BAW-10195
REVISION 00
MARCH 1994

W-44 F* QUALIFICATION REPORT

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B&W NUCLEAR TECHNOLOGIES
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GLOSSARY OF TERMS

F*	The qualified length below which a defect indication could exist, in the roll expanded section of tube in the tubesheet, and still remain in service
GPM	Gallons Per Minute
LOCA	Loss of Coolant Accident
Locked Tube	A tube which is fixed to the tube support plate, through denting or other corrosion by-products, resulting in potential thermal differential growth loads between the tube, the support plate, and the tubesheet
NDE	Non-Destructive Examination
PWSCC	Primary Water Stress Corrosion Cracking
RSG	Recirculating Steam Generator
RPC	Rotating Pancake eddy current inspection Coil
Roll Transition	The area of a roll expansion between the effective part of the roll (that which applies full radial preload into the tubesheet) and the unexpanded area of the tube. Typically, the roll transition is ¼ inch long.
Springback	The amount that a tube expands when it is liberated from a mockup block after roll expansion. This value is used to determine the amount of tube radial preload from roll expansion.
T_{avg}	The average temperature of the reactor vessel inlet and outlet nozzles
TSP	Tube Support Plate
Ultimate Load	The maximum load that the F* qualification joint was able to support prior to [(d)] tube movement during testing
PWHT	Post Weld Heat Treatment

1.0 INTRODUCTION

Primary Water Stress Corrosion Cracking (PWSCC) has been found to occur at the tube-to-tubesheet roll transitions in many Pressurized Water Reactor u-tube steam generators during routine non-destructive inspections. Without an acceptance criteria, such as F*, it is necessary to repair or remove the tube from service when defects are found which exceed the current plugging limits.

The F* acceptance criteria describes a distance of undegraded expanded tube within the tubesheet, below which an indication can exist and remain in service provided that the distance satisfies structural and leakage characteristics. This document describes the testing and analysis supporting an F* distance that is acceptable in terms of both joint strength and leakage for use as an acceptance criteria for the Indian Point-2 W-44 RSGs. Data is presented on the F* design requirements, verification testing, analysis results, nondestructive examinations, and tubesheet corrosion concerns. In addition, a no significant hazards review is provided which documents that use of the F* acceptance criteria does not increase the risk of creating an unanalyzed accident nor does it reduce the margin of safety of the pressure boundary within the steam generator.

2.0 BACKGROUND

The W-44 RSGs at Indian Point Unit 2 were constructed with 0.875 inch OD x 0.050 inch wall mill annealed alloy 600 tubing. The tubing was roll expanded into the tubesheet for [(c)]. A [(c)] was first made at the end of the tube to allow for seal welding at the tubesheet primary face. Next, a [(c)] was made at the end of the tube. This second roll expansion operation was performed for a structural joint. See Figure 2.1 for a representation of the tube-to-tubesheet roll expansion.

Operating experience of steam generators with similar tube material and roll expansion geometry has shown that PWSCC can occur in the tube-to-tubesheet roll transitions and skip roll areas. The F* acceptance criteria is designed to eliminate the need for plugging or other tube repairs when an indication occurs below the effective area of the uppermost roll transition. The F* distance between the uppermost defect and the effective area of the uppermost roll transition must be shown to:

- Exhibit an acceptable joint strength to carry normal operating and faulted loads, as defined by NRC Regulatory Guide 1.121, Reference 7.1.

- Demonstrate a leak rate within plant Technical Specification Limits.

The final F* criteria that is developed must also be inspectable using standard steam generator eddy current techniques. Measurement tolerances associated with remote eddy current measurements must be factored into the final F* value.

Based on the testing and analysis performed by BWNT, and documented in this report, the F* criteria has been qualified for use within the Indian Point Unit 2 W-44 RSGs.

Figure 2.1
Indian Point Unit 2 Tubesheet Roll Expansion Profile

[

(c)

]

3.0 SUMMARY

The F* acceptance criteria has been qualified for use in W-44 RSGs into tubes which have been partially expanded into the tubesheet (up to [(d)] deep from the primary face) by mechanical hard rolling. Specifically, this qualification covers the Indian Point Unit 2 steam generators. The use of this criteria will allow tubes with otherwise pluggable eddy current indications to remain in service as long as the indications are a minimum distance below the lower end of the uppermost roll transition (F*). The F* distance has been determined to be [(d)]. The basis for arriving at the F* criteria was through analysis, testing, and eddy current roll length accuracy determination.

Through analysis, the normal operation and faulted loading conditions were determined using W-44 RSG operating and design conditions for Indian Point Unit 2. The NRC Regulatory Guide 1.121 safety factors of 3 for normal operation and 1.43 for faulted conditions were also used in developing the loads. Loads which could be imparted on the tubes from becoming locked into the tube support plates were also considered. The testing performed bounds those that would be imposed as a result of a LOCA.

The joint strength and leakage of various lengths of the tube-to-tubesheet roll expansions were tested under the most conservative conditions. After performing a thermal soak on the mockup block, leak testing, load testing, pressure cycling, and ultimate load testing were performed. The mockup samples were made to simulate the actual installed roll expansion fabrication variations and loading conditions within the W-44 RSGs.

Further analyses were performed to calculate the effects that operating and faulted conditions have on the residual tube radial stress level. A comparison was made between the as-installed and tested radial stress level to the normal operating and faulted condition radial stresses. The F* value qualified by testing was corrected by the analysis to account for the conditions which could not adequately be simulated through testing (i.e., radial thermal growth and tubesheet bow). The final F* qualification length, based on the results of analysis and testing, was [(d)]. This dimension does not include measurement tolerances from eddy current.

Eddy current testing, using a typical steam generator inspection system, was performed to determine measurement accuracy and repeatability. Both bobbin and Rotating Pancake Coil (RPC) eddy current were used as part of this testing. This resulted in an additional [(d)] being added to the qualified F* length to account for the most conservative ECT method tolerance length measurement.

The final result of this qualification program is that a [(d)] is adequate to restrict tube motion and maintain leakage within the Indian Point Unit 2 technical specification limits for all steam generator tubes.

The effects of boric acid corrosion on the carbon steel tubesheet were examined in the event that the tubesheet is exposed to primary side fluid. The results of this study show that the effects of boric acid corrosion from the primary fluid is considered to be insignificant for defects typically associated with F* criteria.

4.0 DESIGN CRITERIA

4.1 General Requirements

The US NRC Regulatory Guide 1.121 and the ASME Boiler and Pressure Vessel Code were used to establish the safety factors for evaluating the roll expanded tube-to-tubesheet interface associated with F*. These safety factors correspond to 3 for normal operating condition and 1.43 for faulted condition loading per References 7.1 and 7.2. This qualification is to demonstrate that a degraded tube could sever at a F* distance and remain structurally adequate to withstand expected loading conditions while minimizing primary-to-secondary system leakage. The applicable design conditions used for F* criteria evaluation are given in Reference 7.3 and are summarized in this section.

4.2 Functional Requirements

The design (F* criteria), which is based on the original tube roll, shall provide a mechanical leak limiting seal between the tube and tubesheet above the degraded location. Primary-to-secondary system leakage shall be throttled such that the station Technical Specification limits are satisfied. In addition, it shall be assumed that below some overall F* criteria length, the tube severs 360 degrees circumferentially such that the remaining joint carries all anticipated loading conditions, including the margins of safety described above.

4.3 Design and Operational Loading Conditions

The design and operating conditions for the steam generator are used for determining and evaluating the F* criteria. These conditions are listed in Table 4.2.1 for the W-44 RSGs at Indian Point Unit 2. In order to conservatively analyze the tube loads and radial stresses, a composite of the worst case nominal T_{avg} and low T_{avg} operating conditions for temperature and pressure were considered and are listed for the normal operating parameters. The high T_{avg} conditions were considered, but the most conservative analysis and test values were derived from nominal and low T_{avg} operating conditions, as listed in Reference 7.3. The three T_{avg} conditions were presented for the Indian Point Unit 2 steam generators based on present and future operating primary and secondary system setpoints. The operating parameters used to calculate the locked tube loads are also listed. [

(c)

]. Figure 4.2.1 summarizes the key Indian Point Unit 2 steam generator geometry and material constraints.

4.4 Corrosion

The W-44 tubesheet is made of [(c)

]. In the steam generator design, the tubesheet is isolated from the primary coolant by the cladding, the Alloy 600 tubing and the tube-to-tubesheet weld at the primary face of the tubesheet. Any breach of these boundaries, such as through PWSCC cracks in the tubing, may initiate corrosion of the tubesheet. Therefore, the effects of boric acid corrosion, from primary system fluid in contact with the carbon steel tubesheet through F* type cracks, shall be considered.

Figure 4.2.1
Indian Point Unit 2 W-44 RSG General Arrangement

[

(c)

]

Table 4.2.1

Indian Point Unit 2 W-44 RSG Performance Characteristics

[

(c)

]

5.0 DESIGN VERIFICATION

5.1 Analyses

Analyses were performed to determine radial preload stresses associated with the manufacturing shop roll expansion versus those present at operating, faulted, and test conditions. In addition, loads on the tubes during normal operation and faulted conditions and loads associated with tubes locked into the tube support plates were developed per Reference 7.4. NRC Regulatory Guide 1.121 was used for determining the safety factors that were placed on the calculated loads for normal operating and faulted conditions.

All analysis and testing was performed in accordance with the BWNT Safety Related QA Manual, Reference 7.7.

5.1.1 Radial Stress and Loading

During the tube roll expansion operation a residual radial preload stress is placed into the tube. This stress holds the tube against the tubesheet bore. During the operation of the plant three factors affect this shop preload stress. These are the radial differential thermal growth of the tube with respect to the tubesheet, the primary side internal pressure on the tube, and the tubesheet bore dilation as a result of tubesheet bowing.

o [

(c)

].

o [

(c)

].

o [

(c)

] The qualified F* length for the W-44 RSG is for partial roll expansions up to half the thickness of the tubesheet, [(c)].

Note that as the location of the F* joint progresses through the thickness of the tubesheet the effects of tubesheet bow move from the periphery to the center to the tubesheet. F* locations above half the thickness of the tubesheet were not considered as part of this analysis due to geometry changes in performing the tubesheet bow calculations and due to the location of the existing roll expansion at the primary face of the tubesheet.

The initial radial preload stresses were determined from tube installation springback data for operating, faulted, and test conditions. These radial stress values were used to derive a ratio relating the test conditions with those postulated to exist within the steam generator.

The average tube springback, from the testing discussed in Section 5.2.2, was [(d)]. This value was used to calculate the initial radial stress. The effects on tube radial stress from thermal and pressure growth and tubesheet bow were determined and added to the initial springback radial stress. The results of this analysis, per Reference 7.4, are shown on Table 5.1.1. [

(d)

].

The axial loads for each of the analysis and test conditions are also included on Table 5.1.1. [

(c)

].

Seismic and flow tube loads were also calculated for normal and accident conditions. [

(d)

].

Tube radial stress, test loads, and joint leakage were also evaluated for loss of coolant accident (LOCA) conditions of [

(c)

].

[(c)]

5.1.2 Locked Tube Loading

The locked tube load is a secondary loading condition that assumes that a single tube locks into a tube support plate (TSP) at 100% power operating conditions. The pressure strain associated with the normal operating pressure differential and the thermal differential growth between the tube and TSP/shell/wrapper affect the load on the tube. [

(c)

]. The following summarizes the two cases used to determine the maximum locked tube load.

1) [

(c)

].

2) [

(c)

].

[(d)]

[

(d)

].

5.1.3 F* Determination

A technique was developed, in Reference 7.4, for determining the required F* length by correlating the analysis results for postulated steam generator conditions with room temperature mechanical test results. The analysis results are shown on Table 5.1.1, while the test results are discussed in Section 5.2. The equation for determining F* length is:

[

(d)

]

[

(c)

]

Table 5.1.1
Radial Stress and Axial Loading Summary

[

(d)

]

5.2 Mechanical Testing

Mechanical tests were performed to evaluate various F* lengths at room temperature conditions. The test data was then corrected by the analysis to obtain the final F* length for operating conditions.

The tests performed consisted of leak and load testing, pressure and thermal cycling, and ultimate load tests. Normal operation, faulted, and locked tube conditions were simulated during testing. A total of [(d)] specimens were tested as a part of this qualification.

5.2.1 Mockup Block Description

The F* qualification specimens consisted of [(d)] mockup blocks fabricated from material which met the yield strength requirements of the W-44 tubesheet material. Each of these blocks was assigned a serial number [(d)] such that they could be tracked throughout the qualification process. [(d)]. See Figure 5.2.1 for a layout of the mockup blocks.

The [(d)] perimeter tube locations were used as stiffeners to support the F* specimens that were to be installed at the [(d)] interior tube locations. The tubesheet bore of the peripheral locations was specified to be [(d)], the same as within the W-44.

The center holes within the block were machined to various bore sizes to simulate a range of tube wall thinning due to roll expansion. [(c)]

[

(c)

].

The size of the mockup block holes ranged from [

(d)

].

The surface finish of the test bores was also varied so that the effects of a range of surface finishes on the tube-to-tubesheet joint could be determined. The surface finish goal for the holes was [(c)]. For comparison purposes a smooth bore was considered as one with an average surface finish less than [(c)] while a rough bore had a finish greater than or equal to [(c)]. The actual range of tubesheet bore surface finishes tested was from [(d)].

An expander with [(d)], was used for all tube installation. In the event that a tube required longer than a [(d)] long expansion the rollers were slightly overlapped, by approximately 1/16 inch, to avoid skip rolls. The roll expander was driven by an air motor which contained a preset clutch which would shut off the supply of air to the motor at the proper torque setting. [(d)] was used to lubricate the roll expander during all expansions.

[(d)], used to determine the required rolling torque and the tube springback results, had short tubes expanded into all [(d)] holes. Testing was performed by incrementally increasing the torque value to achieve the necessary wall thinning of [(c)]. A torque value of [(d)] was found to achieve this wall thinning, as described in Section 5.2.2.

For the F* qualification blocks, [(d)], the peripheral holes had short tubes roll expanded into them at [(d)]. This is on the low end of the shop range for wall thinning and comparable to that used during the expansion of the tubes into block [(d)]. Next, the [(c)], to be used for pressurizing the F* test tubes, were expanded. These primary side "pressure tubes" were placed into the blocks such that an axial gap existed between the opposite, secondary side, face of the tubesheet and the end of the pressure tube. This distance was used to set the F* test length. After the primary side pressure tubes were roll expanded into the blocks, they were welded to form a pressure tight seal at the primary face.

After the pressure tubes were welded, the "F* test tubes" were installed. The F* test tubes were made from [(d)]. The range of yield strengths was tested to determine if it had an impact on the F* joint leakage or strength. The F* test tubes were inserted through the bore on the secondary side of the block (opposite the pressure tube) until contact was made with the primary side pressure tube section. This physical separation between the F* test tubes and the pressure tube sections was used to represent a full 360° sever at the F* distance. The tubes were then rolled in place, at [(d)], from the primary side. The F* test tubes were roll expanded into the mockup block such that a skip, or partial, roll could not exist within the length of the F* tube.

After the roll expansion of the F* tubes into the mockup blocks, the tube inside diameters were recorded and the F* test length was determined based on the position of the roll expander relative to the tube sever. The range of wall thinning values tested was from [(d)]. Tube installation data is shown on Table 5.2.1.

After tube installation, and prior to other activities on the blocks, bobbin eddy current testing was performed to determine the distance from the bottom of the roll transition to the circumferential tube sever. This information was used to determine the eddy current measurement accuracy and is described in Section 5.3.

After the eddy current inspections were complete in test mockups [(d)] the blocks were heated at [(d)]. The thermal soak was performed on the mockup blocks to simulate the effects of actual steam generator service temperature. By heating the block, thermal residual stress relaxation would be permitted to occur in the roll expanded joint. After the thermal soak, qualification testing commenced, as described in Sections 5.2.3 and 5.2.4.

5.2.2 Roll Expansion Springback Tests

Prior to the start of leak and load qualification testing, [

(d)

].

[(d)] periphery tubes were expanded into this block starting with a low rolling torque. The torque was increased until wall thinning in the range of [(d)] was reached. At a torque value of [(d)] the tube wall thinning was calculated to be [(d)] and the torque was no longer increased. Since this torque value provides wall thinning at the low end of the shop installation range, of the springback values will be conservative. The remainder of the tubes in the block, including the [(d)], were expanded using this torque.

In order to conservatively bound the effects that tubing yield strength may have on springback, a previously used block [(d)], was refitted with [(d)]. The [(d)] peripheral tubes were previously expanded. The [(d)] tubes were expanded at a torque of [(d)].

After the tubes were expanded, the tube inside diameter was measured and recorded. The mockup was then sectioned such that all tubes of interest could be removed from the tubesheet bores without damage. After removal, the tube outside and inside diameters were remeasured. The tube springback was determined [(d)]. This value was used in the analysis to calculate the radial stress in the roll expanded joint.

5.2.3 Leak Test Description

Leak tests were performed by connecting a high pressure pump to the welded pressure tube, which protruded from the primary side of the block. The F* tube was then capped to allow it to be pressurized. [

(c)

]. A diagram of the leak test setup is shown on Figure 5.2.2.

Two pressures were used on each specimen to monitor leakage, a conservative normal operating test pressure differential of [(d)] and a conservative faulted test pressure differential of [(d)]. The normal operating leak test was performed for a minimum of [(d)] while the faulted condition test was performed for a minimum of [(d)]. All tube motion noted during testing was recorded. Results of these tests are provided in Section 5.2.5.

The acceptance criteria for leakage, per tube end, was defined as a leak limit of less than [

(d)

].

5.2.4 Tensile Test Description

Several types of tensile tests were performed on the samples. All of the samples were subjected to the NRC Regulatory Guide 1.121 loads (the worst case load of either three times the normal operating pressure differential or 1.43 times the faulted pressure acting on the tubesheet bore) and to the locked tube loads. In addition, [(d)] the samples were pressure cycled to simulate the pressure differential on the tubes during startup and shutdown of the plant.

The NRC Reg. Guide 1.121 load is the greater of either a maximum of three times the normal operating pressure differential or 1.43 times the faulted pressure differential. For the W-44 this load is [(c)], as shown on Table 5.1.1, which corresponds to three times the normal operating pressure differential multiplied by the nominal tubesheet bore area. Since the most limiting case for the reduction in total radial stress is at faulted conditions, the load was applied by using the faulted condition pressure differential of [

(c)

]. For testing purposes an additional load margin is added to the calculated value to conservatively allow for ease in gauge reading. The final load used during testing was [(d)] During testing this load is cycled [(d)] times, to assure that the tube does not continue to slip after the application of the initial load, and tube motion is monitored. This test load is shown on Table 5.1.1, along with the resulting radial stresses for the test case.

A second test was conducted on each test specimen to consider tubes locked at tube support plate locations. This condition is described in Section 5.1.2. [

(d)

]. Using dial indicators, mounted between the tube and mockup block, tube motion was monitored during loading to assure that the [(d)] displacement limit, the maximum calculated for locked tube differential growth, was not exceeded. If some slippage was noted, the load was reduced accordingly to demonstrate that the joint could handle the remaining load.

A third test, pressure cycling, was performed on [(d)] the samples. This test was done to simulate pressure differential across the tube during the startup and shutdown of the plant. The specimens were subjected to [(d)]. Tube motion was monitored to determine if any slippage had occurred during testing.

After pressure cycling and/or load testing was complete all samples were subjected to leak tests as described in Section 5.2.3. Ultimate load testing was then performed on the samples.

The last test performed was an ultimate load test where the tube joints were loaded until failure. Typically, failure was observed when a distinct audible "pop" was heard, at which point the tube moved a great distance and the load required to move the tube an additional amount decreased. On some occasions the tube began to slide out of the mockup block without an audible "pop", with the maximum load being recorded when cumulative tube displacement exceeded the acceptance limit of [(d)]. The ultimate load test was performed with a minimum test pressure of [(d)].

Results for all of the load tests are provided in Section 5.2.5.

The acceptance criteria for the leak and load tests was cumulative tube motion of less than [(d)] under all test conditions. The test conditions included the normal operating pressure differential and faulted condition pressure differential leakage testing, Reg. Guide 1.121 and locked tube load tests, and pressure cycling. The acceptance criteria was based on residual tube motion recorded after the pressure and load had been removed. The [(d)] criteria was established since some movement of the tube may occur before slight galling between the tube and tubesheet locks the tube in. The [(d)] limit is considerably smaller than the tube spacing and therefore precludes the potential for tube contact in the u-bend region. The acceptance criteria was applied cumulatively so that failure during the ultimate load test was considered to have occurred whenever the total displacement from all tests exceeded [(d)]. The displacement acceptance criteria for locked tube loading tests was a total movement of greater than [(d)]. The sample was considered to have failed the test if this tube displacement occurred prior to the locked tube load being reached.

5.2.5 Results

Tables 5.2.2 and 5.2.3 show the qualification test data. The following is a summary of the results.

5.2.5.1 Leak Testing

[

(d)

]

[

(d)

]

The leak test data for the [(d)] qualification samples was broken into groups according to tubing yield strength, tubesheet bore size and surface finish, and pressure cycling status, and then averaged. The results are presented in Table 5.2.3. [

(d)

].

[

(d)

]. The purpose of this test was to show that even with the tube in a failed condition the leakage is not catastrophic and, in fact, the leak rate from this sample meets the normal operating acceptance limit, for all tubes repaired, of [(d)].

5.2.5.2 Load Testing

The following is a summary of the load tests that were performed on the F* qualification samples. The tube displacements associated with each test are shown on Table 5.2.2.

The range of detectable movement for NRC Regulatory Guide 1.121 loads was from [(c)], with one additional tube pulling out of the block during the test.

The tube that was removed from the block, [

(d)

]. This value was considered to be the ultimate load for the sample. This sample moved at a load less than the other samples due to its test length. Although the tested F* length was much shorter than the final qualified, of [(d)], the leak rate from this sample was within that recorded by other samples. Also, the calculated F* length, as shown on Table 5.2.2, was consistent for all of the [(d)] F* samples. It can be noted that none of the [(d)] F* samples, similar in length to that qualified, had significant motion detected during testing and that all of the longer samples passed all tests.

Much of the motion recorded during testing was believed to be due to test fitting slippage rather than actual tube motion. This was based on observations from marks left on the tubes during testing.

After the Reg. Guide loads were applied, the tubes were loaded to simulate locked tube conditions. [

(d)

]. The displacement of the tubes was monitored during loading. [

(d)

]. The load required to create this motion was considered to be the ultimate load for this sample and no further load tests were performed on it. This sample, [(d)], had an F* test length that was much shorter than the final qualified F* value for use in the steam generator.

[(d)] tubes were pressure cycled to simulate startup and shutdown conditions. The range of tube motion during this testing was [(d)]. No failures were noted during testing. After pressure cycling was finished, all samples were leak tested again.

At the conclusion of leak testing, an ultimate load test was performed on the [(d)] samples which had not exceeded the acceptable movement from the previous load tests. The ultimate load values on these samples ranged from [(d)], with the higher values typically being recorded by the longer F* test lengths. The ultimate load, and a calculation of the F* length, as described in Section 5.4, is presented in Table 5.2.2.

Figure 5.2.1
Mockup Block Layout

[

(c)

]

Figure 5.2.2
Leak and Load Test Setup

[

(c)

]

Table 5.2.1
Mockup Block Tube Installation

[

(d)

]

Table 5.2.2

Qualification Samples Test Data

[

(d)

]

Table 5.2.3
Qualification Samples Average Leak Rate Results

[

(d)

]

5.3 NDE Measurement Testing

Bobbin and RPC eddy current methods were both used to verify accuracy and uncertainty in determining F* lengths. This testing was performed to determine the error associated with the NDE method that will be used in the steam generator to define the actual locations of the defect and the roll transition.

5.3.1 Description of Testing Equipment

The following equipment was used to conduct both the Bobbin and RPC tests:

[

(d)

]

5.3.2 F* Length Verification Methodology

The bobbin eddy current data was acquired per BWNT procedure ISI-428 Rev. 4. [

(d)

].

The RPC eddy current data was acquired per BWNT procedure ISI-510 Rev. 13. [

(d)

].

Two sets of eddy current tests were performed on the F* test blocks.

o [

(d)

].

o [

(d)

].

Using both bobbin and RPC, measurements were made from the bottom of the roll transition (the end of the effective roll expansion) to the F* circumferential sever. This actual distance had been determined by taking measurements of the tubing and the roll expander setup during tube installation. Figure 5.3.1 provides a sample bobbin plot and Figure 5.3.2 is a RPC plot showing where the key points were selected for the measurements.

5.3.3 Eddy Current Results

Analysis was performed to determine the distance from the bottom end of the upper roll transition to the F* sever. [

(d)

]. The results from the ECT verification testing are summarized in Table 5.3.1.

[

(d)

].

[

(d)

].

[

(d)

].

Based on the above data, it is necessary to add [(d)] to the qualified F* length to account for eddy current inaccuracies in measuring the axial distance from the roll transition to the defect. It can be noted that this value

will be conservative for measurements made using [
(d)
].

Figure 5.3.1

Sample Bobbin Plot Showing Selection Points (Sheet 1 of 2)

[

(d)

]

Figure 5.3.1

Sample Bobbin Plot Showing Selection Points (Sheet 2 of 2)

[

(d)

]

Figure 5.3.2
Sample RPC Plot Showing Selection Points

[

(d)

]

Table 5.3.1
ECT Measurement Accuracy Comparisons

[

(d)

]

5.4 Determining Final F* Length

For each of the [(d)] F* qualification samples a final F* length was calculated based on the equation discussed in Section 5.1.3. This length is shown for each sample on Table 5.2.2. The calculated F* length is based on the following:

[ ]

where:

[

]

[

]

The calculated F* lengths for the [(d)] qualification samples were grouped, using the tube yield strength, tubesheet bore size and surface finish, and target test length, as the criteria for averaging. This data is presented in Table 5.4.1. The conclusions from this data are that [

(d)

].

[

(d)

].

The final F* length includes the effects due to ECT uncertainty, of [(d)], as described in Section 5.3. Thus, the final required F* length for Indian Point Unit 2 is [(d)].

Table 5.4.1
Qualification Samples Average Calculated F* Values

[

(d)

]

5.5 Boron Corrosion Within the Tubesheet

The effects of boric acid corrosion on the carbon steel tubesheet were examined as part of the F* qualification program. In the event that the defect in the tube went 100% throughwall, the tubesheet bore would be exposed to primary side fluid. At low temperatures with aerated boric acid solutions, some corrosion may be expected.

[

(d)

].

The defects associated with PWSCC in the tubesheet region are typically minute which limits the ability to replenish boric acid at the tubesheet. Furthermore, dissolved hydrogen in the primary chemistry acts as an oxygen scavenger to minimize corrosion throughout the primary system, thus effectively preventing boric acid attack on the tubesheet.

Some RSGs utilize small concentrations of boric acid in the secondary water chemistry to help mitigate caustic intergranular attack in the crevices. Thus, all of the carbon steel surfaces on the secondary side become exposed to some level of boric acid.

There is a low probability of any significant corrosion of the tubesheet bore associated with boric acid corrosion. Any corrosion that might occur is not expected to exceed more than a few thousands of an inch of localized degradation. Such a small level of degradation would have no impact on the F* joint nor the structural adequacy of the tubesheet.

5.6 Evaluation of Potential F* Joint Relaxation From PWHT

During steam generator manufacture, the channel head to tubesheet weld attachment was stress relieved after the completion of the tube-in-tubesheet roll expansion process. This stress relief may have affected the structural strength of the original tube expansion in the F* region due to thermal relaxation. Thus, analysis and tests were performed to evaluate this potential thermal relaxation effect.

Per ASME Code requirements this heat treatment was to be performed at a temperature of [(c)] per inch of material thickness at the weld location. For the IP-2 W-44 series steam generator, the Code would require a minimum of [(c)].

According to Ref. 7.8 for similar expansion joints in Inconel 600 tubing, contact stresses within a tubesheet bore tend to relax from creep above [(d)] Therefore, a finite element analysis was performed to determine a conservative steady state temperature profile in the F* region of the outermost tubes. This analysis indicated the maximum temperature of the outermost peripheral tube was approximately [(d)] of applied heating [7.9]. The analysis also determined the temperature history of the tubes for an [(d)] hold period with the shell at temperature [(d)]. This temperature history was used in establishing the heating schedule of F* specimens for joint strength testing. F* specimens were prepared identically to those previously tested and then were heated per the schedule indicated above, conservatively including a maximum temperature of [(d)]. Ultimate load testing was performed on these specimens to determine joint pullout strength in terms of the required F* length.

The results from the ultimate load tests are provided in Table 5.6.1. These results indicate a required F* length of

[(d)] confidence limit. This length is well within the [(d)] defined per Section 5.4, indicating no loss in structural performance for the few peripheral tubes which may have experienced the higher temperature heating. Thus, the F* criterion of Section 5.4 can be applied to all tubes.

Table 5.6.1

PWHT Ultimate Load Test Summary

[

(d)

]

6.0 CONCLUSIONS

Based on the design verification testing performed, the following conclusions are provided.

- o A total F* length of [(d)] is structurally adequate to satisfy all of the loading requirements for the NRC Regulatory Guide 1.121 and the leakage limits of the Indian Point-2 technical specification. This F* length is based on an analysis and qualification test length of [(d)], with an added length of [(d)] for eddy current positioning tolerances. If inspection techniques improve in the future it may be possible to decrease the F* length based on the improved eddy current technique.

- o The qualification is valid for a range of tubesheet bores from [

  (c)

  ]. [

  (d)

  ].

- o Both normal operating and faulted condition pressure differential leakage rates are expected to be well within the normal operating technical specification leakage limits of [(d)] for up to 100% of the tube ends for which F* could be applied. The average operating pressure leak rate from testing, if applied to all tube ends, was [(d)].

- o The effects of a loss of coolant accident (LOCA) was considered on the F* joint. The testing performed for normal operating and faulted conditions bound the LOCA parameters.

- o The effect of normal operation pressure differential cycling, as would be experienced during the startup and shutdown of the plant, is expected to slightly reduce the leakage rates.

- o The use of RPC to determine the distance from the bottom of the upper roll transition to the defect resulted in the limiting uncertainty value of [(d)]. While ECT F* verification techniques other than those reported herein may be used to adequately measure the F* length in the steam generator, the accuracy of such techniques shall be demonstrated to be within the [(d)] uncertainty included in the qualified [(d)] F* length.

7.0 REFERENCES

7.1 NRC Regulatory Guide 1.121 (Draft), "Bases for Plugging Degraded PWR Steam Generator Tubes".

7.2 "ASME Boiler and Pressure Vessel Code", Section III, Subsection NB and Division I Appendices, 1989 Edition.

7.3 BWNT Document 51-1228657-03, "Technical Requirements for W-44 F* Qualification".

7.4 BWNT Document 32-1228961-02, "F* Calculation for W-44 RSGs".

7.5 BWNT Document 51-1228678-00, "W-44 F* Springback Test Results".

7.6 BWNT Document 51-1206178-00, "Boric Acid Corrosion of Oconee 1 Upper Tubesheet".

7.7 BWNT Document 56-1201212-00, "BWNS Quality Assurance Program".

7.8 Nuclear Engineering and Design volume 143 (1993) "Residual Stresses Associated With the Hydraulic Expansion of Steam Generator Tubing into Tubesheets" by Middlebrooks, Harrold, and Gold, pages 159-169, North-Holland.

7.9 BWNT Document 51-1229247-00, "IP-2 Thermal Evaluation of F* Joints From Fabrication PWHT".

Appendix

NO SIGNIFICANT HAZARDS REVIEW

BWNT has evaluated the F* criteria as a Technical Specification amendment for the Indian Point Unit 2 plant and determined that it involves no significant hazards considerations. According to 10CFR50.92(c), a proposed amendment to an operating license involves no significant hazards if operation of the facility in accordance with the proposed amendment would not:

(1) Involve a significant increase in the probability or consequences of an accident previously evaluated; or

(2) Create the possibility of a new or different kind of accident from any accident previously evaluated; or

(3) Involve a significant reduction in a margin of safety.

QUALIFICATION SUMMARY

The F* acceptance criteria has been qualified for use in the Indian Point Unit 2 W-44 RSGs into tubes, which have been partially expanded into the tubesheet (up to [(c)] deep from the primary face), by mechanical hard rolling. The use of this criteria will allow tubes with eddy current indications greater than the pluggable indication limits to remain in service as long as the indications are a minimum distance below the lower end of the uppermost roll transition (F*).

Through analysis, the normal operation and faulted loading conditions were determined using the Indian Point Unit 2 W-44 RSG operating and design conditions and the NRC Regulatory Guide 1.121 safety factors for normal operation and faulted conditions. Loads which could be imparted on the tubes from becoming locked into the tube support plates were also considered. Loading and tube leakage from normal operating and accident conditions were determined to bound that which would be imposed as a result of LOCA.

The joint strength and leakage of various tube-to-tubesheet roll expansions were then tested to simulate the actual installed roll expansion, fabrication variations, and loading conditions within the W-44 RSGs.

Further analyses were performed to calculate the effects that tested, operating, and faulted conditions have on the residual tube radial stress. From this comparison, and the qualification test results, the F* value qualified by testing was corrected to account for the conditions which could not adequately be simulated through testing (i.e., radial thermal growth and tubesheet bow). The final F* qualification length, based on the results of analysis and testing, was [(d)]. This dimension does not include measurement tolerances from eddy current.

Eddy current testing, using standard NDE inspection equipment, was performed to determine measurement accuracy and repeatability. Both bobbin and Rotating Pancake Coil (RPC) eddy current were used as part of this testing. From these test results an additional [(d)] inch is added to the qualified F* length to account for ECT length measurement tolerance.

The final result of this qualification program is that a [(d)] F* length [(d)] is adequate to restrict tube motion and maintain leakage within the Indian Point Unit 2 technical specification limits. This criteria applies to all tubes within the steam generator, regardless of location.

The effects of boric acid corrosion on the carbon steel tubesheet were examined as part of the qualification program in the event that the tubesheet is exposed to primary side fluid. The results of this study show that the effects of boric acid corrosion from the primary fluid is considered to be insignificant for defects typically associated with F* criteria. No additional length was added to the final F* value based on these results.

The F* criteria would require an amendment to the Station Operating Technical Specifications for in-service inspection of the reactor coolant system steam generators. However, the incorporation of this criteria into the Technical Specifications changes none of the original plant design conditions or performance characteristics.

IMPACT ON ACCIDENTS EVALUATED AS THE DESIGN BASIS

Since F* involves a condition that exists as part of the original steam generator design, all of the design and operating characteristics of the steam generator and connected systems are preserved. The F* joint has been analyzed and tested for design, operating, and faulted condition loadings in accordance with NRC Regulatory Guide 1.121 safety factors. Furthermore, the F* joint was tested for locked tube loads which may develop during normal operation. At the worst case a tube leak would occur with the result being a primary-to-secondary leak.

Should a tube leak occur, the impact is bound by the ruptured tube evaluation submitted by the utility for the operating license. No new or unreviewed accident conditions are created by the F* criteria. The potential for a tube rupture is not increased from the original submittal, thus there is no impact on accidents evaluated as the design basis.

Thus, 10CFR50.92(c)(1) is satisfied.

POTENTIAL FOR CREATING AN UNANALYZED EVENT

The failure of a tube which remained unplugged with the F* criteria would result in a tube leak, which is a previously analyzed condition. Since this leak would occur below the secondary face of the tubesheet its leak rate would be limited by the tube-to-tubesheet interface. The test results listed within this document indicate that this leakage would be well below technical specification limits even in the event of leakage through all of the tubesheet roll expanded joints. The total leakage would not be on the order created during a tube rupture. This minute leakage result is also evidenced through previous F* programs approved and used within other operating pressurized water reactor steam generators. In addition, in the unlikely event the failed tube severed completely, the remaining F* joint would restrain movement due to the length of expanded contact within the tubesheet bore. Consequently, there is no threat to neighboring tubes and no potential for creating an unanalyzed event.

Thus, 10CFR50.92(c)(2) is satisfied.

IMPACT ON MARGIN OF SAFETY

Based on previous responses, the protective boundaries of the steam generator are preserved. A tube with degradation can be kept in service through an F* criteria, which provides an undegraded expanded interface with the tubesheet and which satisfies all of the necessary structural and leakage requirements per Regulatory Guide 1.121 and the Station Technical Specifications. Since the joint is constrained within the tubesheet bore, there is no additional risk associated with tube rupture or adjacent tube impacting and damage. Therefore, the use of an F* criteria does not reduce the margin of safety.

Thus, 10CFR50.92(c)(3) is satisfied.

CONCLUSION

The use of the F* criteria described herein, to maintain tubes in service, does not represent an unanalyzed safety concern. Furthermore, its use does not increase the risk of creating an unanalyzed accident nor does it reduce the margin of safety of the pressure boundary within the steam generator.