Evaluation of a Steam Generator Tube Repair Process
Using an Explosive Expansion Technique at TMI-1

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ABSTRACT

After a planned shutdown of Unit No. 1 at Three Mile Island, cracks were discovered in the primary side of steam generator tubes in the vicinity of the upper surface of the upper tubesheet. The nature of these cracks was later characterized as intergranular stress corrosion. The licensee, General Public Utilities Nuclear (GPUN), proposed to form a new tube-to-tubesheet seal below the cracks using a repair process wherein a detonating cord and polyethylene cartridge assembly inserted into the tube explosively expand the tube against the tubesheet.

The explosive expansion process has had numerous applications over the years in the initial fabrication of heat exchanger tube-to-tubesheet assemblies and in repair processes using sleeving. However, this is the first use of this process in a steam generator to expand a previously rolled tube and to form a new seal between it and the tubesheet below a defective region in the tube.

The seal obtained between the tube and tubesheet depends on the magnitude of explosive energy released in the detonating process. In this application, it is desired to obtain a mechanical bond rather than a metallurgical welding of the tube and tubesheet. A number of critical variables must be taken into account in order to obtain a successful mechanical seal. These include the explosive power of the detonating cord, the number of expansion shots used, the length of tube which is expanded, cartridge and tube diameters, the diameter of the tubesheet hole, the materials of the tube and tubesheet, and the condition of the surfaces at the time of repair.

The Franklin Research Center (FRC) conducted a review and evaluation of the licensee's procedures and also performed an independent test program for verification of the adequacy of the repair process. The testing was performed on two multiple tube assemblies designed to model the tube-to-tubesheet configuration in a once-through steam generator. In addition, the surfaces and strength levels of the tube and tubesheet components simulated those in the generators. Tubes were explosively expanded into the test blocks and subsequently subjected to axial load cycling, leak tests, and pullout tests, and tubesheets were sectioned for measurement of residual strain. Based on the test results, the proposed procedure was deemed adequate for the repair.
1. BACKGROUND

Under a contract with the U.S. Nuclear Regulatory Commission (NRC), the Franklin Research Center (FRC) conducted an independent review and evaluation of a General Public Utilities Nuclear (GPUN) proposed procedure for repairing tubes in both of the once-through steam generators (OTSGs) in Unit 1 at Three Mile Island (TMI). These tubes had experienced sulfide stress corrosion cracking [1] during a shutdown, owing to contamination of the primary water with sodium thiosulfate. Most of these cracks were at the outer diameter (OD) welds fastening the tubes to the upper surface of the upper tubesheet and at the inner diameter (ID) transition regions of the rolled expansions of the tubes, about 2 inches from the top of the tubesheet.

Based upon a developmental test program, GPUN, in association with Babcock & Wilcox (B&W) and Foster Wheeler Energy Applications (FWEA), proposed a repair method using an explosive (kinetic) technique [2]. A sufficient length of undamaged tube below the defects would be expanded to form a new tube/tubesheet seal. The total length of the expansion joint and the portion of that length to be qualified for specific leak rate and pullout strength goals were selected primarily on the basis of the locations of the tube defects and the maximum number of tubes that would be repairable by a standardised procedure. Accordingly, all OTSG tubes were to be expanded over 17 inches, with the lower 6 inches of this expansion the qualified seal.

Specific details of the expansion process are considered proprietary by GPUN. However, it can be reported that a two-step explosive expansion was deemed optimum with regard to effecting a seal without inducing distortion in the tubesheet. The seal, which is a mechanical interference rather than a metallurgical weld between the tube and the tubesheet, is influenced by such variables as the size and nature of the explosive charge, the mechanical characteristics of the tube and tubesheet materials, the spacing between the components, and the nature of the components' surfaces.

In this case, a detonating cord charge is inserted in a polyethylene tube or candle which, in turn, is placed in the tube to be expanded. The explosive force from the charge drives the candle against the tube, forcing it against the tubesheet. The first expansion is meant to bring the tube and tubesheet into contact, whereas the second is to improve the seal.

A similar explosive technique has been and is being used in the initial fabrication of heat exchanger tube/tubesheet assemblies. However, this is the first time such a process has been applied to expand previously rolled tubes and thus to form a new tube/tubesheet seal below defect regions in the tubes.

Once the repair procedure parameters were established, GPUN and its associates undertook an extensive test program to evaluate whether the repair would meet the various qualification criteria [3]. FRC had access to all the test procedures and data and performed its own parallel testing and evaluation programs. These tests were not as extensive as GPUN's in terms of duplicate tests, since FRC's role was to provide an independent assessment of the efficacy of the repair and of the modifications, if any, to the integrity of the steam generators, rather than to establish a statistical evaluation of the repair criteria.
2. EVALUATION PROGRAM

2.1 Criteria

A detailed test program was developed by GPUN to qualify the repair procedure. There were three primary considerations [2]:

1. The procedure should affect a seal with a leak rate well below the technical specification limit for the plant (1 gal/min or 500.22 lb/hr total leakage for both generators). The leakage rate goal set by GPUN was 1 lb/hr total from both generators or $3.2 \times 10^{-5}$ lb/hr per tube.

2. The seal should be of sufficient strength to resist tube pullout under the worst-case stress condition, a main steam line break (MSLB) resulting in a 3140-lb load on each tube owing to the large difference in temperature between the tubes and the shell/tubesheet assembly.

3. The expansion process should not adversely affect the structural integrity or efficiency of the OTSG. In particular, the tubesheet ligaments should not be overstressed, and the pretension in the tubes (to prevent buckling on a feedwater line break) should not be reduced.

The first of these two considerations could be addressed with samples simulating the OTSG, as described below, while the third could only be partially evaluated on simulation samples; thus, field tests on a full scale generator were conducted by B&W.

2.2 Test Samples

PNC performed leakage, pullout, and residual stress measurements on two 10-tube mock-up assemblies (F-1 and F-2). The tubes and tubesheet components, which were obtained from B&W along with characterization documentation, had been heat treated to simulate strength levels and surface conditions in the OTSGs. Furthermore, both 10-tube assemblies included both high and low yield strength tubing characteristic of the tubes in the OTSGs.

In order to simulate a full circumferential crack 2 inches below the upper surface of the tubesheet, a separate 2-inch section of tubing was rolled into the tubesheet. The test sections were then butted against these stub ends and the expansion carried out over a total of 8 inches, 6 inches of each of the test samples and 2 inches of the stub.

The tubes in one assembly had been expanded one row at a time at PWEA's Livingston, New Jersey, facility, while the tubes in the second assembly were expanded at PNC, using standardized charges and candles supplied by PWEA. These latter tubes were expanded one at a time so that the role, if any, of subsequent after-hits upon an expanded tube/tubesheet joint could be evaluated in the testing.

Following expansion, both 10-tube mock-ups were subjected to a 125 psi primary-to-secondary bubble test to assure that all tubes had indeed been sealed. A few bubbles did emanate from most tubes, but there was no evidence of poor seals.

Next, all tubes were individually subjected to a series of axial stressings to simulate 5 years of service load transitions. The actual stresses in service are induced by temperature differences between the tubes and the shell-tubesheet
assembly. In GPUN's testing program, the 10-tube blocks were either axially stress cycled at room temperature or appropriately thermal cycled (without stressing) [4].

FRC's tests were limited to axial stress cycling since it was felt the axial stresses themselves were of primary importance on the joint. The temperature differences between a tube and the tubesheet at the expanded joint during heating and cooling at rates representative of those in an OTSG must be quite small. Accordingly, the stress cycling were as follows:

1. heatup from cold shutdown to 8% power and cooldown from 8% power to cold shutdown - 
   100 cycles at 780 lb compression to 1100 lb compression
2. power change 0 to 15% and 15% to 0 - 
   180 cycles at 635 lb compression to 175 lb compression
3. power loading 8% to 100% and unloading 100% to 8% - 
   6000 cycles at 510 lb compression to 125 lb compression.

No tubes exhibited any slippage during these conditioning tests.

2.3 Tube Interference

In the 10-tube assembly expanded at FRC, the ID and OD of each tube and the ID of the tubesheet hole were measured at two locations prior to expansion and the ID of each tube was measured at those same locations following each expansion. The average data appear in Table 1. After the first expansion, the D measurements were relatively identical for all sections of the tubes including the stub ends. The first expansion clearly induced an interference as indicated by the fact that the diametral change due to the first expansion was greater than the tube hole clearance. The diametral change due to the second expansion was at least one order of magnitude smaller than that from the first expansion, indicating that the second expansion contributes to the interference fit without imparting excessive deformation to the tubesheet.

2.4 Leaktightness

Following the axial load cycling, the test blocks were subjected to both primary-to-secondary and secondary-to-primary water leakage tests. The leakage rates at room temperature after 72 hours conditioning are summarized below:

<table>
<thead>
<tr>
<th>Tube Assembly</th>
<th>Pressure (psig)</th>
<th>Pressure Direction</th>
<th>Average Leak Rate per Tube (lb/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F-1</td>
<td>1275</td>
<td>Secondary to Primary</td>
<td>6.37 x 10^-5</td>
</tr>
<tr>
<td>F-1</td>
<td>1275</td>
<td>Primary to Secondary</td>
<td>2.49 x 10^-5</td>
</tr>
<tr>
<td>F-1</td>
<td>2500</td>
<td>Primary to Secondary</td>
<td>2.94 x 10^-5</td>
</tr>
<tr>
<td>F-2</td>
<td>1275</td>
<td>Secondary to Primary</td>
<td>1.07 x 10^-5</td>
</tr>
<tr>
<td>F-2</td>
<td>1275</td>
<td>Primary to Secondary</td>
<td>1.28 x 10^-5</td>
</tr>
<tr>
<td>F-2</td>
<td>2500</td>
<td>Primary to Secondary</td>
<td>1.90 x 10^-5</td>
</tr>
</tbody>
</table>

The differential pressure of 1275 psig primary to secondary is representative of the OTSG operation and would tend to hold the tube against the tubesheet. The test with the pressure differential reversed represents a loss-of-coolant accident (LOCA) and is the most severe leakage test since the differential pressure is working to
break the tube/tubesheet seal. The 2500-psig test is representative of pressure conditions under a MSGB. As can be seen from the data, all the leakage rates except that for the test of 1275 psig secondary to primary differential on assembly F-1 were less than GPUN's goal of 3.2 x 10^-5 lb/hr per tube, and all rates were well below the technical specifications.

2.5 Tube Pullout

The data for tube pullout tests on mock-ups F-1 and F-2 are summarized in Table II. As discussed below, six of the tubes in assembly F-1 were left intact in the "tubesheet" so that residual strain measurements could be conducted on the ligaments between tubes on cross sections of the assembly. As stated previously, the qualification pullout load goal of 3140 lb was based on the worst case, MSGB-induced thermal length changes of the tube and tubesheet/shell assembly. Since an elongation strain of 0.0016 in/in in each tube would nullify the thermal length change differences [5], the stress on each tube is strain limited. Accordingly, in the qualification tests, if there was no slippage or reduction in load prior to 0.0016 in/in elastic plus plastic strain, the joint would clearly be adequate for generator service. However, the load to cause this strain could be less than 3140 lb, and in keeping with the original qualification goals, the tests on block F-1 were continued until the maximum load that could be sustained by the joint was achieved.

As shown in Table II for test block F-1, the total elongation at maximum load of each tube relative to the bottom surface of the tubesheet was well above 0.016 in, the elongation corresponding to 0.0016 strain in a 10-in-long tube. The elongations on the high yield (HY) tubing were about half those for the low yield (LY) tubing, consistent with the larger amount of plastic deformation in the latter. These results clearly indicate the ability of the joint to satisfy the pullout strength goals.

For block F-2, the total tube movement (elastic and plastic deformation plus any slippage) was monitored and loads were determined for yielding (when the load versus time curve under constant loading rate deviated from linearity). As can be seen in Table II, as expected, the load on each low yield tube at yielding was close to or below the 3140-lb goal. At elongation of 0.030 in (0.003 in/in strain) and 0.060 in (0.006 in/in strain), the maximum load had not yet been reached in any tubes, but the elongations were so much larger than could be expected on actual steam generator tubes that tests were not continued to actual pullout.

2.6 Ligament Stress

Strain gages were used to measure the tubesheet ligament springback which occurred when expanded tubes were machined out of a cross section of 10-tube block F-1. Based on these tests, the following observations were made:

1. In general, some amount of strain relaxation in the tubesheet ligaments occurred in the immediate vicinity of a tube that was partially machined and removed. This phenomenon was more pronounced for ligaments between low yield strength tubes.
2. The stress state of the tubesheet ligaments away from a tube subjected to machining appeared unaffected by the tube removal process.

3. The small measured amounts of strain relaxation in the tubesheet ligaments indicate that the kinetic expansion did not induce excessive plastic deformation in the tubesheet nor did it alter the dimensional integrity.

3. CONCLUSIONS

1. The kinetic (explosive) expansion technique is an effective means for repairing the cracked tubes in the TMI-1 OTSGs. By forming a new tube/tubesheet seal joint below the cracks in the tubes, the cracked regions are essentially removed from the system.

2. A two-step expansion procedure accomplishes a tight seal without excessive deformation of the tubesheet. The initial expansion expands the tube into contact with the tubesheet, while the second completes the seal.

3. In general, the results of testing and analysis have shown that the repair process should satisfy GPU's qualification requirements. To the extent, then, that the test assemblies used represent a reasonable simulation of the TMI-1 OTSGs, the repair process being implemented at TMI-1 should meet its objectives.

4. It should be noted that the differences between the test assemblies and the actual generator include the following:
   a. length of expansion
   b. number of tubes simultaneously expanded
   c. tube length (different impedance to expansion)
   d. geometry of tube sheet
   e. variation in tube-to-tubesheet crevice conditions.

None of these differences should have a significant influence on the effectiveness of the repair process. In this regard, the hot functional tests, planned as a part of the start-up program following repairs, should serve to verify the adequacy of the tube/tubesheet seals.

REFERENCES

1. A. K. Agrawal, W. M. Stiegelmeyer, and W. E. Berry, "Final Report on Failure Analysis of Inconel 600 Tubes from OTSG A and B of Three Mile Island Unit 1," Battelle Columbus Laboratory, 30-Jun-82


### TABLE I. Tube and Tubesheet Averaged Data

**Tube Data**

<table>
<thead>
<tr>
<th>D₀</th>
<th>D₁</th>
<th>D₂</th>
<th>D₁-D₀</th>
<th>D₂-D₁</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5504&quot;</td>
<td>0.5656&quot;</td>
<td>0.5659&quot;</td>
<td>0.0152&quot;</td>
<td>0.0003&quot;</td>
</tr>
</tbody>
</table>

**Interference Data**

<table>
<thead>
<tr>
<th>IDₜₛ</th>
<th>ODₜ</th>
<th>IDₜₛ-ODₜ</th>
<th>Dᵢₙ = (D₂-D₀)-(IDₜₛ-ODₜ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6396&quot;</td>
<td>0.6283&quot;</td>
<td>0.0113&quot;</td>
<td>0.0042&quot;</td>
</tr>
</tbody>
</table>

**Notation:**

- D₀ = inside diameter of tube before expansion
- D₁ = inside diameter of tube after first expansion
- D₂ = inside diameter of tube after second expansion
- D₁-D₀ = diametral change due to first expansion
- D₂-D₁ = diametral change due to second expansion
- IDₜₛ = diameter of tubesheet hole before expansion
- ODₜ = outside diameter of tube before expansion
- IDₜₛ-ODₜ = clearance
- Dᵢₙ = interference

### TABLE II. Summary of Tube Pull-Out Testing

#### A. Block F-1

<table>
<thead>
<tr>
<th>Tube</th>
<th>Strength</th>
<th>Max Load (lb)</th>
<th>Tube Elongation at Max Load (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>HY</td>
<td>4100</td>
<td>0.051</td>
</tr>
<tr>
<td>3</td>
<td>LY</td>
<td>4000</td>
<td>0.105</td>
</tr>
<tr>
<td>8</td>
<td>HY</td>
<td>4050</td>
<td>0.041</td>
</tr>
<tr>
<td>9</td>
<td>LY</td>
<td>3800</td>
<td>0.092</td>
</tr>
</tbody>
</table>

#### B. Block F-2

<table>
<thead>
<tr>
<th>Tube</th>
<th>Strength</th>
<th>No. of After Hits</th>
<th>Yield Load (lb)</th>
<th>Load (lb) at 0.030-in Elongation</th>
<th>Elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HY</td>
<td>1</td>
<td>3800</td>
<td>3900</td>
<td>4120</td>
</tr>
<tr>
<td>2</td>
<td>HY</td>
<td>2</td>
<td>3500</td>
<td>3740</td>
<td>3900</td>
</tr>
<tr>
<td>3</td>
<td>LY</td>
<td>1</td>
<td>3200</td>
<td>3275</td>
<td>3500</td>
</tr>
<tr>
<td>4</td>
<td>HY</td>
<td>0</td>
<td>3750</td>
<td>3800</td>
<td>4000</td>
</tr>
<tr>
<td>5</td>
<td>HY</td>
<td>6</td>
<td>3700</td>
<td>3820</td>
<td>4000</td>
</tr>
<tr>
<td>6</td>
<td>LY</td>
<td>5</td>
<td>3034</td>
<td>3275</td>
<td>3450</td>
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<tr>
<td>7</td>
<td>LY</td>
<td>0</td>
<td>2900</td>
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<td>1</td>
<td>3750</td>
<td>3860</td>
<td>4060</td>
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<td>3170</td>
<td>3430</td>
<td>3675</td>
</tr>
<tr>
<td>10</td>
<td>LY</td>
<td>1</td>
<td>3150</td>
<td>3300</td>
<td>3500</td>
</tr>
</tbody>
</table>

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