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OTSG REPAIR ROLL QUALIFICATION REPORT
(INCLUDING HYDRAULIC EXPANSION EVALUATION)

FTI NON-PROPRIETARY

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LIST OF ABBREVIATIONS

DELTA	Roll expander toolhead
ECT	Eddy Current Testing
EFPY	Effective Full Power Year
ETSS	Examination Technique Specification Sheet
F*	F Star
HX	Hydraulic Expansion
ID	Inside Diameter
IGA	Inter-granular Attack
MAI	Multiple Axial Indications
MIC	Micrometer
NDE	Nondestructive Examination
OD	Outside Diameter
OTSG	Once-Through Steam Generator
PWSCC	Primary Water Stress Corrosion Cracking
RFO	Refueling Outage
RPC	Rotating Pancake Coil
RSG	Recirculating Steam Generator
RT	Roll Transition
SAI	Single Axial Indications
SCC	Stress Corrosion Cracking
TSID	Tubesheet Bore ID
2D	Two Dimensional
3D	Three Dimensional

1.0 INTRODUCTION

1.1 Background

Eddy current inspection of OTSG tubes has resulted in the detection of indications within the tubesheet region. These indications have been identified as single or multiple axial indications (SAI or MAI), single circumferential indications (SCI), or volumetric (VOL) indications which require repair or plugging per typical plant technical specifications. The indications are generally characterized as ID stress corrosion cracks (IDSCC) in the existing tube roll transitions. The volumetric indications have been characterized as intergranular attack (IGA).

Such indications represent well documented degradation mechanisms in steam generator tubing. IDSCC occurs in susceptible alloy 600 material under the combined action of primary water, elevated temperature, and sustained tensile stresses which exist in the roll transition region of the tubes. Some of the tubes in the ANO-1 OTSG's have OD defects characterized as IGA in the upper tubesheet. These defects are distributed between the tube roll transition and the secondary face of the tubesheet.

The number of tubes [illegible] indications detected in OTSG's is expected to increase in time. If degradation continues then a repair method may either be desirable or necessary to maximize the number of tubes left in service for continued operation. One such repair method is to perform a tube roll expansion (repair roll) within the tubesheet beyond the existing degraded location.

1.2 Purpose

The purpose of this document is to provide a technical justification to implement a tubesheet region repair roll in degraded tubes in OTSG's. A repair roll which is installed beyond the degraded region of tubing provides a frictional joint of undegraded tubing within the tubesheet bore, creating a new primary pressure boundary within the tube. The structural aspects of the repair must be demonstrated in accordance with NRC Regulatory Guide 1.121, by establishing an engagement distance sufficient to withstand the axial tube loadings imposed by normal operating condition and worst case faulted condition differential pressures and thermal displacements. The repair roll leakage must meet requirements for maintaining plant leakage within technical specification limits.

If a repair roll is located near the secondary face, then a crevice region will exist between the original roll and the repair roll. The customer requirements from Entergy for the Arkansas Nuclear One Unit 1 OTSG tubes include performing an evaluation of installing a hydraulic expansion of the tube within the tubesheet to close the crevice. This hydraulic expansion eliminates any concerns associated with potential tube denting due to the Obrigheim effects of a trapped water volume.

2.0 EXECUTIVE SUMMARY

Eddy current inspection of OTSG tubes has revealed tubes with indications at the roll transition within the tubesheet region. These indications have been characterized as either axial, circumferential, or volumetric defects which may exceed the current plugging limit for the tubes. The axial indications have been predominantly attributed to stress corrosion cracking of the tube roll transitions. The volumetric indications have been characterized as IGA.

A process has been developed to repair these tubes allowing them to remain in service. This repair process consists of creating a new mechanical tube-to-tubesheet-structural joint by rolling a new joint below the region of tube defects. This type of repair has been previously qualified and implemented by FTI for Westinghouse Model 27 recirculating steam generators (RSG's) at Connecticut Yankee, Westinghouse Model 44 RSG's at Point Beach 2 and Indian Point 2, Westinghouse Model 51 RSG's at DC Cook Unit 1, and Babcock & Wilcox OTSG's at Oconee Unit 1 (8.6).

The qualification of the mechanical joint is based on establishing a mechanical roll length which will carry all of the structural loads imposed on the tubes with required margins. A series of tests and analyses were performed to establish this length. Tests that were performed included leak, tensile, fatigue, ultimate load, and eddy current measurement uncertainty. The analyses evaluated plant operating and faulted loads in addition to tubesheet bow effects. Testing and analysis evaluated the tube springb nd radial contact stresses due to temperature, pressure esheet bow.

The repair roll is defined as a (d) long, defect free roll expansion beyond the original roll expansion. An optional hydraulic expansion may be performed to close the crevice between the tube and tubesheet bore prior to performing the roll expansion. These repair methods are shown in Figure 3.1.

The repair roll consists of one roll positioned approximately (d) inches (or greater) beyond the original roll. The repair roll length is (d) as defined by the physical length of the roller pins used in the expander tool. No extra roll length is provided in this method for ECT measurement uncertainty. No extra roll is needed to cover crack migration from the original roll, since the repair roll does not overlap the original roll.

When the repair roll is located deep in the tubesheet a trapped volume will exist in the crevice between the tube and tubesheet bore. To decrease water ingress, this volume can be reduced by performing a hydraulic expansion of the tube to close the crevice prior to the repair roll installation. Reducing the trapped volume minimizes the possibility of tube denting during heatup.

The worst case operational leak rates for repairing all 15,531 tubes in each OTSG (31,062 tubes total) will be less than (d) GPD, assuming all tubes have 100% through wall defects. A conservative estimate of MSLB leak rates is (d) GPD at (d) psi differential.

The tubes which require repair are known to be susceptible to stress corrosion cracking. Therefore, the new roll transitions may also exhibit defects. The defects are readily detected by eddy current inspection during normal refueling outage inspections.

Based on the FTI qualification performed, as well as the history for similar industry repair rolls, there are no new safety issues associated with a repair roll.

3.0 REPAIR ROLL DESCRIPTION

3.1 Design

The roll joint consists of installing a roll expansion away from the original roll in the region of unexpanded tubing beyond the degraded section within the tubesheet. The roll expander used for reroll qualification has a total roller length of (d) inches with an effective length of (d) between the tapered ends. If the defects in the tubesheet require that the repair roll be placed deep in the tubesheet, then an optional hydraulic expansion of the tube may be performed before the repair roll expansion. Figure 3.1 provides a sketch of the repair roll and optional hydraulic expansion. The repair roll may be located within or beyond the hydraulic expansion region.

A lubricant is used to lubricate the rollers and enhance the quality of the rolls. The objective of the repair roll is to place a (d) effective roll away from any existing tube defects to satisfy leakage and load capacity requirements.

3.2 Installation

The repair roll is typically performed remotely using a manipulator and a DELTA plugging type tool head. A control system is used to position and install the new roll expansion. The nominal required torque is (d) ((d) minimum) using the standard qualified tooling. Spacers between the tool and tubesheet or tube end are used to establish the proper roll depth for candidate tube locations. If the repair roll will be located deep in the tubesheet, then an optional hydraulic expansion may be performed to close the crevice above the roll expansion.

The following is a summary of the tube repair roll installation process:

The DELTA tool is first calibrated to deliver a roll torque of (d) and to properly measure diameter. The target tubes are roll expanded to the torque setpoint. A time history of the torque and diametral expansion is recorded onto disk.

Based upon field experience, after (d) rolls are performed, the tool is removed and a calibration check is performed. The next group of tubes are then rolled.

After tube repair rolls are completed, post ECT examination is performed. This ECT examination confirms the proper tubes were expanded, verifies proper diametral expansion, and verifies the new (d) roll expansion is free of degradation.

If any anomalies are noted at any time during the process, a Non-Conformance Report (NCR) is written for disposition by Engineering.

3.3 Process Verification

Standard pre-repair roll eddy current techniques are used to identify candidate tube locations for repair and determine where the lowermost defect is located. After repair roll installation, bobbin profilometry or equivalent techniques are used to generate a plot which identifies the new roll expansion length and relationship to the existing defect, and MRPC or equivalent techniques are used to verify that there are no defects in the required roll length region. Bobbin profilometry may also be used to verify the effectiveness of the hydraulic expansion process.

Figure 3.1: Typical Tube Repair Roll Sketch

(c)

4.0 DESIGN REQUIREMENTS

4.1 General

The US NRC Draft Regulatory Guide 1.121 [8.1] prescribes safety factors of 3 on normal operating differential pressure and ASME Code design margins for faulted conditions, respectively. These factors have been used as the basis for establishing a suitable repair roll length for recirculating steam generator (RSG) tubes. [

(c)

]

The repair roll shall be of sufficient length such that the expansion alone (without any support from the original tube expansion and tube seal weld) provides the necessary structural strength to satisfy the normal and faulted tube loadings. In addition, the roll shall provide a mechanical seal between the existing tube and tubesheet. The new joint shall provide leak limiting capability, assuming a full 360° circumferential sever immediately outboard of the new roll region. Leakage must be maintained well below the technical specification limits.

The repair roll becomes the new ASME Code pressure boundary. The new roll carries the structural loadings and performs the function of isolating the primary water from the secondary water. The degraded tube between the minimum required repair roll length and the tube end can be excluded from future periodic inspection requirements because it is no longer part of the pressure boundary once the repair roll is installed.

4.2 Design and Operational Loading Conditions

The design, operational, and accident temperatures and pressures for the Babcock & Wilcox 177 FA OTSG's are provided in Table 4.1. The resulting OTSG tube loads are summarized in Table 4.2.

TABLE 4.1: B&W OTSG (177FA) PERFORMANCE CHARACTERISTICS

DESIGN CONDITIONS	PRIMARY SIDE		SECONDARY SIDE
Design Pressure, psia	[	(c)	]
Design Temperature, °F	[	(c)	]
Number of Tubes (DB-1)	[	(c)	]
LEVEL A (NORMAL OPERATING) CONDITIONS (100% Full Power)			
Pressure, psia	[	(c)	]
Temperature, Inlet, °F(DB-1)	[	(c)	]
Temperature, Outlet, °F (DB-1)	[	(c)	]
Flow Rate, lbm/hr per generator (OCO-1,2,3)	[	(c)	]
Flow Rate, lbm/hr per generator (TMI-1)	[	(c)	]
Flow Rate, lbm/hr per generator (DB-1)	[	(c)	]
Flow Rate, lbm/hr per generator (CR-3)	[	(c)	]
Flow Rate, lbm/hr per generator (ANO-1)	[	(c)	]
Heat Transferred, BTU/hr per generator (OCO-1,2,3)	[	(c)	]
Heat Transferred, BTU/hr per generator (TMI-1)	[	(c)	]
Heat Transferred, BTU/hr per generator (DB-1)	[	(c)	]
Heat Transferred, BTU/hr per generator (CR-3)	[	(c)	]
Heat Transferred, BTU/hr per generator (ANO-1)	[	(c)	]
Typical Full Load Pressure Drop (Max psi)	[	(c)	]
LEVEL D (FAULTED) CONDITIONS			
Main Steam Line Break or Main Feedwater Line Break Maximum Pressure, psia (See additional loads in Table 4.2)	[	(c)	]
Loss of Coolant Accident Maximum Pressure, psia (See additional loads in Table 4.2)	[	(c)	]

TABLE 4.2: B&W (177FA) STEAM GENERATOR TUBE REPAIR
40 YEAR DESIGN LOADINGS

OTSG TUBE OPERATING LOADS			
LOAD SET NUMBER	TRANSIENT DESCRIPTION	TRANSIENT CYCLES	TUBE LOAD (LBS) or (IN-LBS)
1 (Transients 1A,1B,1C,9 11,15,17A,17B)	HEATUP COOLDOWN	(c)	(c)
2 (Transients 2A,2B,14)	0% TO 15% PWR 15% TO 0% PWR	(c)	(c)
3 (Transients 3,4,5,6,7,8)	REMAINING TRANSIENTS	(c)	(c)
OBE	Operating Basis Earthquake (NORMAL)	(c)	(c)
SSE	Safe Shutdown Earthquake (FAULTED)	1	(c)
MSLB	Main Steam Line Break (Due to pressure and thermal differentials) (Due to Dynamic Tube Loading) (FAULTED)	1	(c)

F = Force (LBS), M = Moment (IN-LBS)

5.0 DESIGN VERIFICATION

The design verification as described in this section develops the OTSG specific required length for the repair roll. This development begins by evaluating the design and operating conditions for OTSG plants. A summary of the analysis methodology and results is provided. Additionally, a summary of the repair roll testing is provided which supports the analysis in determining the final roll length. The process NDE requirements follow which describe the necessary post-repair roll verification actions and provide a review of previous testing methods and associated uncertainties. The following is a summary of the design verification methodology:

- Determine tube loadings during normal and faulted conditions.
- Perform design verification testing.
    - Prepare rolled tube samples.
    - Perform leak tests.
    - Perform thermal and axial load cycling.
    - Perform final leak tests.
    - Perform ultimate load tests.
- Determine exclusion zones for application of (d) repair roll length based on tube hole dilation effects.
- Evaluate the effect of the reroll process on the tube axial load.
- Evaluate potential for tube denting due to trapped water in the tube to tubesheet crevice.
- Establish tube hydraulic expansion to minimize tube denting.

5.1 Calculation of Tube Loads

All of the critical physical dimensions and materials of construction of the original design are summarized in Figure 5.1. The performance characteristics of OTSG's are identified in Table 4.1. The following key factors affect the repair roll length as they [(c)]:

o Normal operating primary to secondary differential pressure
o Faulted condition primary to secondary differential pressure
o Primary inlet and outlet temperatures
o Secondary outlet (steam) temperature
o 100% Power temperatures of shell/wrapper, tube, and tubesheet

The pressure and thermal differentials are used in the analysis to calculate the loads imposed on the tubes during normal and faulted conditions.

The primary inlet, outlet, and steam temperatures factor into the analysis by determining the effect on the joint strength as a result of the expansion differences between the tube and tubesheet. The controlling required joint strength loads (from Table 4.2) for Level A and Level D conditions are summarized below in Table 5.1.1.

Table 5.1.1: Axial Tube Load Summary

	Axial Tensile Load (lbs)	Average Tube Temp (°F)	Primary Pressure (psi)
Level A: Cooldown Transient	[	(c)	]
Level D: MSLB Accident			
ANO-1, CR-3, DB-1, TMI-1	[	(c)	]
ONS-1, ONS-2, ONS-3	[	(c)	]

5.2 Design Verification Testing

Mechanical tests were performed during the qualification to evaluate various roll lengths at room temperature conditions. The test data was then corrected by analysis to obtain the final required length, as described in Section 5.3, for operating conditions. Tests performed consisted of leak testing, axial load cycling, thermal cycling, and ultimate load tests. Normal operation and faulted conditions were simulated during testing. A total of [(d)] were tested. Note that previous similar tube repair roll tests had been performed which produced acceptable results. Thus, this allowed focus on the anticipated required torque which minimized the sample size. Note also that test loads were increased per the ASME Code to accommodate the sample size.

Figure 5.1 OTSG General Arrang-ment

(c)

The tube to tubesheet crevice was clean when the test roll expansions were performed. Tube degradation is currently observed in the upper tubesheet roll transition. Based upon numerous OTSG tube pulls, there is no evidence of significant crevice deposits in this region; therefore testing was performed without simulating deposits. Lower tubesheet crevices are known to contain deposits, and thus the potential effects of these deposits will need to be addressed prior to application of the tube repair rolls in the lower tubesheet.

5.2.1 Mockup Preparation and ECT Testing

The tubes used in the mockup were [(d)] nickel-chromium-iron alloy 600, heat 93452. This tubing possessed a yield strength [(d)] psi. The mockup dimensions of tubesheet bore, surface roughness, and measured tube ID are recorded in Table 5.2.1. The tubesheet bore range tested was [(d)] This hole size is near the high end of the [(d)] in operating OTSG's. Figure 5.5 shows the Repair roll Expansion Test Mockup Assembly.

Table 5.2.1: Tube Installation Data

BLOCK -HOLE	TS BORE DIAMETER (INCH)	(c)	EXPANDED TUBE ID (INCH)	
			ID MIC	DELTA
		(d)		

ID MIC: Measured ID using micrometers.
DELTA: Tube ID as indicated by the DELTA installation tool.

The tube samples were roll expanded using a modified FTI Model number [(c)] roll expander mounted on the DELTA tool. The field expansions are performed with an [(c)] expander mounted on the DELTA tool. The expanders used for qualification testing and field application have the same critical dimensions. These expanders produce [(c)] with [(c)] end. Both the qualification tool and the field tool are torque controlled. The primary difference between the qualification expander and the field expander is the length of the expander cage. The qualification expander was modified in length to allow proper axial positioning in the test block.

The tube rolling maximum delivered torques and roll lengths are provided in Table 5.2.2. Roll lengths are shown for both physical measurements and eddy current test inspection measured values.

The actual length was determined by measuring from the tube end to the end of the roll expansion. The configuration results in a roll length [(c)] because the rollers overlapped the ends of the two tube sections, which is conservative.

The acquisition and analysis was performed in accordance with Examination Technique Specification Sheets in Appendix A. [(c)] ECT testing was acquired with [(c)] probe. The [(c)] ECT testing was acquired with [(c)] probe. Refer to Appendix A for details on these probes. Each sample was acquired (d) for both techniques, except for sample (c), which has only [(c)].

Tube expansion is a torque controlled process. To conservatively account for the torque required to expand the tube into contact with the tubesheet bore, a high yield strength tube was used. Since less torque is required to expand lower yield strength tubing, tests performed using the high yield tubing are more conservative than tests performed with the low yield tubing.
The average error for the eddy current roll length is (d) inch at (d) kHz for a RPC probe with a standard deviation of (d) . The average error was (d) inch at (d) kHz with a bobbin probe with a standard deviation of (d) .

Table 5.2.2: Tube Installation Torque and Roll Lengths

BLOCK -HOLE	ROLL TORQUE (IN-LBS)	CALC'D ROLL LENGTH (INCH)	ECT ROLL LENGTH (INCH)		ECT ERROR (INCH)	
			RPC (d) kHz	Bobbin (d) kHz	RPC (d) kHz	Bobbin (d) kHz
(d)	(d)	(d)	(d)	(d)	(d)	(d)
				AVG.	(d)	(d)

* The roll length of (d) was measured following the ultimate load test by pulling the tube from the tubesheet.

5.2.2 Leak Testing

Room temperat''re hydrostatic pressure tests were performed at (d) psi on the mockup samples. This value exceeds both 3 x normal operating pressure and 1.43 x MSLB pressure. The purpose of this test is to look for gross leakage or structural failure of the joints. No mechanical change or gross leakage in the samples were noted. Only one [(d)].

The hydrostatic test was repeated after thermal and load cycles of the samples. Again, no mechanical change was noted in the joints. There was no visible leakage in any sample during the second hydrostatic test.

Room temperature leak tests were performed on the samples at (d) psi. This was done both before and after thermal/load cycling was applied to the samples. Note that room temperature leak tests are conservative since higher temperatures increase the joint tightness due to thermal expansion differences between I600 tube and carbon steel tubesheet. The results of the leak tests are presented in Table 5.2.3.

The leak testing at (d) resulted in an average leak rate of [(d)] before load testing. The final leak testing at [(d)] after thermal cycles and axial load cycles (cyclic tests discussed in 5.2.3). The average of initial and final leak rates[(d)]

Table 5.2.3: Leak Test Results

BLOCK -HOLE	INITIAL LEAK RATE AT (d) (IN^3/HR)	FINAL LEAK RATE AT (d) (IN^3/HR)
(d)	(d)	(d)
AVERAGE	(d)	(d)

If all 15,531 tubes in each upper head of the two OTSG's are repaired by tube repair roll, the worst case normal operational leakage is (d) GPD. This value is conservative due to:

- It assumes all tubes have 100% through wall defects.
- Operating differential pressure of (d) compared to the test pressure of (d).
- The tubes tested were severed 360 degrees.
- The average tested roll length was (d) compared to a nominal repair roll length of (d).
- The tube has a higher coefficient of thermal expansion than the tubesheet, therefore the rolled joint would be tighter at operating temperatures than at room temperature.

A conservative estimation of leakage at MSLB differential pressure ((d)) is based on increasing the leak rate by the square of the pressure ratio, or (d) . This results in a (d) leak rate. This method is not considered exact, but conservative, since the higher primary pressure during the MSLB event will tighten the roll expanded joint. Normally the leak rate would be expected to increase according to the square root of the pressure ratio. Therefore, the worst case MSLB leak rate at (d) is estimated to be (d) for 15,531 tube ends per OTSG (31,062 total tube ends). This value is conservative for the reasons mentioned above.

5.2.3 Thermal and Fatigue Cycling

The two mockup blocks were cycled cycled [(d)] These thermal cycles were performed to allow for any relaxation in the tube to tubesheet joint due to differential thermal expansion of the Inconel and carbon steel.

Axial load cycling was performed to simulate the applied loads imposed on the OTSG tubes due [(d)] These loadings are based on normal operating transients expected to occur over a 40 year design life of the OTSG's from Table 4.2.

The loadings from Table 4.2 are adjusted by increasing the number of cycles for the first and second load sets and by increasing the applied force for the third load set. These adjustments are based on a quantity of (d) samples to conservatively envelope the testing of (d) samples. Table 5.2.4 summarizes the load sets for loading range and cycles developed from Table 4.2 data. No tube motions were observed during this test, thus all samples successfully passed.

Table 5.2.4 Fatigue Test Axial Load Cycles

LOAD SET	AXIAL TEST LOADING RANGE (LBS)	NUMBER OF CYCLES
1	(d)	(d)
2	(d)	(d)
3	(d)	(d)

5.2.4 Ultimate Load Test

An ultimate load test was performed to axially load the tube joints until failure. This test was performed with ID gripper fingers inside the tube pulled by a hydraulic jack using a manual pump. In each case the applied applied [
(d)]

The loads are summarized in Table 5.2.5. Tube movement was monitored by a dial indicator mounted on the mockup block and reacting off the mandrel of the ID gripper[
(d)
] The final pullout loads were used to establish the required roll length in Section 5.3.

Table 5.2.5: Ultimate Load Test Results

BLOCK -HOLE	ROLL TORQUE (IN-LBS)	ROLL LENGTH (INCH)	MAXIMUM PULL LOAD (LBS)	MAXIMUM LOAD CUMULATIVE TUBE MOVEMENT (INCH)
(d)	(d)	(d)	(d)	(d)

* [

(d)

]

[

(d)

]

Applying a one-sided 95 percent tolerance limit factor of (d) (reference 8.4) to the standard deviation of (d) lbs results in a minimum joint load capacity of (d) lbs. This value exceeds the minimum required strength of (d) lbs for an Oconee MSLB condition. Thus, all samples were acceptable. A (d) roll length will be conservatively assumed to correspond to this load of (d) lbs. This load will be used to determine the maximum tube hole dilation allowed due to tubesheet bow.

5.3 Effect of Tube Hole Dilation on Joint Strength

The load testing summarized in Section 5.2 was performed in tubesheet mockups with as-fabricated bore diameters. In an operating OTSG, the tubesheet bore diameter can change during certain operating conditions due to the combined effects of primary to secondary pressure differential and thermal loads. These loads cause the tubesheet to bow in one direction or the other, depending on the particular condition being evaluated. The bowing of the tubesheet will in turn cause the diameter of the tubesheet bore to increase or decrease, depending on its location. The change in diameter is a maximum at the face of the tubesheet, and decreases to zero at the neutral axis. An increase in diameter will decrease the contact stress between the roll joint and the tubesheet, which reduces the pullout strength.

This effect on the strength of the repair roll joint was evaluated analytically, and an exclusion zone was defined to ensure that the repair roll joint is installed only in locations where the effects of tubesheet bow do not reduce the joint strength below what is required to sustain all required loads.

The largest amount of tubesheet bow is predicted to occur during a MSLB event, where the maximum primary to secondary pressure differential occurs in conjunction with the largest predicted tube tensile loads. Both tubesheets will bow inward (towards the secondary side) as a result of these loads. The tubesheet bore hole diameter on the primary side will increase near the periphery (where the tubesheet is in tension from the bow effect) and decrease near the center (where the tubesheet is in compression). On the secondary side the effect is reversed, i.e., the bore hole diameter will decrease on the periphery and increase in the center.

The initial preload of the repair roll joint was estimated from measurements of tube diametral springback. Testing was performed by installing a repair roll joint into a split tubesheet block, measuring the diameter at the joint location, and then removing the tubesheet block. The diameter of the tube in the joint region expands after removal of the block. The difference between the as-installed diameter and the "relaxed" diameter is the spring back, and is a representation of contact stress. (d) test samples were evaluated, resulting in an average spring back of (d) . The room temperature radial (contact) stress was calculated from these results to be (d) psi.

The minimum axial load capacity for a (d) rolled joint at room temperature conditions was determined in Section 5.2.4 to be (d) lbs. The required strength of the joint for worst case normal operating and accident conditions are given in Table 5.3.1. Two bounding conditions were considered as discussed above, including a normal operating cooldown transient and a MSLB. Two different load cases for the MSLB transient were evaluated, the first being a bounding case for the non-Oconee plants, and the second being applicable for Oconee-1, 2, and 3. A finite element analysis was performed to determine the amount of tubesheet bow for each case, as well as the resulting hole dilation as a function of tube position and location within the tubesheet thickness.

For each of the three cases evaluated, an allowable tubesheet bore hole dilation was calculated such that the joint strength remained adequate to sustain the axial loads defined in Table 5.3.1. These calculations were based on the minimum joint strength of (d) lbs determined in Section 5.2.4, and the installed contact stress determined in the spring back testing discussed above.

Table 5.3.1: Tube Hole Dilation Allowables

	F_{NO}	F_{MSLB}	$F_{MSLB,OCO}$
Max Tube Load (lbs)	(d)	(d)	(d)
Roll Length	Maximum Allowable Tube Hole Dilation (inch)		
(d)	(d)	(d)	(d)

The calculated tube hole dilations due to thermal and pressure differentials were compared to the allowable dilations. The maximum tube hole dilations occur in the periphery of the tubesheet for rolls near the tube end for both upper and lower tubesheet. Maximum tube hole dilations occur near the center of the tubesheet at the secondary faces of the tubesheets. The application of a (d) long roll expansion is limited to those portions of the tubesheet where the calculated dilation is less than the allowables.

A roll length of (d) is used for the determination of exclusion zones presented in Figures 5.2 and 5.3. Figure 5.2 graphically summarizes the tube repair roll exclusion zones for all OTSG plants except Oconee 1, 2, and 3. Figure 5.3 graphically summarizes the tube repair roll exclusion zones for OTSG's at Oconee 1, 2, and 3. Zones 3, 5, 8, and 11 are based on maintaining any roll transition (d) from the secondary face. This (d) conservatively allows the tube to remain engaged in the tube hole in the unlikely event of a tube severance at the new roll transition. The exclusion zones are described in detail in Appendix B and the tubes in each zone are tabulated in Tables B.1 through B.6.

FIGURE 5.2: OTSG TUBE REPAIR ROLL LIMITATIONS

(All plants except Oconee 1,2,3)

[

(d)

]

FIGURE 5.3: OTSG TUBE REPAIR ROLL LIMITATIONS

(Oconee Units 1,2,3)

[

(d)

]

5.4 Non-Destructive Examination Effects on Final Repair Roll Location

A minimum actual roll length of (d) is used to determine the areas that a repair roll can be performed. However, this length does not include ECT measurement uncertainty. The location of the (d), if performed adjacent to a defect, shall include an allowance for the uncertainty associated with the ECT measurement technique used to evaluate the defect.

The final repair roll acceptance criteria that is developed for OTSG's must be evaluated using standard steam generator eddy current techniques. Post-repair roll bobbin profiles are required to verify expansion, show the new roll transition(s), and provide measurements of the undegraded roll beyond the defect. Measurement tolerances associated with remote eddy current measurements must be factored into the final value. Bobbin and RPC eddy current methods were both used to verify the accuracy and uncertainty in determining repair roll lengths in 5/8 tubing. 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.

ECT analysis of rotating pancake coil (RPC) and bobbin coil data was performed to determine the distance from the bottom end of the roll transition to a simulated sever. Each eddy current pull was analyzed (d). A total of [

(d)

]

The ECT errors were predominantly conservative, that is ECT underestimated the roll length. As a conservative practice, since [

(d)]

The factor for a 95% one-sided tolerance limit based (d) samples (bobbin) is (d), from reference 8.4. Thus, the additional distance from the defect to the repair roll due to ECT uncertainty will be based on the error of (d) for bobbin and the factor of (d) times the standard deviation of (d). The distance from the defect to the roll transition is (d) times the standard deviation of ECT error, plus the average error:

D = [(d)]

5.5 Repair Roll Effect on Axial Tube Load

Since the OTSG tubes are fixed on each end, the reroll process will induce an axial load into the tubes. This load was determined by measuring how much the tube elongates due to the reroll process. The average test result elongation from the reroll process is (d) inch. This elongation produces a compressive axial load of approximately (d) and a compressive stress of (d) psi in the tube. This axial load would act to reduce the maximum cooldown and MSLB accident tube loads. The increase in compressive load during plant heatup, and during other events which cause the tubes to be in compression, is considered to be insignificant.

5.6 Tube Crevice Evaluation

Testing was performed to define the optimum hydraulic expansion to limit tubesheet ligament stress, while assuring a tube/tubesheet crevice less than that which could result in tube denting. The crevice volume that exists between the tube and tubesheet bore increases as the depth of the roll increases. The diametral clearance varies from (d) to (d) for the range of tube OD's and tubesheet bore ID's in the Oconee-3, Davis Besse, and ANO-1 OTSG's. The diametral clearance varies from (d) to (d) for the range of tube OD's and tubesheet bore ID's in the Oconee-1, Oconee-2, TMI-1, and CR-3 OTSG's. The crevice volume is a maximum of (d) cubic inches per inch of length for the (d) clearance. Therefore, starting a roll (d) from the primary face would produce a maximum trapped crevice of (d) and a maximum volume of (d) cubic inches.

If a crevice fills with water at a low temperature, then the pressure in the crevice will increase as the temperature rises due to the expansion of the water. The specific volume of saturated water increases 32 percent as the temperature increases from 70°F to 532°F (zero power condition). To avoid denting of the tube the expanding water needs time to leak past the roll or the volume of the crevice needs to be minimized. The OTSG tube is able to experience an elastic diametral contraction of approximately (d) due to external pressure and return to its original diameter. Therefore an initial diametral clearance of (d) would be able to accommodate the expansion of trapped water during heatup without denting, assuming no leakage past the repair roll.

The minimum observed leak rate from section 5.2.2 was (d) cubic inch per hour at (d) psi. The water in the maximum postulated crevice volume would expand (d) times (d) cubic inches, or (d) cubic inches during a normal heatup. The time required for this additional volume of water to leak out is approximately (d) , based on the minimum leak rate. The nominal heat up rate is 40°F per hour, from 90°F to 530°F. Therefore, (d) hours might be available for leakage to occur, allowing (d) cubic inch of water to leak out and a possible tube dent of (d) cubic inch.

5.6.1 Tube Denting Test Summary

Testing was performed to confirm if tube denting would occur during rapid heatup of a trapped water volume. This testing included fabrication of (d) and tubesheet mockups as shown in Figure 5.4. The tubes were first roll expanded near the primary face of the tubesheet. Next the mockups were submerged in water to allow the crevice to fill with water. The tubes in samples [(d)] The water was retained in the crevice during this hydraulic expansion by keeping the primary face end oriented downwards. The only water that was removed was due to the expansion process. The hydraulic expansion was performed with the insitu pressure test toolheads secured at each end of the tube. These tools [(d)] After hydraulic expansion, these (d) were roll expanded near the secondary face of the tubesheet to seal the crevice.

The crevice for samples (d) were also filled with water, but no hydraulic expansion was performed prior to the roll expansion to seal the crevice. The tube ID was measured at (d) inch increments from (d) inches to (d) inches and (d) inches to (d) inches from the primary end of each tube sample.

The tubes were plugged on the primary end and the volume of each tube was measured by filling with water. An amount of water equal to half the tube volume was placed in each tube and the tubes were sealed at the secondary end. This water was inside the tubes to allow for internal pressure to build up during the thermal cycle, similar to the primary pressure inside the OTSG. The effects of the internal pressure are (1) to decrease the leakage past the roll expansion and (2) to increase the pressure required to dent the tube wall. Tube stickout measurements were taken at both ends of each tube sample.

The (d) samples without hydraulic expansions, [

(d)

]

The (d) samples with hydraulic expansions, [

(d)

]

After the thermal cycle was finished, tube stickout measurements were repeated. There was no change in tube stickout due to the thermal cycle process. The Swagelok plug was removed from the secondary end of each sample. The volume of water was measured, then the tube volume was measured. The Swagelok plug at the primary tube end was removed and tube ID measurements were repeated. Visual examination of the samples showed that (d) tubes, samples (d) , had dented during the thermal cycle.

5.6.2 Tube Installation

The tube installation data is summarized in Table 5.6.1. The (d) heats of alloy 600 tubing used were (d) ksi and (d) ksi yield strength. The mockup block material was ASTM 1018 carbon steel round bar with a nominal OD of (d) inches, a bored hole ID ranging from [(d)] and a length of (d) inches.

Table 5.6.1: Tube Installation Data

Tube Heat/ Lot	Tube Yield (ksi)	Tube OD (inch)	Tube ID (inch)	Mockup Bore Diameter (inch)	Primary Roll Torque (in-lb)	Sample Number	Primary Roll Diameter (inch)	Secondary Roll Torque (in-lb)	Secondary Roll Diameter (inch)
					(d)				

5.6.3 Trapped Water Volumes

The volume of water trapped in the crevice and in the tube is summarized for each sample in Table 5.6.2 before and after hydraulic expansion (HX). These calculations consider a crevice length of (d) due to the (d) roll expansion at each end of the (d) long mockup blocks.

Example: Volume = (PI/4)*(TSID^2- TUBEOD^2) * (LENGTH)

Sample H1: Volume = (PI/4)*((d))*((d)) = (d) cubic inch

Table 5.6.2: Tube and Crevice Volume Data

Sample Number	Calculated Crevice Volume Before HX (cu. inch)	Calculated Crevice Volume After HX (cu. inch)	Calculated Crevice Volume After Thermal Cycle (cu. inch)	Tube Volume Before Thermal Cycle Measured (ml)	Tube Volume After Thermal Cycle Measured (ml)
			(d)		

[

(d)

]

Dent Volume = (2) * (PI/4) * ((d)) = (d) cubic inch

The crevice volume increases approximately (d) based on the size of the dents for samples (d).

5.6.4 Testing Observations

1. [

(d)

]

[(d)]

2. [

(d)

]

3. [

(d)

]

5.7 Effects of Tube Hydraulic Expansion

5.7.1 Hydraulic Expansion Residual Crevice and Ligament Stress

Testing was performed with the prototype tube hydraulic expander using a computer controlled pressure and volume tracking system. The hydraulic expansion of the tube into contact with the tubesheet was observed to occur at (d) psi and (d) psi for tubes with a yield of (d) and (d) , respectively. The additional pressure above contact with the tubesheet bore results in a tubesheet ligament stress approximately (d) the applied pressure. For example, if contact occurs at (d) and the pressure is increased to (d) , then the maximum hoop stress at the tubesheet bore surface is [(d)] ksi.

The change in tubesheet ligament outside dimension is (d) inch per (d) of applied pressure, based on thick shell theory [8.5]as shown in Equation 5.7.1.

Equation 5.7.1:

$$\text{Delta OD} = (2) * \frac{(Q)(OR)(IR^2)(2-nu)}{(E)\ (OR^2 - IR^2)}$$

Where:	Q	=	Applied Pressure, psi	= (d) psi
	OR	=	Outside Radius	= (d) inch
	IR	=	Inside Radius	= (d) inch
	nu	=	Poisson's ratio	= 0.30
	E	=	Modulus of Elasticity	= 30.2 E6 psi

The change in tubesheet bore ID is calculated in Equation 5.7.2. Again, for an applied (d) psi the ID will increase (d) inch.

Equation 5.7.2:

$$\text{Delta ID} = (2) * \frac{(Q)(IR)}{(E)} \frac{(OR^2)(1 + nu) + (IR^2)(1-2*nu)}{(OR^2 - IR^2)}$$

The hydraulic expansion of a (d) inch OD tube to (d) inch tubesheet bore results in a (d) change in circumference and approximately a (d) ksi increase in yield strength. Assuming a final (d) yield strength the tube OD can relax a distance equivalent to the reduction in tube OD based on removing a (d) psi pressure. This is approximately (d) inch based on Equation 5.7.1, a tube ID of (d) inch, a tube OD of (d) inch, and a modulus value (E) of 31 E6 psi.

As the pressure is released, the tubesheet will relax (d) inch as the pressure decreases from (d) psi to (d) psi, based on a change in tubesheet ligament stress from 20 ksi to zero. The tube will follow the tubesheet for this same change in bore ID and tube OD. Since the tube was plastically deformed above (d) to (d) psi, as the pressure drops from (d) psi to 0 psi the tube OD will continue to relax an additional (d) inch. Therefore, a negligible preload will exist between the tube and tubesheet following a hydraulic expansion, and a diametral crevice of approximately (d) inch would be formed.

Increasing the maximum applied pressure to (d) psi would result in a tubesheet ligament stress of approximately (d), which is (d) percent of the minimum yield strength of the tubesheet material. The diameter increase of the tube OD and tubesheet bore ID would be (d) from above. The relaxation of the tube and tubesheet would be almost equal, so that (d) would remain.

5.7.2 Change in Tube Axial Preload

The hydraulic expansion of the tube in the tubesheet region will result in a (d) of the tube. This change in tube length is calculated based on testing done with a hydraulic expansion (d) inches in length and a range of tube OD expansions of (d) to (d) . Table 5.7.1 summarizes the change in tube length. The length (d) is approximately (d) for each (d) change in tube OD. Therefore, a nominal (d) OD tube expanded into a nominal (d) tubesheet bore would experience a length (d) of (d) . This (d) will (d) the tube tensile load by (d) lbs. The tube roll expansion would recover (d), resulting in a net [(d)] in tensile loading.

The additional tube loading due to hydraulic expansion does not change the repair roll limitations illustrated in Figure 5.2. The tubesheet holes at a radius greater than (d) do not experience dilation near the secondary face. Therefore, the joint strength is sufficient to carry the tube loading. The normal operating and

MSLB accident tube loads decrease to (d) percent of the periphery loads for the center loads. Again, resulting in sufficient joint strength.

Tablo 5.7.1: Tube Change In Length

Tube Sample	Heat/ Yield Stress	OD Before	OD After	Length Before	Length After	Change in OD	Change in Length
(d)	(d)	(d)	(d)	(d)	(d)	(d)	(d)

5.7.3 Summary

Expanding an OTSG tube into contact with the tubesheet bore will result in approximately a (d) diametral crevice. Application of an additional (d) psi beyond the pressure that the tube contacts the bore will result in approximately a (d) diametral crevice and approximately (d) of yield stress in the ligament. And application of an additional (d) psi beyond contact will result in a (d) crevice, but will also stress the ligament to (d) percent of yield.

A tube diametral crevice of (d) is the maximum allowed to prevent any tube denting during heatup with trapped water. Therefore, application of a hydraulic expansion process shall assure contact of the tube with the bore and a maximum additional pressure of (d) psi, and a maximum total applied pressure of (d) psi. This method will prevent tube denting and minimize ligament stresses. The tube repair roll limitations shown on Figure 5.2 and tabulated in Appendix B are still applicable.

FIGURE 5.4: Hydraulic Expansion Test Mockup Assembly

[

(d)

]

FIGURE 5.5: Repair roll Expansion Test Mockup Assembly

[

(d)

]

6.0 EVALUATION OF REPAIR ROLL LIFE

6.1 Tube Integrity in Repair Roll

The significant tube degradation mechanisms in OTSG tubesheets have been characterized as ID PWSCC and OD IGA. These degradation mechanisms in the elevated stress regions associated with a roll transition can potentially limit the life of the repair roll.

Non-destructive eddy current examinations, laboratory examinations of pulled tube samples, and accelerated corrosion tests have all shown that PWSCC will occur in the roll transitions of alloy 600 tubing. Laboratory tests indicate that tensile stresses accelerate the rate of SCC and moderately affect the rate of IGA. The operating temperature can also affect the corrosion rate in the roll transitions. For example, intergranular corrosion tends to occur mainly in the elevated temperature region of the hot leg versus the cold leg. The presence of the high stress area in the new roll transition, along with high hot leg temperature ((d) at DB-1) indicates that the new roll transition will be susceptible to IDSCC as is the existing roll transition.

The main difference between the original roll transition and the transition created by the repair roll is the full vessel stress relief performed during manufacture. Since the repair roll stresses may be higher than those in the steam generator after manufacture, the time to cracking for the new transition is expected to be less than the time for the original transition.

Whether the reroll transitions last as long as the original tube roll transitions or not is uncertain. The rerolls are expected to last a minimum of a few cycles before SCC occurs. Additionally, for those tubes which are hydraulically expanded prior to the re-roll, the hydraulic expansion transition is expected to have lower susceptibility to SCC than the original roll transition, due to the relative residual stress levels.

Because the tubes experienced a thermal treatment during the full vessel stress relief, they still have good resistance to SCC Any cracks that develop are expected to grow slowly. Also, standard ECT inspection during normal refueling outage activities has proven successful in detecting these defects in the early stages of progression to facilitate future repair or plugging.

6.2 Tubesheet Corrosion Beyond Repair Roll

The tubesheet material is expected to be unaffected by corrosion after installing a reroll, even if defects currently exist outside the new pressure boundary. The lack of concern for tubesheet corrosion is based on the restricted flow area for primary water to interact with the tubesheet and the lack of oxygen in the primary system during normal operating conditions.

The existing roll transition defects represent the only flow path that could initiate tubesheet corrosion. The repair roll is located a sufficient distance from the original roll transition or any existing defects, such that defects will be unaffected by the repair roll. The flow path through these defects is not sufficient to initiate corrosion or transport any corrosion products in an oxygen free environment. The fluid flow between the tube and tubesheet is restricted by the repair roll. Therefore, crevice corrosion is not expected to affect the life of the repair roll.

7.0 CONCLUSIONS

This evaluation has shown that application of a tubesheet region repair roll at OTSG plants is acceptable. The following conclusions are provided.

1. A roll length of (d) is structurally adequate to satisfy all of the loading requirements for the NRC Regulatory Guide 1.121 and the leakage limits applicable to the OTSG plants technical specifications.

2. The qualification is valid for locating the roll expansion in the upper tubesheet of OTSG's with the exception of the exclusion zones identified in Appendix B. Application of tube repair rolls in the lower tubesheet is contingent upon verification of roll joint strength with crevice deposits.

3. If 15,531 tube ends per generator were repaired, the conservative worst case leakage would be approximately (d) GPD under normal operating conditions. A conservative estimate of MSLB leak rates is (d) GPD at (d) psi differential.

4. The recommended design parameters for a field implemented repair roll joint are as follows:
   - (d) separated from existing defects and roll transitions, providing (d) of new effective roll
   - (d) in-lbs nominal installation torque ((d) minimum)
   - Installation depth no closer than (d) from the secondary tubesheet face.

5. The repair roll is applicable to repairing ID or OD, axial, volumetric, or circumferential defects. Testing was performed under the conservative assumption that the tube is severed.

6. Applying a hydraulic expansion prior to making a repair roll near the secondary face of the upper tubesheet minimizes the potential for Obrigheim denting of the tube above the roll. Although it does not affect the structural integrity of the tube, potential denting could reduce tube inspection flexibility through tube ID reduction.

8.0 REFERENCES

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

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

8.3 EPRI TR-103824, Steam Generator Reference Book, December 1994.

8.4 Natrella, Mary Gibbons, "Experimental Statistics", National Bureau of Standards, Handbook 91, page T-15.

8.5 Roark & Young, Formulas for Stress and Strain, Fifth Edition.

8.6 BAW-2303P, Revision 03, "OTSG Repair Roll Qualification Report", October 1997.

APPENDIX A:
ETSS for Bobbin and MRPC Examination of OTSG Tube Repair Rolls

[

(d)

]

APPENDIX B: Reroll Exclusion Zones

Exclusion Zone Summary for Non-Oconee Plants
(See Figure 5.2)

[

(d)

]

Exclusion Zone Summary for Oconee Plants
(See Figure 5.3)

[

(d)

]

Tables B.1 through B.6 summarize the tubes in the exclusion zones where a (d) reroll application is limited by tube hole dilation effects on joint strength.

[

(d)

]