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W E-SERIES F* QUALIFICATION REPORT

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TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

1.1 Background

Primary Water Stress Corrosion Cracking (PWSCC) has been found during routine inspections of the tubesheet roll transitions in U-tube steam generators [7.9]. Without an alternate plugging criteria, such as F*, it is necessary to remove the tube from service when the indication exceeds 40% of the tube wall thickness. However, in some instances these defects occur in areas significantly below the tube expansion transition at the secondary face of the tubesheet. Since the tubesheet provides structural support for the tube in this area, plugging these tubes is overly conservative. The F* plugging criteria discussed in this report was established as a means to justify leaving tubes in service which have PWSCC type indications within the rolled region of the tubesheet.

Westinghouse (W) E-Series recirculating steam generators (RSGs) were constructed with 0.749" OD x 0.043" wall mill annealed (MA) alloy 600 tubing. During installation, the tubing was roll expanded into the tubesheet with a tack roll and then seal welded at the primary face of the tubesheet. Step rolls were then performed to close the crevice between the tube and the tubesheet to minimize the possibility of secondary side crevice corrosion. Occasionally, roll expanders were stepped in such a manner that skip roll areas were created (Figure 1.1).

These skip roll areas and roll transitions contain high residual tensile stresses which accelerate the initiation of PWSCC. If this PWSCC occurs within the tubesheet region, then there is a length of tubing roll expanded into the tubesheet above the defect location. This rolled length of tubing above the defect provides structural support for the tube and limits primary to secondary leakage, and is thus the basis for the F* criteria. Thus the F* criteria is the minimum length of undegraded expanded tube within the tubesheet, below which, a tube defect can exist and remain in service. This F* length must be shown to:

- Exhibit a joint strength sufficient to carry normal operating and faulted loads with an acceptable margin of safety.
- Demonstrate a leak rate at the normal operating primary-to-secondary differential pressure which is acceptable for plant operation and within technical specification limits.

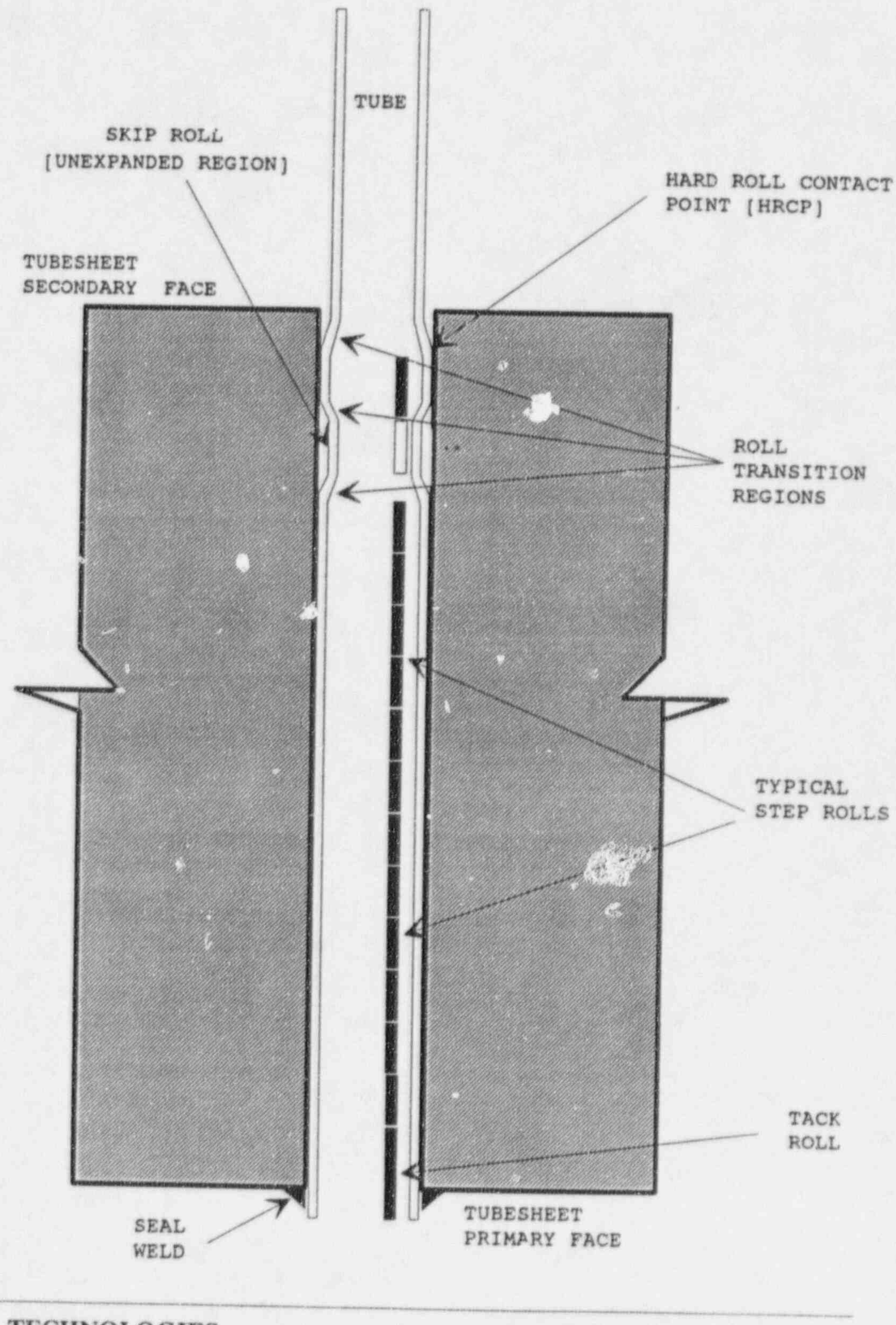
The final F* criteria must be verified using standard steam generator eddy current inspection techniques (ECT). Thus any errors which are inherent with remote ECT measurements must also be factored into the final F* values.

The criteria shall be applicable to all tube locations within the steam generator except those that have "wavy" tubesheet bores. The location of tubes that exhibit this condition are given in Table 3.3.3. Each tube shall be examined using ECT prior to applying F* criteria to ensure that "wavy" conditions do not exist in tubesheet bores where the F* criteria is to be applied.

1.2 Scope of Report

This document summarizes the qualification of an alternate plugging criteria, F*, for application in W E-Series RSGs at South Texas Project Unit 1 (STP-1). This report contains summaries of the design requirements, design verification testing, analysis, ECT verification testing, and tubesheet corrosion evaluation performed to justify the use of F*.

FIGURE 1.1
W E-SERIES TUBESHEET ROLL EXPANSION PROFILE



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2.0 SUMMARY

The F* alternate plugging criteria has been qualified for use in the W E-Series steam generators at South Texas Project Unit 1 (STP-1). The use of the F* criteria will allow tubes with otherwise pluggable ECT indications to remain in service as long as the indications are a minimum distance below an undegraded expanded region within the tubesheet. This minimum length, referred to as F* distance, was determined to be [(d)] inches through a combination of analysis, mechanical testing, and evaluation of ECT measurement accuracy.

An initial analysis was performed to determine the normal operating and faulted loads imposed on the tubes for STP-1. 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 [7.1]. In addition, the potential effects of tubes becoming locked into the tube support plates were considered. Conservative loads were used for the final qualification testing.

The joint strength and leakage of various lengths of the existing tube-to-tubesheet roll expansions were then tested under these conditions. Leak testing, load testing, pressure cycling, and ultimate pull testing were performed on a variety of samples to conservatively bound the actual installed rolled joint and loading conditions within the W E-Series RSGs.

Additional analyses were performed to calculate the effects that operating and faulted pressure, thermal effects, and tubesheet bow have on the tube OD radial stress, and thus their effect on the rolled joint's strength. The F* value qualified by testing was verified by analysis to be adequate for all of these various conditions.

Eddy current testing was performed on a number of F* specimens to determine measurement accuracy and repeatability. Both bobbin and MRPC were used in this testing. Based on the ECT test results, an additional length of [(d)] inches was added to the tested F* length to account for ECT uncertainty.

The effects of boric acid corrosion on the carbon steel tubesheet were examined as part of the qualification program. In the event that the defect in the tube went 100% through wall, a small region of the tubesheet could be exposed to primary side fluid. At worst, small amounts of localized tubesheet degradation, on the order of a few mils, could occur. Such shallow attack represents no structural concerns for the tubesheet or the F* joint.

The qualified F* distance applies to all tube ends within the steam generator. In addition, the use of F* to maintain tubes in service does not represent an unanalyzed safety concern. Furthermore, its use does not increase the risk of an unanalyzed accident nor does it reduce the margin of safety.

3.0 DESIGN REQUIREMENTS

3.1 General Requirements

The ASME Boiler and Pressure Vessel Code and US NRC Regulatory Guide 1.121 were used to establish the safety factors for evaluating the roll expanded tube-to-tubesheet interface associated with the F* criteria [7.1,7.2]. The safety factors correspond to 3 for normal operating conditions and 1.43 for faulted loading conditions. The applicable design conditions used for F* criteria evaluation are given in Reference 7.3 and are summarized in this section.

3.2 Functional Requirements

The F* design 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. It shall be assumed that the tube severs circumferentially for 360° and that the remaining joint carries all anticipated loading conditions, including the margins of safety described above. In addition, primary to secondary leakage cannot exceed the station Technical Specification limits.

3.3 Design and Operational Loading Conditions

The design and operating conditions for the STP-1 steam generators are summarized in Table 3.3.1. Table 3.3.2 summarizes the conservatively bounding conditions under which the F* qualification tests were conducted. Figure 3.3.1 illustrates the key steam generator geometry and material constraints for evaluating F*.

A significant requirement added to the F* design criteria is the assumption that the tube is not free to move through the first tube support plate (TSP). This "locked tube" condition imparts axial loads on the tube, resulting in a conservative design. The loading imparted by the locked tube condition is displacement limited, such that as the rolled tube joint slips, the applied load is reduced. [

(d)

]. The locked tube loading condition is discussed further in Section 5.1.3.

3.4 Corrosion

The W E-Series tubesheet is made of SA-508 Class 2A carbon steel clad with Inconel. 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 wall 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.

TABLE 3.3.1
W E-SERIES DESIGN AND OPERATING CHARACTERISTICS

[

(c)

]

TABLE 3.3.2
F* QUALIFICATION TEST CONDITIONS

[

(c)

]

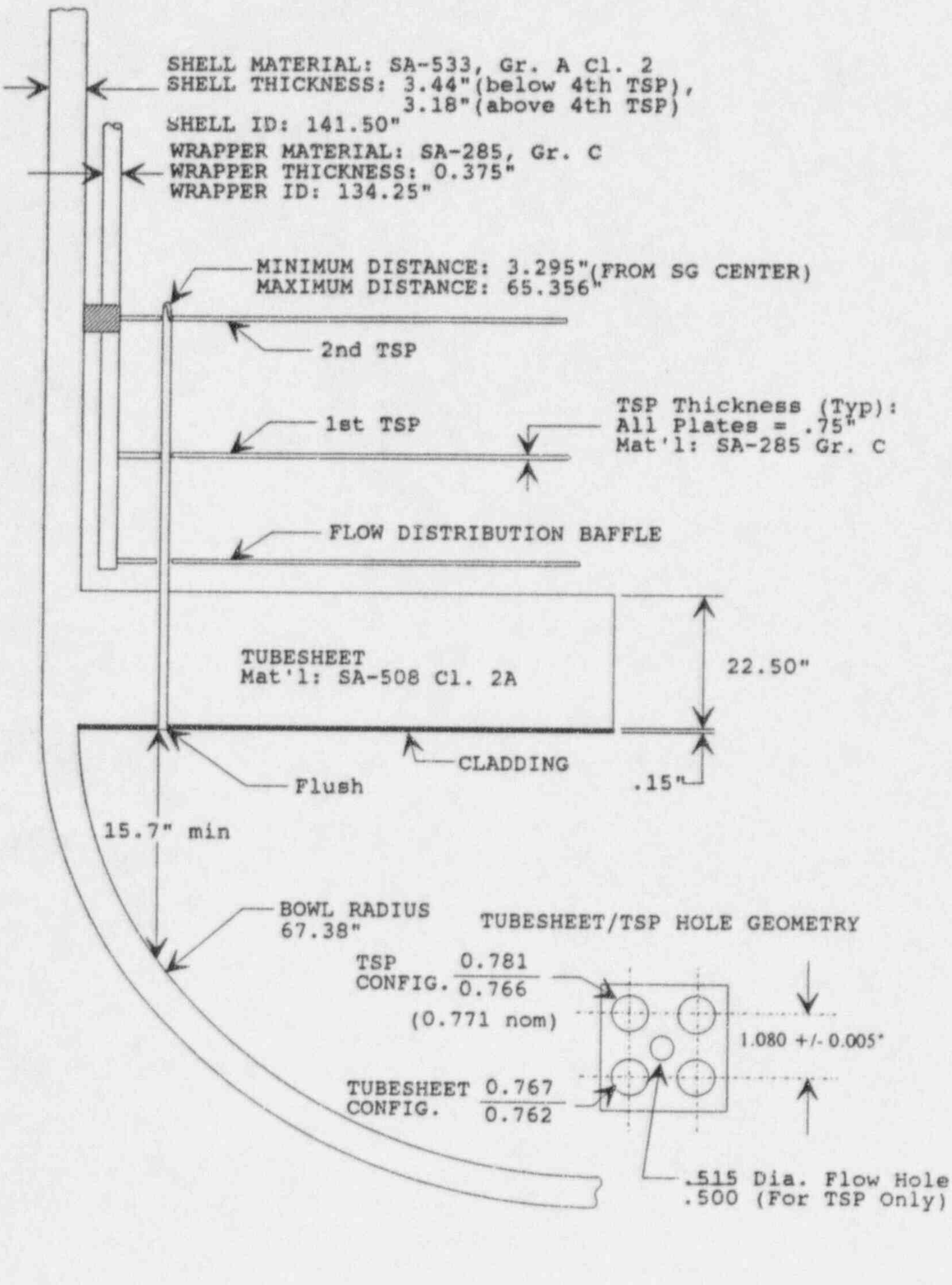
TABLE 3.3.3
F* EXCLUSION ZONE FOR TUBES WITH WAVY TUBESHEET BORES

[

(d)

]

FIGURE 3.3.1
W E-SERIES RSG GENERAL ARRANGEMENT



4.0 F* CRITERIA DEVELOPMENT

4.1 Structural Justification

An analysis was performed which evaluated the joint pullout strength for a degraded tube in which the defect propagated into a full 360 degree circumferential sever at the F* distance [7.4]. This analysis utilized the normal operating and faulted condition loadings as well as Reg. Guide 1.121 and ASME Code safety factors. Tubesheet bow, pressure effects, thermal effects, seismic and flow loading effects were considered relative to their impact on reducing the holding power of the rolled tube-to-tubesheet interface. A secondary loading condition for locked tubes was also considered.

Room temperature mechanical testing was performed on qualification mockups to the loadings described above at various F* lengths. Primary to secondary leakage of the various F* lengths was also determined. Finally, the qualification tubes were pulled to failure to determine the structural adequacy of the rolled tube-to-tubesheet joint over the F* length.

4.2 Establishing F* Criteria

An analytical technique was developed to determine the required F* length for the actual steam generator tubes based on the measured joint strength determined by room temperature mechanical testing [7.4].

The F* length is determined by ratios that correct for the differences between the mechanical test conditions of the mockups and the actual steam generator conditions. The equation used to calculate the required F* length is:

[(d)]

where: [

(d)

]

The above equation establishes the minimum F* length for structural adequacy to resist imposed axial loads. In addition, the minimum F* length must limit primary to secondary leakage to within allowable limits. The leak rates for the F* length were determined through testing mockups representative of the steam generator.

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5.0 QUALIFICATION ANALYSES AND TESTS

The qualification analyses and testing program for the F* criteria focused on satisfying the following objectives:

- o Establish tube loads based on operating and faulted conditions for evaluating F* lengths.
- o Perform mechanical tests necessary to verify the F* criteria as a structurally sound, leak limiting joint which meets Reg. Guide 1.121 margins of safety.
- o Analytically adjust mechanical test condition results for actual steam generator conditions.
- o Perform ECT verification testing to determine the accuracy associated with length measurements for final F* criteria determination.

The analytical approach used to determine tube loads was discussed in Section 4.1 and is detailed below in Section 5.1.

Mechanical testing was performed on mockups designed to represent the range of conditions existing in the steam generators. The tubes in these mockups had full 360° severs at the F* length being tested. Testing included pressure cycling, thermal evaluation, locked tube load tests, ultimate joint strength tests, and leak tests. These tests are described in Section 5.2 below.

The F* length to satisfy structural requirements was calculated using the equation in Section 4.2 and the mechanical test results. These results were adjusted for the operating conditions analyzed in Section 5.1.

The ECT measurement accuracy testing was performed using multiple probe types in multiple mockups. A statistical evaluation of the results was performed to establish the final F* correction factor for measurement accuracy.

5.1 Analyses

Analyses were performed to determine axial tube loads for operating and faulted conditions for use in the mechanical testing described in Section 5.2. The combined radial stresses imposed on the installed tube-to-tubesheet joint determine the axial strength of the joint and thus determine the required tube engagement length (F*). The following parameters were included in the analyses:

- Radial preload stress from tube installation
- Thermal effect
- Internal (primary) pressure effect
- Tubesheet bow effect (TS bow)

[

(d)

]

The axial load that the joint must resist varies depending on the design condition being evaluated. Thus multiple cases were analyzed, and the testing was performed to encompass the worst case.

The calculations (radial stress and axial load) were performed for four different cases and are summarized in Table 5.1.1:

- normal operating condition
- faulted condition
- locked tube condition
- tested mockup configuration

5.1.1 Radial Stress

The radial preload stresses were determined by testing mockups with tubing installed in the same manner as the steam generators at STP-1. After tube installation, the tubesheet was cut away from the tubing and the expanded tube OD measured. By comparing the measured tube OD with the tubesheet bore, the tube springback was determined. [(d)] [7.5]. The radial stress equivalent to this springback was then calculated [7.4] and is presented in Table 5.1.1.

The differential thermal growth between the tube and tubesheet increases the tube OD radial stress and thus serves to strengthen the tube-to-tubesheet joint. For conservatism, the effect of differential thermal growth is calculated for the cold leg, since the higher temperature in the hot leg gives a higher radial stress and thus a stronger joint.

[

(d)

]

[

(d)

]

Because of the analysis model used, the "Total Radial Stress" does not equal the sum of the individual radial stresses. The ring model geometry used in the analysis changes when the residual radial stress is set to zero to quantify the other individual effects. Thus, the individual radial stresses are close approximations of the actual stress.

5.1.2 Axial Loading

The axial loads imposed on the tubes for the four cases are summarized in Table 5.1.1 [7.4]. The normal operating load is determined by the end force applied to a tube from three times normal operating differential pressure. The faulted load was derived by applying a safety factor of 1.43 to the force generated during faulted conditions. The derivation of the locked tube loading is discussed in section 5.1.3.

5.1.3 Locked Tube Loading

[

(c)

]

[

(c)

]

[

(d)

]

5.1.4 F* Determination and Correction

By analyzing the three steam generator loading conditions summarized in Table 5.1.1, it was determined that the combination of radial stress and axial load for the faulted condition is the most limiting. The F* equation (Section 4.2) used to correct for differences between the testing mockups and actual steam generator conditions can be reduced to:

[

(d)

]

[

(d)

]

5.2 Mechanical Testing

The structural adequacy of the tube-to-tubesheet joint was evaluated by testing different F* lengths for joint strength and leak tightness. The effects of different rolled tube lengths, tubing yield strength, pressure and thermal cycling, tubesheet bore surface finish, and tubesheet bore diameter were included. Normal operation, faulted, and locked tube conditions were tested.

5.2.1 Specimen Description

The F* qualification specimens consisted of mockup blocks fabricated from material with the same material properties as the W E-Series tubesheet material. The blocks, which had a 4 x 4 square pitch array, were 4 inches thick. [

(d)

]

After the perimeter and primary side tube sections were expanded into the block, the F* test tube specimens were installed. These tubes were inserted in through the bore in the top of the block until contact was made with the primary side tube section. The tube was restrained from moving and rolled in place from the primary side. The physical separation between tubing sections represented a full 360 degree sever at the F* distance. Roll expansion lengths of [(c)] were tested.

Various installation parameters such as tubesheet bore diameter, tubesheet bore surface finish, and tubing yield strength were evaluated to address a wide range of potential steam generator conditions. [

(d)

]

Table 5.2.1 provides a summary of the qualification specimen installation parameters.

5.2.2 Leak Tests

The leak rate was determined by maintaining the test assembly at test pressure with a calibrated pressure generator, and measuring the volume of makeup water injected to maintain the test pressure over the test interval. The leak rate of the rolled tubesheet joints was determined at room temperature. The tests where conducted at pressures of [(d)], which conservacively bounds the normal operating differential pressure [(d)], and at [(d)], the maximum faulted differential pressure. The leak test at [(d)] was repeated after specimens were subjected to [(d)] pressure cycles (Section 5.2.3) to simulate normal startup and shutdown transients.

The acceptance criteria for leakage was based on the technical specification limit of 1 GPM. This limit was divided by the number of tube ends to be evaluated against the F* plugging criteria. With 4 steam generators, 4864 tubes per steam generator, and two tube ends per tube, the technical specification allowed leakage of 1 GPM equates to an <u>average</u> leak rate of 0.356 in^3/hr for each tube end at operating conditions. For conservatism, the <u>maximum</u> allowed leak rate during the qualification testing was set at [(d)]

The technical specification leakage limit is based on the maximum allowed primary to secondary leakage for continued plant operation. Thus the leakage limit only applies to normal operating differential pressure. The test specimens were also leak tested at faulted differential pressure to ensure that excessive primary to secondary leakage would not occur in the event of a faulted transient.

The results of the leak tests are summarized in Table 5.2.2. Several observations from these leak rates are discussed below.

[

(d)

]

5.2.3 Tensile Tests

A series of tensile tests were performed to determine the strength of the rolled tube-to-tubesheet joint. First the joints were subjected to the maximum loading from Table 5.1.1. The joints were then subjected to locked tube loadings and to pressure and axial load cycling. Finally the joints were pulled to ultimate load. Table 5.2.3 provides a summary of the specimens, the tests performed, and the results. [

(c)

]

From Table 5.1.1, the largest axial load is [

(d)

]

A second test evaluated the locked tube condition described in Section 5.1.3. For this test, specimens were subjected to [

(d)

]

[(d)] As discussed in Section 5.1.3, the locked tube loading is displacement limited. This means that as the joint moves, the applied load reduces linearly with the movement. Thus during testing, the applied load was reduced when joint movement was detected to simulate locked tube loading in the steam generator.

The third test was load cycling to simulate normal plant transients. Normal startup and shutdown transients were conservatively simulated by pressure cycling specimens from [

(d)

]

Joint slippage was monitored for both cycling tests and leakage rates were measured after the pressure cycling.

[

(d)

]

The final test was an ultimate load test where joints were loaded until failure. Consistently, failure was observed when a distinct audible "pop" was heard, at which point the load required to move the tube an additional amount decreased. [

(d)

]

The acceptance criteria for the load tests was no excessive slippage under operating and faulted condition loads. [

(d)

] However, excessive movement would indicate that the joint had little or no structural integrity and could eventually lose much of its leak tightness. The movement criteria does not apply to locked tube loading since this is a secondary load and is displacement limited.

The results of the tensile tests are summarized in Table 5.2.3 and discussed below.

[

(d)

]

5.3 NDE Measurement Testing

The F* lengths tested were measured in a laboratory environment with precise equipment. Applying the F* criteria in the steam generator will be based on a length measured by ECT. Any errors associated with ECT measurement of the F* rolled tube length beyond an ECT indication must be included in the final F* criteria. Thus, testing was performed to determine the accuracy of ECT measurement techniques.

5.3.1 Test Equipment

Standard ECT equipment and techniques that are commonly used during normal in-service inspections were used to measure the F* length of the mockups used during the mechanical joint testing described in Section 5.2. [

(c)

]

5.3.2 F* Length Verification Methodology

[

(c)

]

[(c)] All measurements were made from the initial excursion of the tubesheet signal. Distances were then measured to the initial excursions of the roll signal and the crack signal.

The ECT data was then analyzed to determine the F* length of each specimen. Physical measurements of the same lengths were taken for comparison using calibrated digital calipers. Figures 5.3.2.1 and 5.3.2.2 provide sample plots showing where the key points were selected for the ECT measurement of the F* length.

5.3.3 Results

Four test blocks with four F* tubes per block were pulled 3 times each with bobbin and MRPC probes and the ECT measurements for each specimen were averaged [7.6]. The differences between the ECT F* lengths from the various ECT techniques and the actual measured F* lengths are summarized in Table 5.3.3.

[

(d)

]

5.4 Determining Final F* Criteria

The final F* length is determined by combining the F* equation derived in Section 5.1 with the mechanical test results and with the uncertainty associated with ECT measurement:

[

(d)

]

Several mockup blocks were heated to determine what effect, if any, plant operating temperature had on the rolled tube-to-tubesheet joints. Since the heated blocks more accurately represent the conditions expected in actual steam generator conditions, the test results from these samples were used to determine the required F* length.

[

(d)

]

[

(d)

]

5.5 Boric Acid 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% through wall, the tubesheet bore would be exposed to primary side fluid. At low temperatures with aerated boric acid solutions, some corrosion may be expected.

[

(c)

]

The defects associated with PWSCC in the tubesheet region are typically minute which limits the amount of "flowing solution" available 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. These two factors make boric acid attack on the tubesheet an unlikely scenario.

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

For the reasons discussed above, there is a very low probability of any significant corrosion of the tubesheet bore associated with boric acid corrosion. [

(c)

] Such a small level of degradation would have no impact on the F* joint nor the structural adequacy of the tubesheet.

TABLE 5.1.1
RADIAL STRESS AND AXIAL LOADING SUMMARY

[

(c)

]

FIGURE 5.2.1
MOCKUP BLOCK LAYOUT

[

(c)

]

TABLE 5.2.1
QUALIFICATION SPECIMEN INSTALLATION SUMMARY

[

(d)

]

TABLE 5.2.2
LEAK TEST RESULTS

[

(d)

]

TABLE 5.2.3
TENSILE TEST RESULTS

[

(d)

]

FIGURE 5.3.2.1
SAMPLE BOBBIN PLOT SHOWING SELECTION POINTS
(Sheet 1 of 3)

[

(d)

]

FIGURE 5.3.2.1
SAMPLE BOBBIN PLOT SHOWING SELECTION POINTS
(Sheet 2 of 3)

[

(d)

]

FIGURE 5.3.2.1
SAMPLE BOBBIN PLOT SHOWING SELECTION POINTS
(Sheet 3 of 3)

[

(d)

]

FIGURE 5.3.2.2
SAMPLE MRPC PLOT SHOWING SELECTION POINTS

[

(d)

]

TABLE 5.3.3
ECT MEASUREMENT ACCURACY COMPARISONS

[

(d)

]

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6.0 CONCLUSIONS

Based on the design verification analyses and testing performed, the following conclusions are provided:

- A total F* length of [(d)] inches is structurally adequate to satisfy all of the requirements for normal operating conditions with a safety factor of 3, faulted loading conditions with a safety factor of 1.43, and locked tube loading conditions for STP Unit 1 W E-Series steam generators. The F* criteria will not be applied to tube locations that exhibit the "waviness" condition as described in Section 1.1 and listed in Table 3.3.3.

- The primary to secondary leakage expected from applying the F* plugging criteria to all tube ends in all four steam generators will be substantially less than the technical specification limit. The expected primary to secondary leakage during faulted conditions will also be substantially less than the technical specification limit for normal operation.

- Considerable conservatism exists in the derivation of the F* criteria. Specifically,

  1) The joint strength was conservatively determined for use in developing the F* criteria.

  2) The factor for ECT uncertainty is based on the least accurate NDE technique tested. Other NDE techniques may be utilized, provided it is demonstrated that the accuracy is within the 0.2" reported herein [7.6].

  3) The conservative loads and pressures used in the testing.

- The application of the F* plugging criteria at South Texas Project Unit 1 does not raise any concerns over boric acid attack of the tubesheet.

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7.0 REFERENCES

7.1 NRC Regulatory Guide 1.121, "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 51-1233798-03, "Technical Requirements for STP-1 F* Qualification".

7.4 BWNT Document 32-1233826-00, "F* Calc for Westinghouse E-Series RSGs".

7.5 BWNT Document 51-1228675-02, "Summary of Springback Test Results for W D-Series RSG's".

7.6 BWNT Document 51-1228688-01, "Summary of ECT Verification Testing for W D-Series F*".

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

7.8 BWNT Document 02-1189609, "Bobbin Coil Probe Speed/Data Sampling Rate Test".

7.9 EPRI Report NP-6864-L, COMMITTEE FOR ALTERNATE REPAIR LIMITS FOR EZ PWSCC, Rev.1.

7.10 BWNT Document 51-1227909-01, "Test Plan for F* Qualification".

7.11 BWNT Document 51-12233809-00, "Justification for Using W D4-Series Test Data for STP-1 F*".

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APPENDIX A
DERIVATION OF F* CRITERIA EQUATION

Because all the F* qualification testing was done at room temperature, the results of the testing had to be equated to actual steam generator (SG) temperature and pressure conditions (see Section 4.2). The equation was derived (based on standard stress equations) to relate the results of room temperature testing to the SG operating conditions.

[

(d)

]

[

(d)

]

ATTACHMENT 4

W E-Series F* Qualification Report
BAW-10203P