mock-ups and C-ring specimens was 10% NaOH (100± 3 g of NaOH in 900 ml of deionized water) at 662± 5°F. Two separate tests were run with (1) the OD of the mock-ups exposed to the test environment (secondary side test) and (2) the ID of the mock-ups exposed (primary side test).

The secondary side test included four mock-ups (P54-16, P54-19, P54-21, and P54-23) and all of the C-ring specimens. All were tested by immersion in the specified test environment which was contained inside a nickel 200 cylinder fabricated from 6 inches diameter schedule 40 pipe that was 54 inches in length. The nominal ID of the cylinder was 6.07 inches. The nickel 200 cylinder was used because the autoclave in which the test was conducted was stainless steel which will crack if exposed to caustic conditions. Sample lines that passed through the top head of the autoclave to an accumulator pressurized the mock-ups. The samples were pressurized as a group. If leakage occurred (and pressure decreased) the identify of the leaking sample could be determined by isolating the samples individually and pressurizing each in turn to see if pressure was maintained.

Prior to loading the mock-ups into the test chamber, they were pressurized to 2000 psig and visually inspected for signs of leakage. They were then placed into the nickel 200 liner containing the test environment. After loading of all specimens, the nickel 200 cylinder was sealed and leak tested with 30 psig nitrogen to verify leak tightness before loading into the autoclave. The autoclave was 144 inches in length, had an inside diameter of 12 inches and was fabricated from stainless steel. The autoclave was filled with deareated DI water, which does not pose a threat to the stainless steel autoclave shell.

The temperature of the test was recorded continuously by two calibrated thermocouples. One was attached by a clamp to the wall of the nickel 200 cylinder and recorded the temperature at the cylinder wall. The other was positioned to record the temperature of the autoclave water. In addition, a technician manually recorded the temperature from both thermocouples and the autoclave pressure and the pressure in the samples twice a day during week-days. In addition to these data, a water sample from the autoclave (not the cylinder) was collected after the autoclave was at the specified temperature and pressure and at weekly intervals thereafter for a pH determination. An increase in pH would indicate leakage from the nickel 200 cylinder, an undesirable condition which would require autoclave shutdown to repair the leak. During this test, the autoclave pH did not increase indicating there was not any leakage from the nickel 200 cylinder.

The test heat-up occurred over a two day period. On the first day, the autoclave was heated to approximately 550°F and allowed to stabilize overnight. Test heat-up continued to the specified conditions on day 2. After the specified temperature (662±5°F) was reached, the mock-ups were pressurized to approximately 1500 psig. Pressures were monitored on a twice a day basis on week days with results recorded to a laboratory logbook

3.1 Secondary Side Tests

The secondary side corrosion test mock-ups were pressurized for a maximum of 2623 hours and the C-ring specimens were at the specified temperature for a maximum of 2458 hours. Test exposures were accumulated during five separate operating periods (runs) of the autoclave. Test conditions are summarized as follows:

Run 1

- Total time at specified temperature - 1032 hours
- Cylinder temperature range (most representative of what mock-ups experienced) - 657.9 to 663.9°F
- Mock-up differential pressure range (DP) - 1330 to 1745 psig

Run 2

- Total test time - 169 hours
- Mock-ups P54-21 and P54-19 were depressurized after 66 hours because of leaks. Mock-ups P54-16 and P54-23 were in test for the run duration.
- Cylinder temperature range - 662.0 to 662.5°F
- Mock-up DP range - 1050 to 1460 psig
- Test shutdown to repair leaking mock-ups. During leak testing, all four mock-ups leaked at a plug weld in the tubesheet simulation. Leaks were not associated with the sleeves.

Run 3

- Total test time - 856 hours
- Mock-up temperature range - 659.2 to 660.3°F
- Mock-up DP range - 1510 to 1765 psig
- Scheduled shutdown to remove specimens in a non-related test using the same cylinder.
- The 18 C-ring specimens were removed for examination

Run 4

- Total test time - 155 hours

- Mock-up temperature range - 658.9 to 659.6°F

- Mock-up DP range - 1365 to 1535 psig

- Scheduled shutdown to remove samples in a non-related test

- Fifteen C-ring specimens(less ABS-2, 13,14) were reinserted to test

Run 5

- Total test time - 401 hours

- Mock-ups P54-19 and P54-23 were depressurized after 218 hours because of leaks. Mock-ups P54-16 and P54-21 were in test for the run duration.

- Cylinder temperature range - 662.2 to 663.7°F

- Mock-up DP range - 1225 to 1500 psig

- The test was shutdown when an autoclave rupture disk failed. The test was terminated at this point and all mock-ups and C-ring specimens were removed from the cylinder. The specimens were washed with water to remove any residual NaOH residue prior to final leak testing and destructive examination. These test results are discussed in the following sections of this report.

The total test times for the various mock-ups and specimens were (for the mock-ups, only hours pressurized were tabulated):

P54-16	2623 hours
P54-19	2337 hours
P54-21	2520 hours
P54-23	2440 hours
C-ring specimens ABS-2,13,14	2057 hours
All other C-rings	2458 hours

3.2 Primary Side Tests

The primary side test was conducted in the same manner as the secondary side test except the test environment was inside the mock-ups and there were not any C-ring specimens included in the test. The specimens were assembled and leak tested in the same manner as the secondary side mock-ups and were loaded into a Hastelloy C-276 6-inch schedule 40 pipe that was 54 inches in length and had a nominal ID of 6.07 inches. The Hastelloy C-276 cylinder was used to contain any leakage of NaOH that might occur from the mock-ups and thus prevent cracking of the stainless steel autoclave which housed the cylinder. After loading of the specimens, the cylinder was sealed and leak tested with 30 psig nitrogen before loading into the autoclave which was filled with deareated DI water. The temperature instrumentation and mock-up pressurization system were identical to that of the secondary side test.

The internal Hastelloy C-276 cylinder had previously been used for another corrosion test involving a very aggressive environment. Although the autoclave was cleaned prior to this test, concern about possible residual chemicals resulted in periodic sampling for chemical analysis of the solution inside the cylinder.

Test heat ups occurred over a two day period, just as for the secondary side test. After the specified temperature (662± 5°F) was reached, the mock-ups were pressurized to a differential pressure of approximately 1500 psig. Mock-up pressures were monitored on a twice-a-day basis on week days with the results recorded to a logbook.

The primary side mock-ups were pressurized for a maximum of 3306 hours at the specified temperatures over six separate operating periods (runs) of the autoclave. Shutdowns were the result of autoclave problems and were not originally planned except to remove leaking specimens from test. Test conditions are summarized as follows:

Run 1

- Total test time at specified temperature - 112 hours
- Cylinder temperature range - 656.2 to 660.3°F
- Mock-up DP range 1600- 1800 psig

Run 2

- Total test time - 1490 hours
- Cylinder temperature range - 652.9 - 668.5°F
- Mock-up DP range - 1150 - 1700 psig

Run 3

- Total test time - 1009 hours
- Cylinder temperature range - 651.9 - 665.2°F
- Mock-up DP range - 1200 – 1650 psig

Run 4

- Total test time - 211 hours

- Cylinder temperature range - 659 – 662.5°F
- Mock-up DP range - 1330 - 1600 psig

Run 5
- Total test time - 76 hours
- Cylinder temperature range - out of action, but water temperature was 659 - 665.9°F
- Mock-up DP range – 1200 - 1430 psig

Run 6
- Total test time - 408 hours
- Cylinder temperature range - 657.2 - 663°F
- Mock-up DP range – 1440 - 1775 psig

The total test time for all primary side mock-ups was 3306 hours.

After the final test runs, and at intermediate times when specimens were removed from the autoclaves, the mock-ups and C-rings were rinsed with DI water to remove any residual NaOH. The C-ring specimens were visually inspected for cracks with a Nikon SMZ-10A stereomicroscope at magnifications of 7.5 to 49X. At the completion of the test, selected C-ring specimens were sectioned transversely at the mid-point of the specimens and mounted so as to view the mid-plane and one edge. The metallographic samples were ground and polished using standard metallographic techniques and were then examined with light optical microscopes in the as-polished conditions.

After removal from the autoclaves, the sleeved mock-ups were pressurized and examined for indications of leakage. They were also allowed to sit at ambient temperature for several days and then re-examined visually for indications of seepage from cracks. Based on these observations and pressure tests, one mock-up from the primary side test and one mock-up from the secondary side test were destructively examined as described below to characterize the defects.

Mock-up No. P54.24 from the primary side test was examined as follows:

1. An initial transverse cut through the tube and sleeve was made with a hacksaw just above the top of the simulated tubesheet.
2. The mock-up identification (P54.24) was transferred to the tube OD surface by vibraetch.
3. The top fitting was removed with a cut-off wheel.

4. The tube-sleeve combination was cut transversely at three locations as follows:
    a. below the third expansion - the piece above was identified as 1
    b. below the fifth expansion-the piece above was identified as 2
    c. 2 - 1/8 inches below the 6th expansion- the piece above was identified as 3. The piece had a visible circumferentially oriented crack.
    d. the remaining piece, which did not have any expansions, was identified as 4.
    e. Prior to sectioning, the mock-up ID number and "Top" was vibra etched onto the top of each section. Also, an identifying "+" was cut into the tube at the interface between each section to permit orientation to be maintained after sectioning.

5. Each of the four pieces was slit axially. The half sleeves and tubes were identified with the letter "A" or "B" to maintain identification and were placed in individual plastic bags identified by mock-up number, piece number, side number and sleeve or tube.

6. Each piece (ID and OD) was examined with a Nikon SMZ-10A stereomicroscope at magnifications of 7.5 to 49X and observations recorded to a notebook

7. Each piece was then flattened in a hydraulic press. Flattening will open up ID cracks, especially those axially oriented.

8. Each section was then re-examined with the Nikon SMZ-10A stereomicroscope and observations recorded to a notebook

9. Sections 1 and 3 were cut to provide samples for metallographic examination of defects. These were mounted, polished, etched, and examined by microscope.

Mock-up number P54.19, from the secondary side test, had a circumferential crack indicated by white deposits on the tube. The mock-up was photographed to document the presence of the deposits, examined with the previously discussed stereomicroscope and then sectioned and examined in the same manner as the primary side mock-up.

SECTION 4

TEST RESULTS

4.1 Primary Side Test

The three primary side mock-ups, consisting of Alloy 600 tubes and Alloy 800 mechanical sleeves, did not leak during the 3306 hours when the mock-ups were pressurized and at test temperature of 660°F. At the time of test termination, all mock-ups were still holding the test pressures. After several days at ambient temperature, the mock-ups all had indications of leakage, which was visible as areas of dry, loose, white deposits. Mock-up P54.24 had an apparent circumferential, through-wall defect approximately 5 - 3/4 inches above the tubesheet (Figure 2) and three axial, through-wall flaws approximately 10-1/4 to 10-1/2 inches above the tubesheet. Mock-up P54.20 had a circumferential indication approximately 9 inches above the tubesheet. After the deposits were brushed away, cracks were readily visible when the mock-ups were examined with the stereomicroscope. The mock-ups were leaked tested at 1600 psig at room temperature. Mock-up P54.24 leaked at a rate of 0.00082 gal/hour. The other mock-ups did not leak. After the visual examination and leak testing, mock-up P54-24 was destructively examined. The other mock-ups were not further examined.

After sectioning, three axial cracks were visible on the OD of the Alloy 600 tube of section 1 of mock-up P54.24. This section had three expansions; the cracks were at approximately the location of the second expansion. The expansion locations were obvious on the ID but cracks were not visible on the ID at any magnification up to 49X. The three cracks were more pronounced when the section halves were flattened and had lengths on the OD surface of 1/4, 5/32 and 3/32 inch (approximate). There were no other cracks noted on the OD.

Severe cracking was evident on the ID of tube section 1 after flattening, with the most severe cracking below and above the 2nd expansion. There was cracking at all three expansions, with lighter cracking being present in the expanded regions. There was some cracking between the expansions and some shallow indications above the top expansion.

Section 2, which had two expansions, also had extensive ID cracking from end to end after the section was flattened, but the most severe cracking was adjacent to the expansions on the top side of the expansions. There appeared to be some shallow cracking on the OD surface above the 4th expansion.

There was a series of circumferential cracks visible on the OD of Section 3 that extended around the circumference. There was also possibly some minor OD initiated cracking elsewhere in this section. Examination of the ID of section 2 showed the circumferential cracks were near but below the bottom-most expansion. There were also numerous axial cracks in this section with some occurring between the circumferential cracks and expansion. The most severe were near the expansion but axial cracks were present along the length of the section.

In Section 4, the only cracks were axial cracks on the ID near the weld attaching the tube to the tubesheet.

The Alloy 800 sleeves were examined in a similar manner with Sections 1 and 4 having no cracks visible and Section 2 and 3 possibly having several very shallow cracks, on the ID and OD generally associated with scratches and gouges. These appeared not to be significant in axial extent or depth, based on the stereomicroscope examination.

To determine if cracks were present, a transverse cut was made through some of these features in Sections 2 and 3 and the resulting sections were mounted for examination with the light microscope. They were ground and polished with typical metallographic techniques, etched with an electrolytic nital etch (reveals the grain boundary network) and examined by light microscope at magnifications up to 500X. This examination confirmed these features were shallow predominately intergranular penetrations with a depth of less than 1 grain. Figure 3 is typical of the areas examined.

4.2 Secondary Side Test

Two of the four mock-ups used in the secondary side corrosion test (corrosive environment was in contact with the Alloy 600 tube OD) still maintained test pressure when the test was terminated. These mock-ups, P54.16 and P54.21, survived 2623 and 2520 hours, respectively, without developing leaks in or near the sleeve expansions. Mock-ups P54.19 and P54.23 developed leaks and were depressurized and isolated from the accumulator approximately 183 hours before the test was terminated. Their total exposure times were 2337 hours (P54.19) and 2440 hours (P54.23).

The mock-ups were pressurized to 1600 psig after removal from the autoclave to identify leak locations. Mock-up P54.23 leaked in the area of the weld that attached the upper fitting to the Alloy 600 tube. This location was not near any of the sleeve expansions and thus not associated with the sleeving process. This leak was not further investigated since it was an obvious artifact associated with the specimen fabrication process.

Mock-up P54.19 leaked in the area of the upper sleeve expansions. After several days at ambient temperature, a circumferential band of white deposits, extending greater than 180°, was visible approximately 6 inches above the tubesheet location. After sectioning and flattening, numerous short axial and circumferential cracks were visible on the ID surface of the Alloy 600 tube at the 5th expansion from the top. The areas of the expansions were readily visible on the ID surfaces as a change in color of the ID oxides. The cracks were confined to the 5th expansion region. There were not any cracks visible at any of the other five expansions nor were there cracks present in non-expanded parts of the Alloy 600 tube.

The Alloy 800 sleeve in mock-up P54.19 was examined in the same manner as the tube. There were not any crack-like features noted on the OD or ID surfaces of any of the flattened surfaces.

After 2000 hours exposure, only one C-ring specimen, ABS-2 (1.5% strain) had crack-like indications when examined with the stereo-microscope at magnifications up to 49X.

After 401 additional hours of exposure, there were not any additional cracked C-ring specimens based on the stereomicroscope examination. Several specimens were mounted for metallographic examinations. Three specimens (ABS-4, 5, 6) loaded to 0.3% strain had numerous deep intergranular cracks, generally greater than 50 percent through-wall with the deepest cracks being near the apex (highest stress part). There were many shallow (less than two grains deep) intergranular penetrations between the deep cracks. This suggested a general shallow intergranular attack of the exposed surfaces with a few of the penetrations becoming dominant and developing into cracks. Specimens ABS-13, 14 and 15, which were initially loaded to 0.5% strain and then relaxed to a final strain of 0.3% did not have any deep cracks, but did have numerous shallow intergranular penetrations (less than 2 grains deep) on the OD and ID (compressive stress) surfaces.

A second set of C-rings had similar characteristics. Specimens ABS-7, 8, 9, which were loaded directly to 0.5 percent strain, had numerous deep cracks, up to approximately 70 percent through-wall. Between the deep cracks, and on the ID sides of the specimens, there were many shallow intergranular penetrations. Specimens ABS-10, 11 and 12, which were loaded to 0.7 percent strain followed by a relaxation to 0.5 percent, did not have any deep cracks, but did have many shallow (2-3 grains deep maximum depth) intergranular penetrations on the OD (tensile stress) and ID (compressive stress) side of the specimens.

SECTION 5

DISCUSSION

The tests described in this report confirmed the expected good corrosion resistance of Alloy 600 steam generator tubes with Alloy 800 mechanical sleeves installed. Although intergranular stress corrosion cracking (IGSCC) occurred in the tests with 10 percent NaOH at 660°F (with the caustic on both OD and ID of the tubes), the IGSCC was confined to the Alloy 600 tubes and did not propagate through-wall in any of the mock-ups in less than 2000 hours. There was not any degradation of the Alloy 800 other than some very shallow (less than one grain deep) intergranular penetrations. The Alloy 800 was also exposed to the test environment on both the OD and ID of the sleeves. This testing, the prior extensive service experience of Alloy 800 and other laboratory test data indicate that Alloy 800 sleeved tubes will have excellent corrosion resistance under the anticipated nominal primary and secondary environment conditions as well as faulted conditions. Use of the Alloy 800 sleeve in Alloy 600 tubes, especially those that have been degraded, will result in decreased potential for corrosion induced failures of the pressure boundary part of the tubes. The basis for this conclusion, including prior service histories and laboratory test results, are discussed in succeeding paragraphs.

The principal concern on the primary side with a sleeved joint is ID initiated stress corrosion cracking. Based on service experience and laboratory results, Alloy 800 is essentially immune to IGSCC in deareated primary water, unlike some nickel base alloys such as Alloy 600. The most significant data on primary side stress corrosion cracking of Alloy 800 is that from operating plants. There are 17 PWRs designed by one vendor, primarily in Europe, that have 59 steam generators tubed with Alloy 800. These 17 units have been in operation for 7 to over 20 EFPY (through 12/31/96) with hot leg temperatures of 582 to 620°F. Twelve of the plants operate with temperatures of 606°F or above. There have been no occurrences of primary side cracking in the over 235,000 tubes in these steam generators in the tube sheet expansion transition or the U-bends regions where the stresses are highest (1). Several additional plants in Europe have replaced degraded steam generators tubed with Alloy 600 with new steam generators tubed with Alloy 800. These plants have also not had any primary side degradation of the Alloy 800 tubes although their service experience is relatively brief.

The absence of primary side stress corrosion cracking in Alloy 800 in-service is supported by laboratory testing. Reference 2, for example, summarized laboratory testing of Alloy 800 and noted no failures.

The Alloy 600 tubes in PWR stem generators are susceptible to PWSCC with the locations where it occurs being tubesheet expansion (predominately on the hot leg), short radius U-bends (typically rows 1 or 2), the transition from straight-leg to U-bend (more common on the hot leg) and dented tube-support locations. The deformation of the tubes at these locations provides the high residual stresses that initiate and propagate PWSCC. There is significant variability in PWSCC rates resulting from variations in metallurgical conditions of the tubes, the level of residual stresses (which vary with various forming techniques) and temperature. The most

PWSCC sensitive Alloy 600 has been characterized (3) as having high strength, fine grains and predominantly intragranular carbides. In CE plants, most tubes are low strength, have coarse grain microstructures and have predominantly intergranular carbides (4).

The tube installation process producing the highest residual stresses is the hard roll process while explosive expansion and hydraulic expansion produce lower residual stresses. Explosive expansion was used for all tubesheet expansions in the CE plants. CE plants, because of the metallurgical condition of the tubes and lower residual stresses, have had relatively few occurrences of PWSCC. Calvert Cliffs-1 and 2, for example, have operated for over 140,000 EFPH at a hot leg temperature of approximately 596°F and only 2 of the 34076 tubes in these plants have been plugged because of ID initiated defects. Similarly, ANO-2 has operated for over 125,000 EFPH at temperatures of 607 or 600°F without any ID defects in the 16,822 tubes.

Installation of the Alloy 800 mechanical sleeves uses a hydraulic expansion process that results in minimal expansion of the Alloy 600 tubes. The samples included in this test program had tube expansions of 0.15 percent to 0.50 percent while tubesheet expansions are usually 2-3 percent or more. Thus, the sleeves will have lower residual stresses and, as a result, longer PWSCC lifetimes than the expansion transition of the tubes into which they are installed. Since operating CE plants have experienced few PWSCC failures, use of the sleeves will not result in any increased susceptibility and current experience provides a conservative estimate of the life of the sleeved joint with respect to PWSCC - i.e., the sleeve joint will last at least as long as the tubesheet expansions without ID cracking.

Tests similar to the ones described in this report were conducted to evaluate the sleeves for application in non-CE plants with PWSCC susceptible 3/4 inch and 7/8 inch OD tubes. In these plants, tubes were installed with a hard roll (high residual stress) process in material with yield strengths of 42 ksi and 57 ksi. Control samples included roll transition mock-ups. PWSCC initiated in the plants of interest in one cycle of operation. The 10% NaOH tests indicated that the sleeve joints would last more than 3 times as long as the roll transitions before PWSCC initiated.

OD initiated IGSCC has occurred in the tubesheet expansion transitions, at tube support locations and at free span locations in many steam generators. ODSCC occurs because of high stresses and the development of concentrated chemical solutions beneath thick deposits on the OD surfaces of tubes (for example, tubesheet sludge piles) or at crevices between tubes and tube supports. If a crack extends through-wall in an Alloy 600 tube, the Alloy 800 sleeve may be exposed to the secondary side environment that caused the Alloy 600 cracks. Alloy 800 has been studied in various faulted secondary side environments in model boiler and pot boiler tests conducted by ABB and has extensive service experience.

In the 21 PWRs previously described, there have not been any Alloy 800 tubes repaired because of OD initiated stress corrosion cracking, intergranular attack (IGA) or pitting. These corrosion mechanisms that have caused many thousands of Alloy 600 tubes to be repaired by plugging or sleeving and has led to some steam generator replacements. The only secondary side corrosion mechanism that has required tubes to be repaired is phosphate wastage. As of 12/96, 833 Alloy

800 tubes were plugged because of phosphate wastage. Although Alloy 600 is very susceptible to this corrosion problem, phosphates are no longer used to control secondary side chemistries in any Alloy 600 tubed steam generators. Thus, this is not a potential degradation mechanism for the Alloy 800 sleeves. In summary, operating experience in more than 20 plants indicates that secondary side corrosion will not be a concern for the Alloy 800 sleeve.

The favorable service experience is supported by various model and pot boilers in which Alloy 800 tubes were tested by ABB in various faulted secondary side environments at typical operating temperatures and heat flux conditions. For example:

Model Boiler 8 - Three tubes of Alloy 800, which were included in this 16 tube model boiler test, were exposed to 30 ppm chloride added as sea water for 173 days. There was no corrosion observed in the Alloy 800 tubes.

Model Boiler 5B - Three Alloy 800 tubes were included in this 16 tube model boiler test which operated for 527 days with 0.2 ppm chloride in the secondary side water. There was not any corrosion of the Alloy 800 while some Alloy 600 tubes had intergranular attack or transgranular SCC up to 15 mils deep (30% through-wall).

Model Boiler 9 - There were 2 Alloy 800 tubes in this sea water fault test which operated for 282 days with 30 ppm chloride as sea water after 114 days of a pre-fault nominal AVT chemistry. There were some pits in the Alloy 800 tubes, less than 3 mils deep while Alloy 600 tubes had pits up to 9 mils deep. There were shallow patches (2 mils deep maximum) of IGA in both Alloy 800 and Alloy 600 tubes.

Model Boiler 7 - Six Alloy 800 tubes were included in this sea water fault test which operated for 208 days. Pits were deeper in the Alloy 800 than in Alloy 600 tubes but there was also some shallow IGA in the Alloy 600 tubes but none in the Alloy 800 tubes.

These model boiler tests by ABB indicated that Alloy 800 was superior to Alloy 600 in sea water fault conditions. Other tests indicated similar performance in other possible secondary side environments. For example:

Model Boiler 1 was a fresh water fault test that ran for 287 days with shallow pitting being the only degradation noted. Pits did not exceed 0.3 mils in the Alloy 800 and 2.9 mils in the Alloy 600.

Model Boiler 10 which operated with 40 ppm sulfate and 3 ppm chloride (to simulate cooling tower fault conditions) for 472 days. The only corrosion of the Alloy 800 tubes was a wastage type (general) corrosion that was less than 3 mils deep. The Alloy 600 tubes showed more severe wastage (up to 16 mils deep) but more significantly had OD initiated circumferential cracks above the tubesheet and at tube supports.

There were several other ABB model or pot boiler tests with fresh water faulted or resin faulted secondary environments in which significant Alloy 800 corrosion did not occur. These relatively prototypical tests confirmed the conclusions of Reference 2 that, in the various primary and secondary side environments possible, there are not any material specific problems with Alloy 800.

Tests of the actual Alloy 800 sleeve in secondary environments are relatively few and limited to 10 percent NaOH. The European tests previously described concluded sleeve installation would not result in an appreciable increase in the potential for ODSCC risk. Field experience and laboratory testing indicate that OD SCC, like ID SCC, will occur in areas where the stresses and temperatures are highest. In addition, OD SCC is also driven by chemical conditions, i.e., in areas where contaminants have been concentrated by the heat transfer process. This will occur beneath thick deposits (such as tubesheet sludge piles) and in tube support crevices. Installation of Alloy 800 sleeves will not enhance the potential for cracking. As indicated above, residual stresses from installation will be minor (certainly less than at tube sheet expansions) and the sleeve itself will reduce heat transfer in the area of the sleeve expansions, producing lower temperatures and reduced tendencies to concentrate contaminants. Further, the sleeves expansions will be above any sludge piles and exterior to any support crevices with the result that the expansions will be exposed to bulk water conditions and not to concentrated solutions of contaminants. These factors will reduce the potential for cracking of the Alloy 600 tubes with sleeves installed. The lifetimes of the sleeve joints should be significantly greater than lifetimes of expansion transitions because of reduced stresses and of tubes at support locations because of the absence of concentrated solutions of contaminants.

The limited tests described in this report support previous experience and test data. The primary side tests, which had average tube deformations of 0.24 to 0.45 percent, survived over 3300 hours in the 10 percent NaOH 660°F test. This test time is significantly longer than prior European tests where one set of samples failed at less than 1400 hours and where a second set survived approximately 700 hours without any leakage or cracking based on post-test results. Two of the three samples did have through-wall circumferential cracks but they did not leak at test conditions. One did leak at a low rate (0.00082 gal/hr) at 1600 psig at room temperature. The other samples did not leak during the room temperature leak test. The probable explanation was that the NaOH solution leaked past the expansions during the initial pre-test pressure test and subsequently remained in the crevice. At temperature, the expansion of the sleeve created a leak tight joint so that when the through-wall crack developed from the exposure of the Alloy 600 tube ID to the NaOH solution in the crevice there was not any leakage. The Alloy 800 sleeve was not significantly affected by exposure to the NaOH solutions, confirming prior observations of good corrosion resistance in this environment. Comparisons of the test time in this test with the test times in prior sleeve tests indicates that this type sleeve will survive several cycles of operation without risk of primary side degradation.

The secondary side test results were also favorable relative to prior sleeve tests. The four mock-ups all survived more than 2300 hours and two survived 2520 hours and 2623 hours. Only one of the four developed a through-wall crack in the area of a sleeve expansion and leaked during the test. All of the mock-ups survived significantly greater times in 10 percent NaOH than did the mock-ups in the previously discussed tests.

SECTION 6

CONCLUSIONS

1. Field experience and laboratory test results indicate that Alloy 800 in the same conditions as planned for the mechanical sleeves will not be susceptible to stress corrosion cracking initiated in nominal primary side environments. The tubesheet expansion transitions and U-bend regions in operating steam generators have higher residual stresses than will be present in the hydraulically expanded transition in the Alloy 800 sleeves. Thus, the Alloy 800 sleeves can be considered immune to PWSCC for more than 10-20 EFPY.

2. The Alloy 600 tubes in CE steam generators have better resistance to PWSCC than tubes in other PWRs where numerous failures have occurred. The sleeve expansions have less plastic deformation than tubesheet expansions and, as a result, will have lower residual stresses which will translate to longer lifetimes. The PWSCC lifetimes of the sleeved Alloy 600 tubes can conservatively be assumed to be greater than the current operating times for the expansion transitions, which means that most sleeved tubes will survive more than 10 EFPY without PWSCC of the Alloy 600 tubes.

2. In nominal and faulted secondary side environments, installation of Alloy 800 mechanical sleeves will not significantly increase the potential for OD SCC of the Alloy 600 tubes in the area of the expansions. The expansions will have lower residual stresses than tubesheet expansions of the tubes or U-bend regions as a result of less plastic deformation. Further, the expansions will be in areas where they will be exposed to nominal bulk-water conditions as opposed to the concentrated solutions present in tube support crevices and sludge piles. The sleeved tubes should have lifetimes exceeding those of tubes that have cracked at tubesheet expansions or tube support locations. In CE plants, for example, this should be at least 10 EFPY.

4. If any Alloy 600 tubes with Alloy 800 sleeves installed develop through-wall cracks, the Alloy 800 sleeves will last at least as long as the Alloy 600 tubes did before cracking. Extensive laboratory testing in high caustic, seawater faulted, freshwater faulted, cooling tower water faulted and resin faulted environments under prototypical temperature and heat transfer conditions indicate that Alloy 800 is superior or at least equivalent to Alloy 600.

5. Alloy 600 tubes with Alloy 800 mechanical sleeves installed will have good corrosion resistance and, as a result, these tubes will have decreased potential for corrosion induced failures of the pressure boundary part of the tube.

6. Comparison with results of other testing indicates the Alloy 800 sleeved tubes will survive several cycles of operation without risk of ID or OD initiated failures of the Alloy 600 tubes.

SECTION 7

REFERENCES

1. Steam Generator Progress Report, Revision 13, EPRI, November 1997.

2. R. Kilian, N. Wieling, and L. Stieding, "Corrosion Resistance of SG Tubing Material Incoloy 800 Mod. and Inconel 690TT", Werkscoffe und Korrosion, V43, pp 490-496, (1991).

3. J. A. Gorman, "Status and Suggested Course of Action for Non-Denting Related Primary-Side IGSCC of Westinghouse - Type Steam Generators", EPRI NP-4594-LD, May 1986.

4. C. M. Owens, "The Primary Side Stress Corrosion Cracking Performance of Mill Annealed Inconel - 600 Tubing in C-E Designed Steam Generators", NEQ/CSNI-UNIPEDE Specialist Meeting on Steam Generators, Stockholm, Sweden, October 1-5, 1984.

TABLE 1

C-RING SPECIMEN TEST RESULTS

ID	PEAK STRAIN %	FINAL STRAIN %	TEST EXPOSURE, HOURS	VISUAL RESULTS	MICROSCOPE EXAM RESULTS
ABS-1	1.5	1.5	2458	NC	NE
ABS-2	1.5	1.5	2057	CRACKS	NE
ABS-3	1.5	1.5	2458	NC	NE
ABS-4	0.3	0.3	2458	NC	CRACKS > 50%
ABS-5	0.3	0.3	2458	NC	CRACKS > 50%
ABS-6	0.3	0.3	2458	NC	CRACKS > 50%
ABS-7	0.5	0.5	2458	NC	CRACKS > 70%
ABS-8	0.5	0.5	2458	NC	CRACKS > 70%
ABS-9	0.5	0.5	2458	NC	CRACKS > 70%
ABS-10	0.7	0.5	2458	NC	NC
ABS-11	0.7	0.5	2458	NC	NC
ABS-12	0.7	0.5	2458	NC	NC
ABS-13	0.5	0.3	2057	NC	NC
ABS-14	0.5	0.3	2057	NC	NC
ABS-15	0.5	0.3	2458	NC	NC
ABS-16	1.7	1.5	2458	NC	NE
ABS-17	1.7	1.5	2458	NC	NE
ABS-18	1.7	1.5	2458	NC	NE

Note: NC - No Cracks
NE - Not Examined

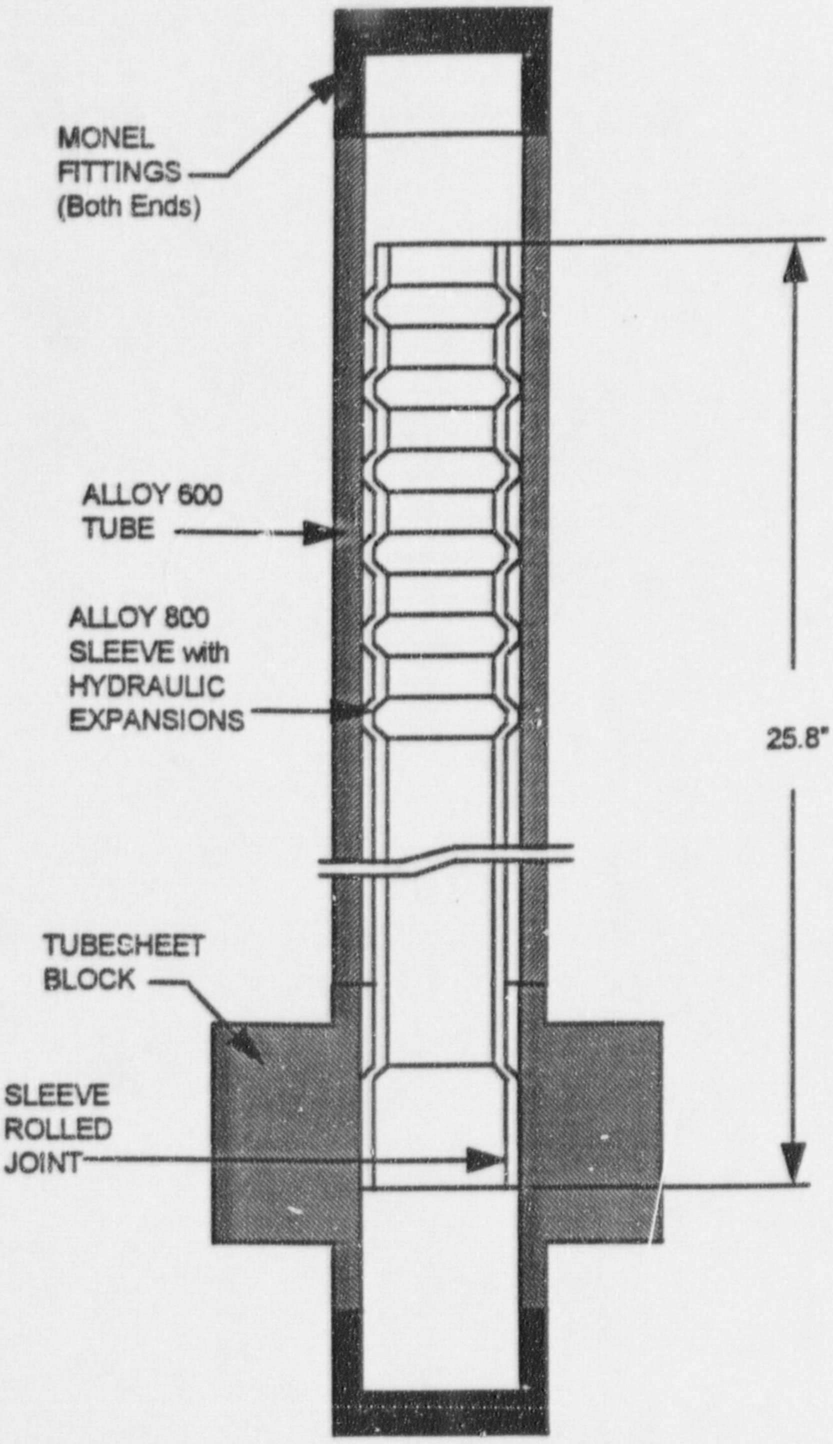
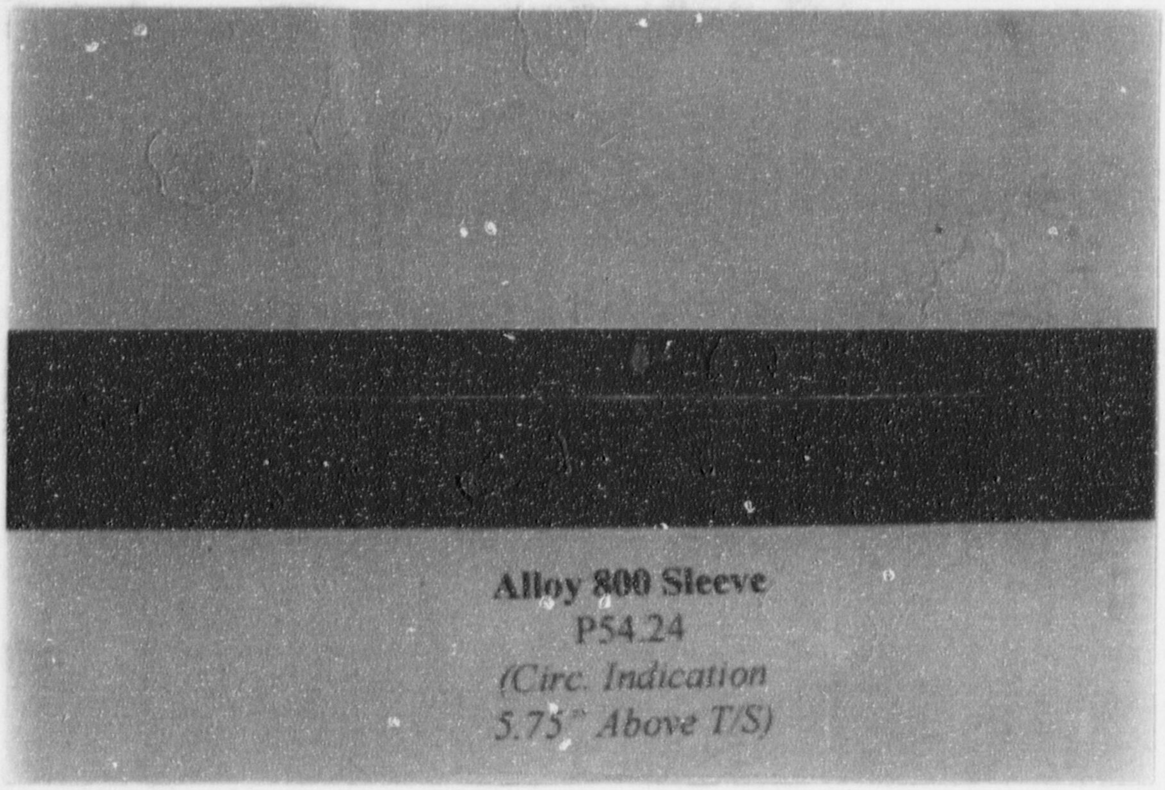
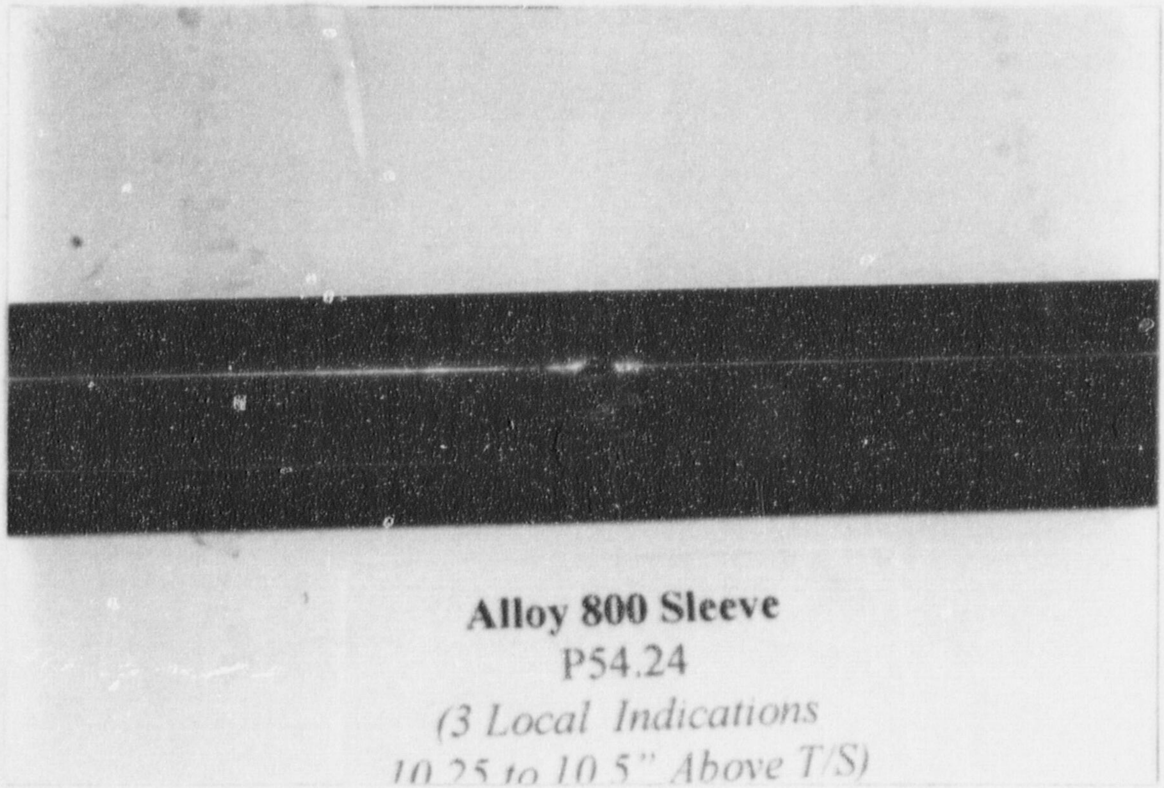


Figure 1. Schematic of Sleeved Tube Mock-ups



Circumferential Crack 5-3/4 Inches Above Tubesheet



Three Axial Cracks 10-1/4 to 10-1/2 Inches Above Tubesheet

Figure 2. Cracks Visible in Primary Side Test Mock-up P54.24

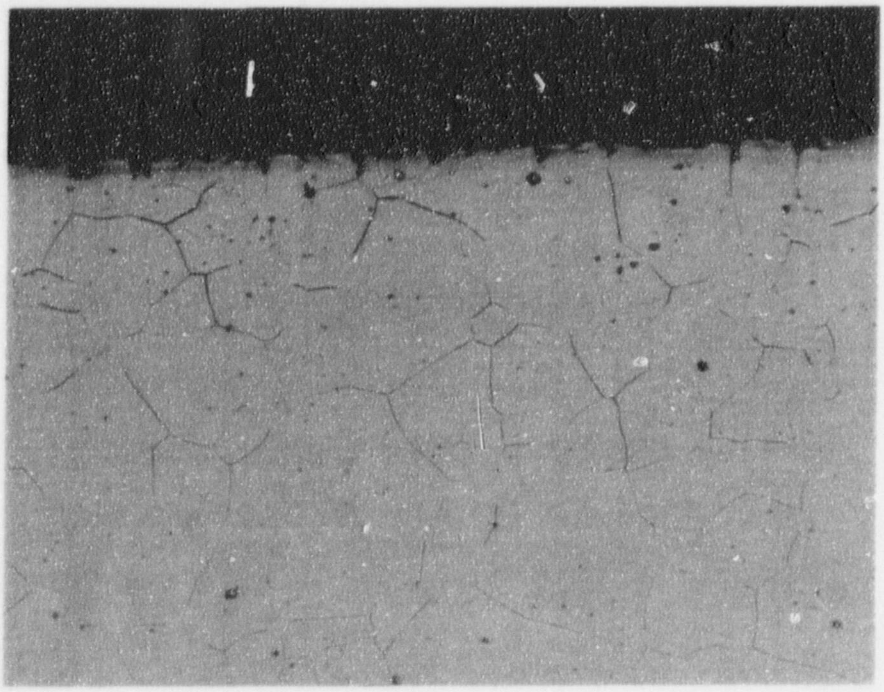


Figure 3. Shallow Intergranular Penetrations in the Alloy 800 Sleeve from Mock-Up P54.24 (200X, Electrolytic Nital Etch)

ATTACHMENT (1)

ABB-CE Report No. 98-FSW-021

Baltimore Gas & Electric Company
Docket Nos. 50-317 and 50-318
May 25, 1999