Duke Power
A Duke Energy Company

M. S. Tuckman
Executive Vice President
Nuclear Generation

Duke Power Company
A Duke Energy Company
EC07H
526 South Church Street
P.O. Box 1006
Charlotte, NC 28201-1006

(704) 382-2200 OFFICE
(704) 382-4360 FAX

October 4, 2000

U. S. Nuclear Regulatory Commission
Washington D. C. 20555-0001

ATTENTION: Document Control Desk

Subject: Duke Energy Corporation
Oconee Nuclear Station, Units 1, 2, & 3
Docket Numbers 50-269, 50-270, and 50-287
License Amendment Request for Technical Specifications 5.5.10e.6, Steam Generator Tube Surveillance Program (TSCR 2000-07)

Reference: M. S. Tuckman (Duke Energy Corporation) Letter to the U. S. Nuclear Regulatory Commission, ATTENTION: Document Control Desk, Dated September 12, 2000
SUBJECT: Oconee Nuclear Station Units 1, 2, & 3
Docket Numbers 50-269, 50-270, and 50-287
License Amendment Request for Technical Specifications 5.5.10e.6, Steam Generator Tube Surveillance Program (TSCR 2000-07)

In the letter referenced above, Duke Energy Corporation committed to submitting a non-proprietary version of Topical Report, BAW-2303P, August 2000, *OTSG Repair Roll Qualification Report*, Revision 4. The proprietary version of this topical report was included in the referenced letter in support of a Duke license amendment request applicable to Oconee Technical Specification 5.5.10e.6. Therefore, in accordance with the guidance of NUREG-0390, 12 copies of the non-proprietary version of this topical report (BAW-2303NP) are enclosed with this letter.

A001 1/12

Inquiries on this matter should be directed to J. S. Warren at (704) 382-4986.

Very truly yours,

M. S. Tuckman

M. S. Tuckman

xc w/Attachment:

L. A. Reyes, Regional Administrator
U. S. Nuclear Regulatory Commission, Region II
Atlanta Federal Center
61 Forsyth St., SW, Suite 23T85
Atlanta, GA 30303

D. E. LaBarge, NRC Senior Project Manager (2)
U. S. Nuclear Regulatory Commission
Mail Stop O-8 H12
Washington, DC 20555-0001

M. E. Shannon
NRC Senior Resident Inspector (ONS)

V. R. Autry, Director
Division of Radioactive Waste Management
Bureau of Land and Waste Management
South Carolina Department of Health and
Environmental Control
2600 Bull Street
Columbia, SC 29201

<u>bxc w/o Attachment:</u>
J. S. Forbes
M. K. Nazar
W. W. Foster
L. E. Nicholson
R. C. Douglas
J. E. Smith
C. J. Thomas
M. T. Cash
G. D. Gilbert
W. M. Sample
B. B. Lowery
R. O. Sharpe
D. P. Rochester
J. S. Warren
Oconee Site Master File
NRIA/ELL

BAW-2303NP
Revision 04
August 2000

THE B&W OWNERS GROUP

STEAM GENERATOR COMMITTEE

OTSG REPAIR ROLL QUALIFICATION REPORT

FRAMATOME
TECHNOLOGIES

BAW-2303NP
Revision 04
August 2000

OTSG REPAIR ROLL QUALIFICATION REPORT

NON-PROPRIETARY

FRAMATOME TECHNOLOGIES
P.O. BOX 10935
LYNCHBURG, VA 24506-0935

This document is the non-proprietary version of the proprietary document BAW-2303P, Revision 4. In order to qualify as a non-proprietary document, certain blocks of proprietary information have been withheld. The criteria used for withholding information are provided below.

b) The information reveals data or material concerning FTI research or development plans or programs of potential economic advantage to FTI.

c) The use of the information by a competitor would decrease his expenditures, in time or resources, in designing or producing a similar product.

d) The information consists of test data or similar data concerning a process, method, or component, the application of which results in an economic advantage to FTI.

e) The information reveals special aspects of a process, method, component, or the like, the exclusive use of which results in an economic advantage to FTI.

Approvals

Prepared by C. K. Chandler — Date: 9/22/00

This report was reviewed and was found to be an accurate description of the work reported.

Reviewed by J. A. Burgess — Date: 9/22/00

Verification of Independent Review.

Approved by S. B. Brown
Manager
Steam Generator Engineering — Date: 9/22/00

This report has been approved for release.

Released by D. J. Firth
Program Manager
B&W Owner's Group — Date: 9/26/00

Executive Summary

A repair roll process has been qualified to repair tubes with eddy-current indications within the tubesheet region of the Once-Through Steam Generators (OTSG). The repair roll is a roll expansion installed inboard of the original roll expansion and existing defect indications. The repair roll becomes the new leak-limiting primary-to-secondary pressure boundary for the tube.

A [e] single repair roll, excluding the roll transition closest to the primary side of the tubesheet (heel transition), has been qualified for installation in the OTSGs. [e]

[e]

Repair rolls are qualified in this document for installation in both the upper and lower tubesheets. In addition, multiple repair rolls in a single tube are qualified. A [e] overlapping repair roll, such as those previously installed in some OTSGs under a prior qualification, is bounded by the qualification of the single [e] repair roll.

Plant-specific exclusion zones have been developed for repair roll installation (Appendices A through D). There is a generic exclusion zone that spans the first [e] from the tubesheet faces, primary and secondary. Additional plant-specific exclusion zones are based on plant-specific tube loads and tubesheet deflections.

Initial eddy current (EC) inspection identifies tubes that are candidates for repair roll and locates and characterizes defect indications. Post-repair EC inspection verifies repair roll installation, provides a profile of the inside diameters and verifies that the effective repair roll is free of defects.

All repair rolls installed under previous submittals meet the repair roll qualifications of this topical report.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

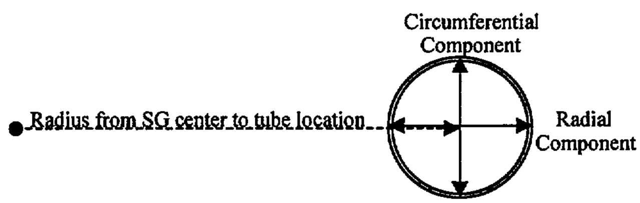
ACRONYMS AND ABBREVIATIONS

ANO-1	Arkansas Nuclear One, Unit 1
AFW	Auxiliary Feedwater
CR-3	Crystal River Unit 3
DB-1	Davis Besse Unit 1
EC	Eddy Current
ECCS	Emergency Core Cooling System
ECT (ET)	Eddy Current Techniques
FE	Finite Element
FTI	Framatome Technologies Inc.
HL	High Load Leak Test
HS	High Load Slip Test
ID	Inner Diameter
IGA	Intergranular Attack
LL	Low Load Leak Test
LS	Low Load Slip Test
LTS	Lower Tubesheet
MSLB	Main Steam Line Break
NOP	Normal Operation
OD	Outer Diameter
ONS	Oconee (Units 1, 2, and 3)
OTSG	Once-Through Steam Generator
PWSCC	Primary Water Stress Corrosion Cracking
RCS	Reactor Coolant System
SBLOCA	Small Break Loss of Coolant Accident
SSE	Safe Shutdown Earthquake
TMI-1	Three Mile Island Unit 1
TSP	Tube Support Plate
UCL	Upper Confidence Limit
UTS	Upper Tubesheet

DEFINITIONS

Differential dilation

The calculated difference between the transient-induced change in the tubesheet bore ID and the tube OD. Equal to the tubesheet bore dilation (due to tubesheet bowing and free thermal growth) minus the tube dilation (due to internal pressure and free thermal growth). Based on diametrical changes along two perpendicular axes (See Figure below). A positive differential dilation represents a decrease in the interference between the tube repair roll joint and the tubesheet bore. A negative differential dilation represents an increase in the interference between the tube repair roll and the tubesheet bore.



Bore dilation

The change in the diameter of the tubesheet bore ID relative to the "as manufactured" condition. Normalized transient bore dilations refer to the predicted transient conditions, corrected for test temperature and pressure conditions. Test bore dilations refer to the bore dilations applied to the test mock-ups during room temperature testing.

Heel transition

The roller on the roll expander has tapered ends that produce a transition between the expanded tube region and the non-expanded tube region. The heel transition is the transition closest to the primary face of the tubesheet (the upper roll transition for a repair roll installed in the upper tubesheet). The heel transition is not considered part of the new pressure boundary.

Toe transition

The roller on the roll expander has tapered ends that produce a transition between the expanded tube region and the non-expanded tube region. The toe transition is the transition closest to the secondary face of the tubesheet (the lower roll transition for a repair roll installed in the upper tubesheet). The toe transition is part of the new leak-limiting pressure boundary, but it is not

	included as part of the effective length of the repair roll.
Exclusion Zone	A tubesheet depth and radial location that has not been qualified for installation of a repair roll. An exclusion zone of [e] from the secondary tubesheet face prevents the tube from slipping out of the tubesheet. An exclusion zone of [e] from the primary tubesheet face prevents overlap of the original tube-to-tubesheet expansion roll. Additional exclusion zones are identified based on the limits defined by the qualifying repair roll tests.

1.0 INTRODUCTION

1.1 Purpose

The purpose of this report is to provide a technical justification to implement a tubesheet region repair roll in degraded tubes in Once-Through Steam Generators (OTSGs). A repair roll installed inboard of the degraded region of tubing provides a frictional joint of undegraded tubing within the tubesheet bore, which creates a new leak-limiting primary-to-secondary pressure boundary within the tubesheet.

A repair roll in the upper tubesheet has been qualified under previous submittals; however, requalification is necessary due to identification of a more limiting Small Break Loss of Coolant Accident (SBLOCA) that was not included in the previous evaluation. In addition, the Main Steam Line Break (MSLB) transient has been re-analyzed, resulting in a new set of design loads for each plant. Also, repair rolls are qualified in this document for installation in both the upper and lower tubesheets and multiple repair rolls in a single tube are qualified. [c]

Repair rolls that have been installed under previous submittals remain qualified based on the requirements of this topical report.

The qualification of the OTSG repair roll presented in this report applies to the following OTSG plants:

Arkansas Nuclear One, Unit 1 (ANO-1)

Crystal River Unit 3 (CR-3)

Davis Besse Unit 1 (DB-1

Oconee Units 1, 2, and 3 (ONS-1, ONS-2, and ONS-3)

Three Mile Island Unit 1 (TMI-1) in-service steam generator tubes were kinetically expanded in the early 1980's after a cold shutdown. The kinetic expansion serves as the primary-to-secondary pressure boundary. Therefore, TMI-1 does not anticipate the need for repair rolls in the upper tubesheet. An addendum may be added to this report in the future if the need arises for repair rolls at TMI-1.

1.2 Background

Eddy Current (EC) inspections of OTSG tubes have resulted in the detection of indications within the upper and lower tubesheet region. These indications are typically axial crack-like indications located within the existing upper tubesheet. A much smaller number of circumferential crack-like indications have been identified in this region. Tube pull examinations have shown that these indications are generally characterized as Primary Water Stress Corrosion Cracks (PWSCC). Volumetric indications attributed to Intergranular Attack (IGA) have also been identified within the original manufacturer's roll joint and in the unexpanded portion of the tube within the tubesheet crevice.

A repair roll installed in the tubesheet inboard of these types of indications establishes a new leak-limiting pressure boundary and allows the tube to remain in service.

2.0 REPAIR ROLL DESCRIPTION

2.1 Repair Roll Design

Two types of repair rolls have been developed for installation in the OTSGs, a single [e] roll expansion and an overlapping roll that consists of two [e] roll expansions. The single roll expansion provides a [e] effective roll. For the overlapping roll, a second repair roll is installed that overlaps a single repair roll. Figure 2.1 provides an illustration of the repair rolls. The overlapping roll provides a minimum [e] effective roll expansion.

There is an additional [e] roll transition region on each end of the roll expansion. The new leak-limiting pressure boundary created by the repair roll does not include the heel transition, which is the transition closest to the tube end (primary side).

Both the single repair roll and the overlapping repair roll may be installed in the upper tubesheet or the lower tubesheet. Multiple repair rolls may be installed in a single tube. [e]

During installation of repair rolls, a [b] load is imparted to the tube. Testing was conducted by measuring the amount of tube protrusion past the [b] face of a mock-up block (at four positions around the tube), both before and after each rolling process. The average change in protrusion was considered tube elongation induced by each rolling process. [b] loads were calculated based on the stress-strain relationship. The 95/95 upper tolerance limits for the [b] loads are [b] for a single [e] repair roll and varies from [b] to [b] for an overlapping repair load depending on the method of installation.

There are three overlapping roll configurations that may be installed. [e & b]

The preferred configuration is dependent on the [b] load limits and the characterization of the degradation requiring a repair roll.

The [b] load due to installation of a repair roll is added to the predicted [b] load due to operating transients. The additional [b] load due to [b] single [e] repair rolls, [b], or the maximum additional [b] load due to [e] overlapping repair roll, [b], is negligible compared to the worst-case [c] loads due to [c] presented in Table 4-1. Additional repair rolls may be installed on a case-by-case basis by evaluating for acceptable [b] tube loads.

2.2 Repair Roll Installation

The repair roll is typically installed 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 required roll torque is [e] using the standard qualified tooling. Spacers between the tool and tubesheet or tube end are used to establish the amount of overlap, if any, and the proper roll depth within the candidate tube. [e] is used to lubricate the expander rollers to enhance the quality of the roll expansion by reducing energy loss.

The qualified repair roll process tool assembly (e.g. DELTA tool) is calibrated to deliver the specified roll torque of [e] within a measured tube inner diameter. A test roll is performed prior to roll expansion of the target tubes. A time history of the torque and diametrical expansion is recorded for reference for each candidate location. At the completion of a specified number of repair rolls (or batch), a post-calibration check is conducted to verify that the tool was calibrated during the installation of the repair rolls.

2.3 Process Verification

Qualified Eddy Current Techniques (ECT) are used to identify candidate tube locations for repair and to determine the defect locations. After repair roll installation, bobbin profilometry is used to confirm diametrical expansion. Inspection with a rotating coil is used to verify that the new effective roll expansion is free of degradation. (See Section 8.0.)

Figure 2-1 Tube Repair Roll Configuration

[e]

3.0 DESIGN REQUIREMENTS

3.1 General Design Requirements

The OTSG tubes are constrained at the upper and lower tubesheet; therefore, tube burst within the new roll expansion is precluded by the presence of the tubesheet. The new roll expansion will be subjected to axial tube loads that must be considered when evaluating the structural integrity of the joint. The source of the axial tube loads is the differential pressures across the tubesheets and the differential thermal growth of the tubes and tubesheet relative to the OTSG shell. [e]

[e]

In addition, the repair roll shall provide a mechanical pressure boundary seal between the existing tube and tubesheet. The new joint shall provide leak-limiting capability, assuming a full sever between the repair roll and the tube end. Total leakage must be maintained below the technical specification limits for normal operation and plant-specific limits for faulted conditions.

The repair roll must be installed remote from the original roll expansion and all EC indications of degradation.

3.2 OTSG Performance Characteristics and Design Transients

The applicable design, operational, and accident performance characteristics, including pressures and temperatures for the Babcock and Wilcox 177 FA OTSGs are provided in Table 3-1. Figure 3-1 is an illustration of the OTSG general assembly. The transients listed in Table 3-2 represent the range of limiting conditions that could challenge the structural and leakage integrity of the repair rolls. The Functional Specification transients for the OTSGs are either applied or are considered bounded by the transients listed in Table 3-2.

Table 3-1 B&W OTSG (177FA) PERFORMANCE CHARACTERISTICS

	PRIMARY SIDE	SECONDARY SIDE
DESIGN CONDITIONS		
Design Pressure, psig	2500	1050
Design Temperature, °F	650	600
LEVEL A (NORMAL OPERATIONS) CONDITIONS (100% FULL POWER)		
Pressure, psia	2200	925
Temperature, Inlet, °F (DB-1)	604 (608)	459 (470)
Temperature, Outlet, °F (DB-1)	554 (556)	570 (570)

LEVEL D (FAULTED) CONDITIONS

(Additional information and loads provided in Section 4.0)

Main Steam Line Break

Maximum Primary-to-Secondary Pressure Differential, psig 2575

Small Break Loss of Coolant Accident*

Maximum Secondary-to-Primary Pressure Differential, psig 1050

*[c]

Figure 3-1 OTSG General Assembly

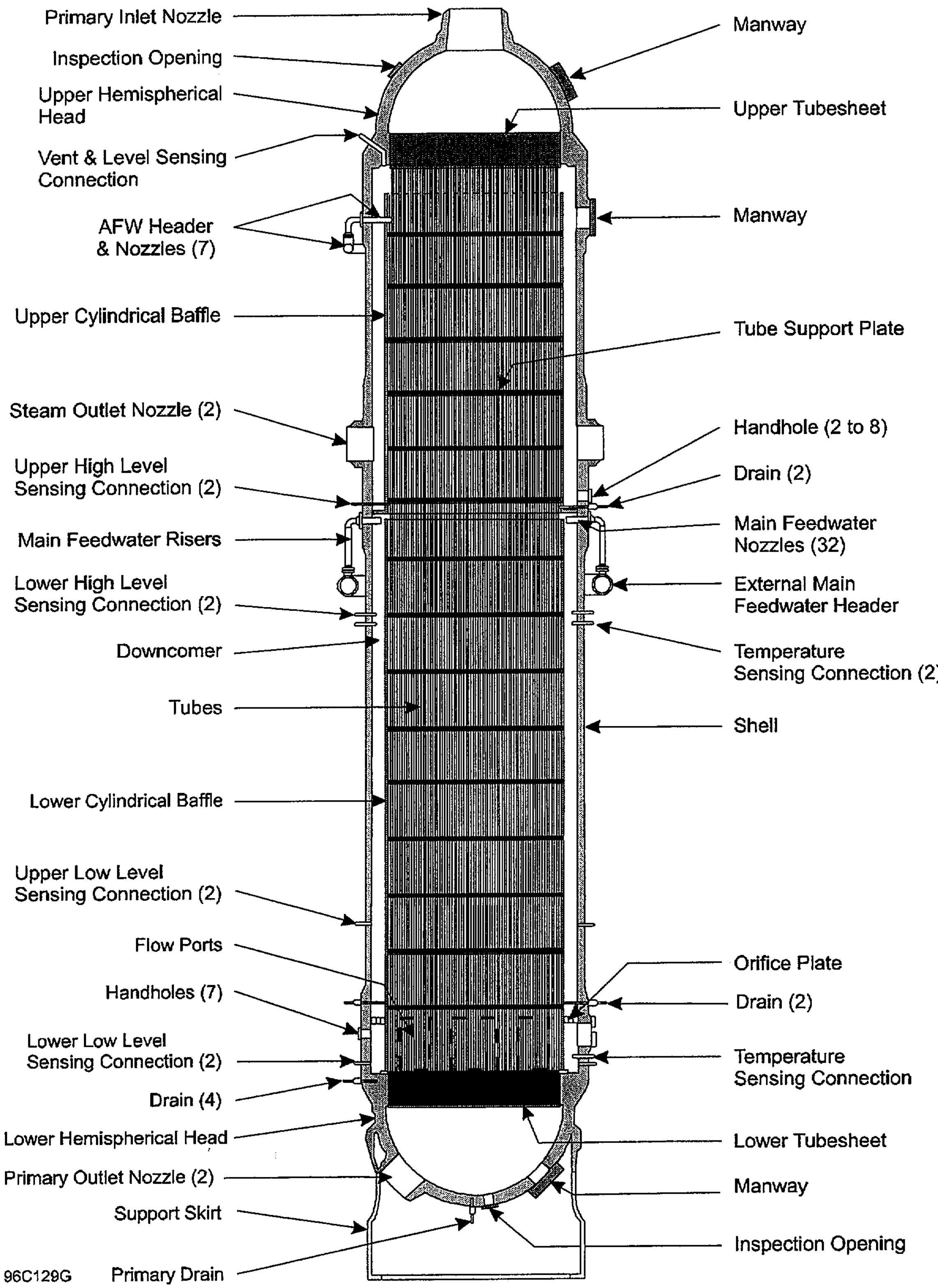


Table 3-2 Bounding Repair Roll Design Transients

[c]

*Refer to Section 4.8 for further discussion on bounding transients.

4.0 TRANSIENT ANALYSES

The general structural behavior of the OTSG during the various operating and accident transients was quantified by the development of a finite element (FE) model of the overall OTSG, including the tube bundle, the tubesheets, shell, heads, and support skirt.

Due to the straight tube design of the OTSG, the axial stiffness of the tubes interacts with the axial stiffness of the adjacent secondary shell. The interaction of the tubes and shell results in axial tube loads, which are dependent on the combinations of temperatures and pressures. Transients that result in a temperature differential between tubes and the shell cause a bowing of the tubesheets, which results in higher tube loads in the periphery, where the tubesheet is fixed. The pressure differential across the circular (flat plate) tubesheets causes a "diaphragm effect" that also results in tubesheet bowing. The pressure differential may augment or resist the thermal bowing effects. The resulting bowing effect can produce a dilation of the tubesheet bore in the region of the tube-to-tubesheet joint, which may reduce the load carrying capability of the rolled joint. Therefore, the FE analysis was developed to model the general structural behavior of the OTSG, including deflections and axial tube loads, and the local structural behavior (hole dilations).

The FE analyses provided axial tube loads and the data required to calculate tube and tubesheet bore dilations. The tube dilations were calculated based on the applicable tube temperature and pressure values. The tubesheet bore dilations, when coupled with the tube dilations, provide a representation of the joint interface, which is referred to as differential dilations (See Section 4.8).

The axial tube loads calculated by these analyses supersede all previously calculated axial tube loads.

4.1 Development of the Finite Element (FE) Model

The general structural behavior of the OTSG is governed by the response of the OTSG to applied thermal loads such as temperature transients as well as mechanical loads such as preload, primary pressure, and secondary pressure. The development and execution of a FE model of the overall OTSG quantified the general structural behavior. Figure 4.1 depicts the lower portion of the OTSG model and provides an example of the model grid.

To represent the structural behavior affecting the axial tube loads and associated tube hole dilations, the OTSG FE model included the tubes, tubesheets, secondary shell, the upper and lower heads, and the support skirt. The tubesheet components have been subdivided into two regions – 1) the region perforated with tube holes (over 15,000 tube holes per tubesheet), including the [b] solid center and 2) the solid region (outside of the perforated region). This division facilitated the application of the "equivalent plate" material properties to the perforated region.

Because the key results are a function of the overall OTSG stiffness, as reflected by the shell and tubes, it was important to represent the [b] stiffness of these sub-components. Therefore, the model used the [b] thickness for the shell and tubes.

The original manufacturer's tube-to-tubesheet joint includes both a rolled joint, typically [e] long at the primary face of the tubesheet, and a fillet weld. The rolled expansion produced an interface pressure between the tube OD and the tubesheet bore ID. The residual pressure generated a localized residual stress in the tubesheet around each tube hole. The collective effect of these residual stress fields, acting in the [c] layer at the primary tubesheet faces, on the effective stiffness of the [b] thick tubesheet was [c] in the transient analyses. The effect of this local residual stress field is an [c] influence on the general response of the OTSG.

The OTSG internal structures were [c] in the model. An evaluation determined that the lateral support/restraint provided by the tube support plates (TSPs) has a [c] impact on the general structural behavior of the OTSG. The evaluation [c] the lateral restraint of the tubes at the TSPs, the restraint of the tubes at the [c] face of the tubesheets due to [c] prior to impacting the tubesheet bore, and stress stiffening of the tube under displacement. The collective bending resistance of the tubes [c] that [c] reaction moment resulted at their connections to the tubesheets. Thus, [c] due to this reaction moment [c] for tubesheet motions or the associated tubesheet hole dilations.

The vertical support provided to the TSPs by the tie-rods and spacers was [c] in the model. These components generally produced a [c] to the lower tubesheet, which would be applied as a [c] to the tubesheet at [b] support spacer locations. For the case of a secondary side blowdown, such as during the initial phase of a Main Steam Line Break (MSLB) transient, the collective differential pressure across the support plates may potentially result in a [c] reacting on the [b] tie-rod locations of the lower tubesheet. This [c] load would occur only during the blowdown phase, which lasts a short time, and is dissipated before the more dominant loads caused by maximum tube-to-shell temperature differential and primary-to-secondary pressure differential are developed.

The mounting plate of the lower shroud, which mounts directly on top of the recessed area of the lower tubesheet, was [c] in the FE model. The mounting plate [b] heat flow from the [b] water into the interfacing tubesheet rim (or out of the tubesheet rim into the [b] water). Effective heat transfer coefficients that accounted for the [b] heat flow [c] to the interfacing tubesheet area. Therefore, [c] the mounting plate was [c], its effect on the thermal distributions of the lower tubesheet [c].

The upper shroud shelf plate [c] in the model as an [c] of the steam and feedwater downcomer regions of the model. The shelf plate had [c] relating to the structural behavior of the overall model.

Based on the nature and the magnitude of the loads, a linear-elastic, axisymmetric model was selected as the appropriate model type. The constructed FE model is representative of all B&W 177FA OTSGs. The major sub-components for the various plants have essentially the same dimensions and material designations. However, there are some minor differences that required assessment and disposition.

Figure 4-1 Lower Portion of OTSG Finite Element Model

[c]

4.2 Model Parameter Assessment

As noted above, there are some minor differences among the OTSGs. Parameter assessments were performed to assure that the analytical model conservatively includes any significant effects of these features. Each parameter assessment consisted of comparing the results from representative test loading on the model with the feature included to the results for the same test loading without the feature (base case). The key results used in the comparison were the axial tube loads and the associated maximum tubesheet bore dilations. The conclusions from the assessments resulted in the incorporation of model features based on conservative effects or as a more realistic representation of the physical OTSG.

The parameter assessments included, but were not limited to the following:

[b & c]

[b & c]

[b & c]

[b & c]

[b & c]

[b & c]

[b & c]

4.3 Analyzed Transients

The OTSG structural model described above was used to analyze transient conditions for assessment of the tube-to-tubesheet joints.

The design transients listed in Table 3-2 were analyzed. The Functional Specification transients for the OTSGs are either applied or are considered bounded by the transients listed in Table 3-2. The normal operating and upset transients were evaluated as transients that result in cyclic loadings and the bounding transients were selected for analyses. The emergency and faulted transients were evaluated as transients that are postulated to occur only once or a minimum number of times in the life of the OTSGs, but generally result in more severe loading conditions than those of the normal operating and upset transients. The bounding transients for emergency and faulted conditions were selected for analyses. [c], an evaluation was performed to verify that the bounding transient for normal operating and upset conditions also bounds the emergency transients for load and differential dilations as discussed further in Section 4.8.

[c]

4.4 Thermal-Hydraulic Results

The transient time points that represent the most severe temperature distribution for each accident transient were determined from the results of the FE model thermal analyses. The thermal analyses were performed by FTI, except for the [c], which was provided by Duke Power Company. The FTI thermal-hydraulic analyses were performed using RELAP5/MOD2. The two prime contributions to tube loads and accompanying tube hole dilations are the primary-to-secondary pressure differential and the tube-to-shell temperature differential, with the dominant contribution from the [b]. [c]. The thermal analyses provided primary and secondary fluid temperatures, primary flow, average shell temperature, heat transfer coefficients, and film coefficients and bulk fluid temperatures for the downcomer region.

Figure 4-2 provides a time-history of the tube-to-shell temperature difference and primary-to-secondary pressure differential for the [c] Note that the maximum MSLB primary-to-secondary pressure differential, based on the maximum possible pressure differential of 2575 psig (derived from the safety relief valve setpoint with a 3% allowance for the setpoint tolerance) occurs [c] the maximum tube-to-shell temperature differential that occurs at approximately [b] into the transient. All of the plant-specific [c] analyses were based on a maximum possible pressure differential of 2575 psig. (The [b] transient analyses ended just prior to reaching a pressure differential of 2575 psig.)

Figure 4-3 provides the time-history of the tube-to-shell temperature difference and primary-to-secondary pressure differential for the [c]. Note that the primary-to-secondary pressure differential is [c] than the primary-to-secondary pressure differential for the [c] and is nearly [c] at the time of maximum tube-to-shell temperature difference.

Figure 4-4 provides the time-history of the tube-to-shell temperature difference and primary-to-secondary pressure differential for the [c]. Note that the primary-to-secondary pressure differential is [c] than the primary-to-secondary pressure differential for the [c].

Therefore, the [c] is the limiting accident for [c], based on [c].

The transient time point of maximum [c] was analyzed with the time of initial conditions, time points before and after the maximum [c], and near the end of the transient. The nodal temperatures throughout the FE model for each time point were used as input to the static structural analyses.

Figure 4-2 [c] Thermal-Hydraulic Results

[c]

Figure 4-3 [c] Thermal-Hydraulic Results

[c]

Figure 4-4 [c] Thermal-Hydraulic Results

[c]

4.5 Thermal Boundary Conditions

For the analyzed transients, the [b] load relative to axial tube loads and dilations is the [b]. The thermal loads were applied to the FE model by specifying a bulk fluid temperature at a surface and a corresponding heat transfer film coefficient or by specifying an assigned temperature. For example, the appropriate bulk fluid temperature and heat transfer coefficient were applied versus time for surfaces such as the upper and lower head inside surfaces, solid tubesheet rim surfaces, shell steam annulus, and shell feedwater downcomer above and below the water level. On the other hand, temperatures versus time were assigned based on the parameters of the specific transient to the perforated portion of the upper and lower tubesheets and the free length of the tubes.

The heat transfer film coefficients were calculated for the normal operating transients based on standard correlations using the transient specific parameters, including temperature ramps and flow rates. However, the heat transfer coefficients for the accident transients were taken from the thermal-hydraulic transient analyses to assure a continuity and consistency with the structural analysis for the rapidly varying and change-of-phase heat transfer regimes.

The outside surface of the OTSG was assumed to be perfectly insulated. This assumption has no significant effect on the range of loads/dilations for normal operating transients and yielded [c] for the accident transients. Thus, the assumption tended to maintain the shell temperature at a higher temperature, maximizing the tube-to-shell temperature difference.

The lower portion of the support skirt was assigned a constant temperature of 120°F to approximate ambient conditions. This has no significant effect on the loads or dilations since this region is well removed from the tube-tubesheet-shell interaction.

The thermal boundary conditions described above were applied to the FE model and the temperature distribution was calculated versus transient time as nodal temperatures.

4.6 Structural Boundary Conditions

As described above, a static structural analysis was performed for critical transient time points determined in the thermal analyses. The applied thermal boundary conditions for each time point or the nodal temperatures from the thermal analyses and the mechanical loads that occur simultaneously with the nodal temperatures were applied to the structural model. The mechanical loads included primary pressure, secondary pressure, and installed tube preload (OTSG tubes were preloaded during fabrication). The dynamic loads were added to the results of the FE analyses and assessed during the qualification testing (Section 5.1.5).

Consistent with the actual OTSG geometry, the pressure loads on the faces of the upper and lower tubesheets were adjusted to account for the tube holes. Plugged tubes were modeled with pressure acting on the plug ends. Poisson's effect in the tube axial direction caused by the pressure differential across the tube wall was applied to the model by imposing an equivalent axial strain on the tube elements.

Similar to the axial tube load due to internal pressure, the tube preload was applied to the model as an axial strain equivalent to the force associated with the tube elongation applied at the time of OTSG fabrication.

4.7 Plugged Tubes

Tube loads and dilations were generated for the case of a steam generator with no plugged tubes (0%) and for the case of a steam generator with [c] plugged tubes. Two configurations were evaluated for plugged tubes. One configuration incorporated the [c] plugged tubes uniformly distributed over the tube bundle. The other configuration used [c] of the plugged tubes concentrated at the periphery of the tube bundle and [c] of the plugged tubes distributed over the remainder of the tube bundle. These distributions are representative of the existing plugging patterns of the OTSGs. The [c] and [c] plugged tube cases were [c] for the OTSGs. Note that no OTSG is approaching [c] plugging.

The difference in the analyses of the plugged and non-plugged tube cases was the temperature imposed on plugged tubes and the absence of primary pressure in the plugged tubes. The plugged tubes were assigned the secondary side temperature and pressure.

4.8 Structural Analyses Results

The FE model was analyzed for each critical time point identified in the thermal analyses. The key results include:

a) Axial tube loads as a function of tubesheet radial position,

b) Tube-to-tubesheet hole differential dilations as a function of tubesheet radial position, and

c) Tube-to-tubesheet hole differential dilations as a function of depth into the tubesheet.

Differential dilation is a term that is used to refer to the interface between the tube OD and the tubesheet bore diameter, which allows a comparison of the relative interface of the joint for any transient condition. The differential dilation is equal to the tubesheet bore dilation (due to tubesheet bowing and free thermal growth) minus the tube dilation (due to internal pressure and free thermal growth). A positive value indicates that the increase in bore diameter is greater than the increase in the tube OD with a reduced interference within the rolled joint. A negative value indicates that the tube free expansion would be greater than the bore expansion resulting in an increase in the interference pressure of the rolled joint. The differential dilations are expressed as diametrical changes along two perpendicular axes. "Radial" refers to the dilation along the radius from OTSG center to the tube centerline and "circumferential" refers to the dilation perpendicular to the radial dilation.

The finite element transient analyses results were summarized for both the upper and lower tubesheets.

Tables 4-1 and 4-2 provide the key analysis results at the time of maximum load. A positive tube load indicates a tensile load and a negative tube load indicates a compressive load.

Table 4-1 provides the key analysis results for the normal operating and upset transients. The results are provided at the time of maximum tube load. For information and to compare the transient conditions, the differential dilations at the [c] are provided. The differential dilations vary through the thickness of the tubesheet and are typically [c]. The development of the exclusion zones for the repair rolls are based on the calculated differential dilations at a specific tubesheet depth and radial position. As stated previously there is an exclusion zone that spans the first [e] from each tubesheet face.

Table 4-2 provides the analyses results for the bounding [c]. Results are provided at the time of maximum tube load. Figures 4-5 and 4-6 show example plots of differential dilations versus tubesheet radius and depth for the [c] transient. As noted previously, the average differential dilations are [c]. The exclusion zones are based on axial tube loads and differential dilations at a specific tubesheet depth and radial position. Figure 4-7 provides an example plot of the [c] loads as a function of tubesheet radial location.

Based on the results of the transient analyses shown in Table 4-1, the bounding normal operating transient for [c]. The [c] transient represents the [c] differential dilations for normal operation. The [c] transients that were analyzed bound the [c] transients for all OTSGs. The emergency transient, a Stuck-Open Turbine Bypass Valve, was not analyzed and was considered bounded by the [c] transients. However, the emergency transient was evaluated for axial loads, differential dilations, and primary-to-secondary pressure differential and compared to the [c] transient. The maximum tube load is approximately [b], which is bounded by the [c] as shown in Table 4-1. The differential dilations are also bounded by the [c] because the tube loads are [b] and the tubesheet metal remains above [b]; therefore [b] radial strains are generated which causes tubesheet bore dilations. Therefore, the [c] bounds all [c] transients for slippage. The maximum pressure differential for the emergency transient is approximately [b], which is limited by the [c]transient for leakage.

The bounding transient for [c] loads, normal operating and accident, is the [c] transient. Additional repair rolls installed on a case-by-case basis must be evaluated for acceptable [c] tube loads by adding the additional [c] load from the repair roll to the [c] tube load from the [c] transient for the tube radial position.

Based on the results of the thermal-hydraulic analyses shown in Figures 4-5, Figure 4-6 and Figure 4-7, the [c] is the limiting accident transient for [c], based on the [c]. [c] [c].

The limiting accident transient for load-carrying capability of the repair roll is a function of [c]. For [c], the [d] is the limiting accident transient since both the maximum [c] are much greater than for the [c]. For [c], the limiting transient varies depending on the combination of [c] as a function of tubesheet depth and radial position. Based on [c] alone, the [c] is the limiting transient for [c] and the [c] is the limiting transient for [c].

In summary, the [c] is the limiting transient for normal operating transients, upset transients, and emergency transients in regards to [c] The [c] is the limiting transient for [c]. Overall, the [c] is the limiting transient for faulted transients in regards to [c]

Table 4-1 Normal Operating Transient Analyses Results

Transient	Maximum Tube Load (lbs)	Radial Differential Dilation* (mils)	Circum. Differential Dilation* (mils)	Primary Pressure (psia)	Secondary Pressure (psia)
[c]	[c]	[c]	[c]	[c]	[c]
[c]	[c]	[c]	[c]	[c]	[c]
[c]	[c]	[c]	[c]	[c]	[c]
[c]	[c]	[c]	[c]	[c]	[c]
[c]	[c]	[c]	[c]	[c]	[c]
[c]	[c]	[c]	[c]	[c]	[c]
[c]	[c]	[c]	[c]	[c]	[c]
[c]	[c]	[c]	[c]	[c]	[c]
[c]	[c]	[c]	[c]	[c]	[c]

*[c & e]

Table 4-2 Faulted Accident Transient Analyses Results

Transient	Maximum Tube Load (lbs)	Radial Differential Dilation* (mils)	Circum. Differential Dilation* (mils)	Primary Pressure (psia)	Secondary Pressure (psia)
[c]	[c]	[c]	[c]	[c]	[c]
[c]	[c]	[c]	[c]	[c]	[c]
[c]	[c]	[c]	[c]	[c]	[c]
[c]	[c]	[c]	[c]	[c]	[c]
[c]	[c]	[c]	[c]	[c]	[c]
[c]	[c]	[c]	[c]	[c]	[c]
[c]	[c]	[c]	[c]	[c]	[c]

*[c & e]

Figure 4-5 Differential Dilations versus Tubesheet Radial Location

[c]

Figure 4-6 Differential Dilations versus Tubesheet Depth

[c]

Figure 4-7 [c] Axial Tube Loads versus Tubesheet Radial Position

[c]

5.0 REPAIR ROLL TEST PROGRAM

5.1 Test Requirements and Conditions

The OTSG transient conditions specified in Section 4.8 were evaluated to develop a set of bounding test conditions for application to single repair rolls and over-lapping repair rolls. Determination of repair roll joint integrity required both slip and leak tests. Slip tests include an applied axial tube load and tubesheet bore dilations with no internal pressure. Tube movement was monitored to detect slippage. Leak tests included internal pressure and applied axial tube load and tubesheet bore dilations. The test pressure was held for 20 minutes while leakage and tube movement were recorded.

5.1.1 Effects of Crevice Deposits

Examination of tube sections removed from the upper tubesheet crevice has shown this region to be free of solid particles. However, the lower tubesheet crevice is known to contain solid particles in the sludge that collects in this region. Previous testing had demonstrated that leak rates are [b] for repair rolls [b] crevice deposits. Therefore, leak tests performed [b] crevice deposits provided conservative leak rates for upper tubesheet and lower tubesheet repair rolls. In addition, previous testing has shown that the joint strength is [b] for rolled joints [b] deposits. Therefore, testing [b] crevice deposits is conservative for both leakage and structural integrity.

5.1.2 Effects of Cyclic Loading

During the design life of the repair roll, the rolled joint is subjected to compressive and tensile tube loads associated with normal operating and steam generator transient conditions. Previous testing has shown that the cyclic loading associated with normal operating and steam generator transient conditions [b] the integrity of the repair roll. Cyclic loading has been shown to result in [b] joint strength for both high yield and low yield tubing. Previous repair roll leak test resulted in [b] leakage for test samples [b] deposits that were [b] to cyclic loading prior to testing than for sample [b] deposits that [b] to cyclic loading prior to testing. Therefore, all leak and load testing to support this qualification of the repair roll was conservatively performed on samples that were [b].

5.1.3 Tube Yield Strength

Recent tests have indicated that the yield strength of the tubing affects the load capacity of the rolled joint, with a [b] yield tubing resulting in a [b] roll joint strength. Application of the axial load on the tube results in [b] the contact pressure over some extent of the rolled joint. As the yield strength of the tubing is [b], a larger extent of the roll joint is affected, resulting in a [b] load carrying capability. Therefore, tubing with a room temperature yield strength equal to the [d] of the tubing installed in the OTSGs was conservatively used in the tests.

5.1.4 Differential Dilations

Each transient case corresponds to a set of temperatures, pressures, and resulting tubesheet deflections that may result in a change to the contact pressure of the rolled joint relative to the condition at installation. As described in Section 4.8, differential dilations is a term used to described the interference between the tube and tubesheet bore.

[c]

Differential dilations can not be measured directly under test conditions because the tube dilation is inaccessible. Therefore, the tubesheet bore dilations were used with analytical adjustments for the effect of internal test pressure and temperature on the tube, such that the test conditions are representative of the bounding differential dilations. These adjustments are discussed in detail in the following subsections.

5.1.4.1 Primary Pressure Adjustment

The differential dilation includes the contribution of the primary pressure that is applied to the ID of the tube during the transient. Internal pressure [b] the tube dilation; thereby [b] the differential dilations and [b] the interference fit. For tests with internal pressure, the tubesheet bore dilation was [b] to maintain the differential dilation value. The [b] was based on the diametrical primary pressure displacement of the tube OD as shown by Equation 1.

Equation 1 Free Tube Dilation Due to Pressure

$$\Delta d_P = 4 \times \frac{P \times R_{tube}^2 \times R_{TS}}{E_{tube} \times (R_{TS}^2 - R_{tube}^2)}$$

where:

Δd_P	Diametrical dilation of tube OD due to primary pressure (inches)
P	Primary pressure (2575 psig)
R_{tube}	Expanded inner radius of tube ([b] inches)
R_{TS}	Tubesheet bore radius ([b] inches)
E_{tube}	Modulus of elasticity of tube (31.7 x 10^6 psi @ room temperature)

Thus, the adjustment for primary pressure, Δd_P, = [b] inches was [b] to the tubesheet bore dilation applied during tests performed with internal pressure (leak tests) to achieve the differential dilation for the test.

5.1.4.2 Primary Temperature Adjustment

As the temperature increases, the tube-to-tubesheet interference fit is [b] due to the reduction in the tube modulus of elasticity. The installed diametrical interference fit of [b], defined by previous testing, was adjusted by the ratio of the tube modulus of elasticity at room temperature to the tube modulus of elasticity at the transient temperature as shown in Equation 2.

Equation 2 Dilation Correction for Temperature

$$\Delta d_T = (1 - \frac{31.7 \times 10^6}{E_{transient}}) \times [\quad b \quad] inches$$

For each transient temperature condition, Equation 2 was used to determine the necessary differential dilation adjustment, Δd_T. The transient radial and circumferential differential dilations were then [b] by the transient temperature correction value.

5.1.4.3 Test Tubesheet Bore Dilations

The transient analyses dilation data were reviewed, adjusted as described above, and bounding test dilation sets were developed. Table 5-1 provides the bounding dilation sets, which represent tubesheet bore dilations. (Note that the test results, Tables 5-3, through 5-8, are reported for differential dilations, not tubesheet bore dilations.) As described above, Test Case 8 was not tested due to equipment limitations.

Table 5-1 Tubesheet Bore Test Dilations

[c]

5.1.5 Axial Loads and Internal Pressure

As described above, the FE analyses results were reviewed to determine a bounding set of dilation test cases. Then a set of corresponding, bounding axial loads were developed, which together with the tubesheet bore dilations effectively bound all normal operating and accident transients for the OTSG.

The [c] transient axial tensile loads and differential dilations bound the [c] transients for slip tests. The time of maximum tube load was selected as the bounding time point for the slip tests.

[c] transients bounded the [c] transients. The time of maximum tube load was selected as the bounding time point for the [c] for slip tests. Two time points were selected for the [c] transients, the time of maximum load for slip tests and the time of maximum primary-to-secondary pressure differential for leak tests. The time of maximum load occurs [c] into the transient, and the time of maximum pressure differential occurs [c]. For [c] the time of maximum load is [c] the time of maximum pressure differential. For [c], the thermal-hydraulic analysis [c] to the maximum pressure differential; therefore, the axial load and differential dilations at the [c] time point was [c] used. All leak tests were conservatively performed at the maximum possible pressure differential of 2575 psig, derived from the safety relief valve setpoint with a 3% allowance for the setpoint tolerance. The maximum pressure differential of 2575 psig provides a bounding leak rate for all transients.

An axial load of [b] was conservatively added to the faulted transient tube loads to account for dynamic tube loads associated with SSE. The dynamic tube loads associated with [b] occur early in the transient prior to the time of maximum tube loads. The dynamic tube loads associated with the [b] transient also occur early in the transient prior to the time of maximum tube loads and [b].

The [c] was analyzed after the development of the test cases; therefore, this transient was not included in the development of the test cases. However, the test results were applied to the results of this transient analysis and differential dilations that were not bounded by the test cases result in an exclusion zone.

The test loads were corrected to account for testing at room temperature. As the primary temperature increases, the yield strength of the tubing decreases] and the load carrying capability of the rolled joint may be [b]. Equation 3 shows the temperature correction.

Equation 3 Load Correction for Temperature

[b]

where T is the transient temperature (°F) and ΔL_T is the load adjustment factor. The applied test load = Transient Load x ΔL_T.

5.2 Single [e] Repair Roll Testing

5.2.1 Mockup Block and Test Samples

Cruciform blocks, which allow for simulation of tubesheet bore dilations by applying a biaxial load to the block, were used as a tubesheet mockup. The cruciform blocks were fabricated of material that is representative of the OTSG tubesheets. For testing, the block was mounted in a frame with hydraulic jacks mounted in both the vertical (y) and horizontal (x) axes to place dilation loads on the mockup block as shown in Figure 5-1.

The tube samples were [e] SB-163 alloy 600 tubing that were conservatively representative of OTSG tubing (See Section 5.1.3). One [e] yield tube was tested and the results are provided for information, but were not included in the qualification of the repair roll.

Because it was not possible to measure tubesheet bore dilations at the center of the cruciform block or the roll joint after the repair roll was installed, the blocks were calibrated to verify that the tubesheet bore dilations were the same at the primary face of the block as at the center of the block. Calibration loads were applied to the cruciform block and the resulting dilations at the primary face and the center of the block were recorded. The calibration loads resulted in representative test dilation configurations, taking care not to yield the cruciform block.

Figure 5-1 Mounted Cruciform Test Block

[b]

5.2.2 Tube Installation and Mockup Conditioning

The tubesheet block and tubes were oxidized prior to tube installation to more closely represent the existing OTSG condition. Tubes were installed using the DELTA roll tool with a target torque [e]. The minimum acceptable torque for a single repair roll is [e]. [e] was used for lubrication, which is consistent with the field installation procedure. The roll expander roller design provided a [e] effective roll. The tubes were roll expanded using a spacer such that there was no heel transition in the tested repair roll, representing a complete circumferential sever at the end of the [e] effective roll (primary side). This configuration is conservative for leakage and slip because typical degradation in the repair rolls is represented by short axial cracks. After tube installation, the blocks were thermally cycled between 100°F and 635°F for [b] 3 to 6 hour cycles. The thermal cycles represent the effects of [b] heat-up and cooldown cycles.

Previous testing indicates that additional relaxation after [b] cycles is minimal.

5.2.3 Leak Tests

The purpose of the leak testing was to quantify leak rates for repair rolls for accident conditions. As noted above, the tested condition did not take credit for the heel transition, representing a full circumferential sever at the end of the [e] effective roll (primary side).

[c]

5.2.4 Slip Tests

The purpose of the slip tests was to verify that the repair roll could withstand axial loads [e]. As noted above, the tested condition did not take credit for the heel transition, representing a full circumferential sever at the end of the [e] effective roll (primary side). Applicable tubesheet bore dilations were achieved and an axial load was applied using a swage-lock fitting or an ID gripper attached to the free end of the tube. Tube movement was monitored during the test and verified by measuring the depth of the tube end after each test.

5.2.5 Test Matrix

As described above, the transient analyses data was reviewed and bounding differential dilations and axial loads were identified to develop a test matrix. Tubesheet bore dilations, radial and circumferential define each test case as shown in Table 5-1. The test matrix includes a set of applied loads for each slip test case and a combination of internal pressure and applied load for leak tests. In general, the [b] test cases bounded the [c] transient and the [b] test cases bounded the [c] transient, the [c] transient, and the [c]transient for all the OTSGs.

All leak tests were performed with the maximum 2575 psig internal pressure. The pressure end cap load, which contributes to the axial tube load during leak tests must be added to the applied axial load for the total axial tube load. For a test pressure of 2575 psig and a nominal mockup bore area of

[b], the end cap load is [d]. The test pressure is applied to the tubesheet bore area.

Table 5-2 provides the test matrix, including tubesheet bore dilations and applied axial load. The applied loads for the leak tests include the pressure end cap load of [b]. The test sequence is discussed in Section 5.2.6.

Table 5-2 Test Matrix

[d]

Notes:

1) N/A indicates no test required.

5.2.6 Test Sequence

The test sequence progressed from less severe conditions (tubesheet bore dilations and/or axial loads) to more severe conditions. The tests were performed on each block in sequence with "Low Load Slip Test Case 1" followed by "Low Load Leak Test Case 1" through the low load tests (Table 5-2). Then "High Load Leak Test Case 2" was performed followed by the sequence of high load leak tests. Then "High Load Slip Test Set 1" were performed for each dilation case, followed by "High Load Slip Test Set 2" and "High Load Slip Test Set 3".

When tube movement was noted, the initial sequence of tests was terminated for that sample. Post-slip leak tests were performed following slip of the repair roll, following the sequence of the initial leak tests.

For some samples, the test sequence was adjusted in order to obtain as wide a range of data as possible.

5.2.7 Test Results

The test data was compiled and summarized to develop slip and leak criteria to qualify installation of a repair roll on a plant-specific basis. The test results, Tables 5-3 through 5-8 are reported for differential dilations, not the tubesheet bore dilations used in the testing.

5.2.7.1 Slip Test Results

Table 5-3 provides a summary of the joint strength data. The test number refers to the test case dilation set from Table 5-1 with the tubesheet bore dilations adjusted to tubesheet differential dilations as described in Section 5.1.4. "LS" indicates a low load slip test, "LL" indicates a low load leak test, "HL" indicates a high load leak test, and "HS" indicates a high load slip test. Other tests were added as noted to obtain additional bounding data where needed. The joint strength results column provides the number of samples tested at the target conditions and the number of samples that slipped with the load at which slip occurred.

Table 5-4 provides a summary of the slip data. The slip load is provided for each test block with the differential dilations. The roll torque for the repair roll is provided for information.

The results in Table 5-4 shows an outlying test sample that slipped at [d] for differential dilations of [d]. The target load for this test was [d] and the load was overshot. Two other samples were tested at this dilated condition; one slipped at [d] and one slipped at [d]. Another sample slipped at [d] for differential dilations of [d]. The [d] slip load may have been due to the presence of lubricant on the tube OD, but no residual was found on inspection. Since no justification for discarding the outlying data point could be verified; [d] was taken as the limiting load at this dilation even though it appears to be very conservative. Therefore, the limiting load of [d] was applied to locations with a major dilation between [d] and a minor dilation less than or equal to [d].

As shown in Table 5-4, the minimum slip load for cases with a major dilation less than [d] was [d] for test block C-237-5 at differential dilations of [d]. The average slip load for these cases was [d] with a standard deviation of [d]. A limiting slip load of [d] was applied to all locations with a major dilation less than [d] with a minor dilation less than [d] or with major and minor dilations less than [d].

Table 5-3 Summary of Joint Strength

[d]

Table 5-3 Summary of Joint Strength (con't)

[d]

Table 5-3 Summary of Joint Strength (con't)

[d]

Table 5-4 Slip Data

[d]

5.2.7.2 Leak Test Results

The leak test data was used to establish leak rates to be applied to repair rolls. The bounding leak rates were developed based on the tests performed on effective [e] single repair rolls and may be conservatively applied to overlapping repair rolls.

Table 5-5 and Figure 5-2 provides a summary of the leak test results based on average dilation for low load leak tests and high load leak tests. These results apply to joints that are not predicted to slip under the applied axial load. [d]

Table 5-5 Average Low Load and High Load Leak Rates (No-Slip)

[d]

Note: N/A indicates no test was performed for this configuration.

Figure 5-2 Comparison of High Load and Low Load No-Slip Leak Rates

[d]

As shown in Table 5-5 and Figure 5-2, the no-slip leak rates [d] with loads and/or differential dilations. Therefore, a 1-sided 95% upper confidence limit (UCL) was calculated by [d] the test data as shown in Table 5-6. The result was [d].

Table 5-6 MSLB Leak Rates for No-Slip Condition Repair Rolls

[d]

The leak rate for the [b] was calculated by multiplying the [d] leak rates by the square root of the ratio of the pressure differentials, based on a deterministic model for leakage from an axial crack (EPRI NP-6864-Rev.2). The maximum pressure differential during the [c] transient is [c] and occurs [c] to the time of maximum load (approximately [c] minutes into the transient). The pressure differential during the [c] at the time of maximum load (approximately [c] into the transient), then continues to [c] after the time of maximum load. The tube-to-shell temperature difference at the time of maximum pressure is approximately [c] temperature difference at the time of maximum load. Thus, if the tube does not slip at the time of maximum load, it is [c] that it would slip at the time of maximum pressure. Since the [c] no-slip leak rate for [c] is bounded by the [c] no-slip leak rate, the leak rate for the [c] is calculated for the time of maximum load for post-slip leakage.

Thus, the leak rate (LR) for the [c] is calculated as:

[c]

Leak tests were performed for additional information for 2 test blocks with dilations of [d] at [d] internal pressure and [d]. The average leak rate at [d] was [d]. The average leak rate at [d] was [d]. The results of these leak tests provide confirmation that calculating a leak rate for the [c] using the ratio of the square root of the pressure differentials is a valid approach.

Repair roll leakage during normal operation is predicted using the ratio of the square root of the pressure differentials. The pressure differential at steady-state 100% power is 1275 psi as presented in Table 4-1. Thus, the predicted steady-state operation leak rate is [d] for each repair roll that serves as a pressure boundary. Leakage is monitored during steady-state operation and the plant is shut down if the leakage exceeds the technical specification limits. The steady-state leak rate is provided to provide assurance that the total leakage from repair rolls would not result in leakage that would require the plant to be shut down.

Post-slip leak tests were performed to establish a bounding leak rate for all tubes that are predicted to slip. The results are provided in Table 5-7 and Figure 5-3. Again, the leak rate is [d] by the internal pressure and [d] considerably with [d] as shown in Figure 5-3. Therefore, the [d] post-slip leak rate is applied to all locations where the repair roll may potentially slip.

Table 5-7 Post-Slip Condition Leak Test Results

[d]

Note: N/A indicates no test was performed for this configuration.

Binning [d] the post-slip leak data [d], the [d] post-slip leak rate for a repair roll is [d].

The application of repair rolls leak rates described above is a very conservative approach because only repair rolls with large circumferential cracks will actually slip and the majority of the degradation in the tubesheet are short, axial cracks. Therefore, the probability of maintaining structural integrity between the new roll and the tube-to-tubesheet weld is very high and the potential for a joint to slip is very low. In addition, leak rates from short axial cracks would be much lower under tensile loads than the circumferential sever that was tested. Thus, the applied leak rates are conservative whether the repair roll slips or not.

The leak rate from each single repair roll or overlapping repair roll that is serving as a pressure boundary is summed to obtain a total leak rate for the OTSG. Plant-specific total leakage would vary depending on the total number of repair rolls and the number of repair rolls that could potentially slip.

Figure 5-3 Comparison of High Load and Low Load Post-Slip Leak Rates

[d]

5.2.8 Conclusions

Table 5-8 provides the bounding differential dilations and loads used to predict repair rolls that may potentially slip. The term Δd refers to the differential dilation from the transient analyses after normalization to room temperature. The room temperature leak rates to be applied to repair rolls are provided in Table 5.9. The application of the slip criteria and leak rates is discussed further in Sections 6.0 and 7.0 respectively.

Table 5-8 Repair Roll Slip Criteria

[d]

Table 5-9 Bounding Repair Roll Leak Rates (Room Temp.)

[d]

5.3 Overlapping Repair Rolls

For the overlapping roll, a second repair roll is installed that overlaps the first repair roll. Figure 2-1 provides a sketch of the repair rolls. The overlapping roll provides a minimum [e] effective roll expansion.

[b] of the tube due to repair roll installation can be minimized by the installing the [b] repair roll first, thereby overlapping the [b] transition of the first repair roll. However, the [b] roll can be installed first, followed by an [b] roll or a [e] roll expansion can be installed

that overlaps an existing repair roll. The [d] transition may be eliminated by installing an [b] repair roll first, followed by installing overlapping [d] repair rolls [b].

The joint strength increases with the overlapping repair roll, due to the [b]. Leakage would be less since the pressure differential would be the same, but friction losses through the longer leak path would be increased. The leak and load testing of a [e] single repair roll conservatively bounds overlapping repair rolls. The [e] single repair roll leak rates may be conservatively applied to the overlapping repair rolls for evaluation purposes.

6.0 Repair Roll Exclusion Zones

A repair roll exclusion zone is a location where installation of a repair roll has not been qualified. An exclusion zone may be generic, which is applied to all OTSGs, or specific to a particular plant.

6.1 Generic Exclusion Zones

Generic exclusion zones for the repair rolls are applied within the first [d] from the primary and secondary faces of the tubesheets. These generic exclusion zones ensure that the following repair roll design requirements are met:

- The repair roll is remote from the original roll expansion.
- The tube will not slip out of the tubesheet.

An exclusion zone of [e] from the tubesheet primary face conservatively ensures that a repair roll will be remote from the original [e] roll expansion.

An exclusion zone of [e] from the tubesheet secondary face ensures that tube will not slip out of the tubesheet. The maximum axial tube load for the OTSGs is [c]. Assuming 100% of the strain is relieved, the axial deflection due to this load is:

$$\delta = \frac{PL}{EA}$$

Where: P is the axial tube load = [c]

L is the tube length = [b]

E is the modulus of Elasticity = [b]

A is the nominal OTSG tube area = [b]

[b]

Therefore, an exclusion zone of [e] from the secondary face ensures that the tube will not slip out of the tubesheet.

Thus, generic exclusion zones of [e] from the primary and secondary faces of the tubesheets are applied to all OTSGs.

6.2 Plant-Specific Exclusion Zones

The repair roll design requires that tube failure does not result from tube bow [c] conditions. Tube buckling under subsequent heatup from decay heat is bounded by the [c] loads during a normal operating [c]. If the tube slips during a faulted accident, it is unlikely the tube will slip back into its original location. If the tube slips, a tube could potentially bow between tube support plate locations at the end of the faulted accident due to compressive loads caused by decay heat. As calculated above, the maximum amount of tube slip is approximately [b] over the length of the tube due to the bounding axial tube load. The total slippage of [b] would be distributed over the length of the tube [b]. The tube-to-shell temperature differential and resulting compressive loads due to heatup from decay heat would be much less than the temperature differential due to a normal [c]. Thus, post-slip tube buckling due to decay heat would be bounded by the normal [c] compressive loads prior to slip. Therefore, no plant-specific exclusion zones are required based on post-faulted transient tube bow.

The differential dilations from the FE transient analyses results for each plant were evaluated based on the criteria presented in Table 5-8 to determine plant-specific exclusion zones for the repair roll. The following bounding conditions were evaluated:

[c]

The criteria presented in Table 5-8 were applied to each tubesheet depth and radial position to determine if the differential dilations are within the tested parameters and if there is a potential for repair roll slip under normal operating conditions. Differential dilations that are greater than [d] for any transient resulted in an exclusion zone simply because test data is not available for differential dilations greater than [d]. In many cases, the criteria may result in conservative exclusion zones. The limiting differential dilations were typically due to [c] and the limiting dilation was a minor dilation of [d]. Since the repair roll [e] and leakage under [c] would be minimal for most of the transient due to the [d] pressure differential (See Section 4-4 and Figure 4-3), this is a conservative approach.

Potential repair roll slip during a [c] transient resulted in an exclusion zone because the repair rolls are [c]. None of the plant-specific exclusion zones (provided in the Appendices) were the result of potential slip of a repair roll during a [d] transient.

Appendices A through D provide figures of the Exclusion Zones as a function of tubesheet depth and radial position.

7.0 Application of Leak Rates

Based on evaluations of differential dilations and loads for the bounding faulted conditions for each plant (See Section 6.0), potential slip of the repair roll was determined as a function of tubesheet depth and radial position. Margin against slip was calculated for each tubesheet depth and radial position.

The bounding applicable no-slip leak rate (Table 5-9) was applied to locations identified as having no potential for repair roll slip.

A bounding applicable post-slip leak rate was applied to locations that may result in repair roll slip. The bounding leak rate is applied to the entire transient time, which is a conservative approach since the maximum pressure differential typically occurs late in the transient. In the case of the [c], the maximum pressure differential occurs [c] in the transient and [c] with time.

The repair roll will actually slip only if there is a circumferential flaw that is large enough in extent to prevent the tube-to-tubesheet weld from carrying any of the load. Since the majority of the degradation in the region of the roll joints has been identified as small axial cracks, the probability of the repair roll maintaining structural integrity is very high. Application of only a non-slip leak rate may be used if the tube is inspected full length, including the region of tube outside of the new pressure boundary and the tube-to-tubesheet weld transition region, to verify that there are no limiting circumferential cracks present.

As described in Section 5.2.7, the applied leak rates are very conservative since the tests were performed on samples with a full circumferential sever outboard of the repair roll. The majority of degradation in the tubesheet are short, axial cracks which result in a much lower leak rate under tensile loads than the tested circumferential cracks.

The leakage from each repair roll that serves as a pressure boundary is added to the total leakage from all other sources and must be below the technical specification limits.

8.0 Non-Destructive Examination of Repair Rolls

Repair roll candidates are identified by EC inspection of the OTSG tubes. ET methods may vary from plant to plant and may change as improved methods are made available. In general, adherence to the EPRI Guidelines for ET tube inspections is recommended. The acceptability of an ET method of inspection for repair roll installation is based on the following requirements.

8.1 Pre-Repair Roll

The following ET information for repair roll candidates shall be established as a minimum base line:

1) Generator, Channel Head, Tube Row and Tube Column must be defined.
2) Pull speeds and frequencies shall be in accordance with plant Steam Generator Eddy Current Data Analysis Guidelines and/or other applicable plant-specific documents.
3) Location of the tip of the indication of degradation furthest from the primary face of the tubesheet.

8.2 Post-Repair Roll

The following ET information for repair rolls shall be collected as a minimum:

1) Generator, Channel Head, Tube Row and Tube Column
2) Pull speeds and frequencies shall be in accordance with plant Steam Generator Eddy Current Data Analysis Guidelines and/or other applicable plant-specific documents.
3) Profile of new tube ID (absolute or relative), including the new inside diameters of the hard-rolled section of the tube, inside diameter of original hard roll, and the nominal unexpanded tube ID.
4) Verify that the effective repair roll is free of defect indications.

9.0 Repair Roll Installation Parameters

The design parameters for a field implemented repair roll joint are as follows:

(a) A minimum [e] effective repair roll remote from existing defects and previous roll transitions.

(b) An optional overlapping repair roll, with a minimum [e] of new effective roll remote from existing defects.

(c) An installation torque of [e] using a qualified repair roll process tool assembly (e.g. DELTA tool).

(d) Installation no closer than [e] from the primary and secondary tubesheet faces.

(e) Repair rolls are not qualified at locations shown as exclusion zones in Appendices A through D.

(f) [b] single [b] repair rolls or [b] overlapping repair roll that results in a maximum of [b] additional [b] load may be installed at a qualified location in any one tube. Additional repair rolls may be installed on a case-by-case basis by evaluating for acceptable [b] tube loads.

10.0 Conclusions

This evaluation has shown that installation of a single [e] repair roll or a [e] overlapping repair roll in the OTSGs is acceptable based on the following:

Structural Integrity

The single [e] minimum repair roll is structurally adequate to prevent tube slip during all [e] transients. [e].

The qualification is valid for locating the roll expansion in the OTSGs with the exception of the generic [e] exclusion zones at each face of the tubesheet, primary and secondary, and the plant-specific exclusion zones identified in Appendices A through D. The plant-specific exclusion zones may be conservative in that application of these exclusion zones was based on the limitations of the test equipment for differential dilations greater than [d]. Many of the locations that resulted in an exclusion zone experience differential dilations that are only slightly greater in the minor dilation ([d]) with a major dilation less than [d].

An optional [e] minimum overlapping roll is structurally acceptable based on the bounding evaluation of the single [e] repair roll.

The repair roll is applicable to repairing axial, volumetric, or circumferential indications. Testing was conservatively performed with the assumption that the tube is severed at the heel transition (360° and 100% through-wall circumferential defect).

The joint strength margin (actual load / limiting load) was calculated for each tubesheet depth and radial position for the [c] transient to ensure margin against slip for [c] conditions. All locations showed a joint strength margin less than [e] with an acceptable margin less than 1.0.

Leakage

Bounding leak rates are applied based on tubesheet depth and radial position. A post-slip leak rate is applied to any location where there is potential for repair roll slip during a [c]. The bounding leak rates are very conservative because the leakage is based on test samples with a full circumferential sever outboard of the repair roll. The majority of the degradation in the tubesheets is short, axial cracks for which the leakage would be much less under axial tensile loads than for the tested severed tube. In addition, repair rolls will actually slip only if there is a large circumferential crack present in the tube outboard of the repair roll.

It may be desirable in some cases to further limit the number of repair rolls that are predicted to slip; thereby avoiding the application of the post-slip leak rates. Application of only a non-slip leak rate may be used if the tube is inspected full length, including the region of tube outside of the new pressure boundary and the tube-to-tubesheet weld transition region, to verify that there are no limiting circumferential cracks present.

The leakage from each repair roll that serves as a pressure boundary is added to the leakage from all other sources and the total leakage must be within the technical specification limits.

Conservatism Elements (Analyses and Testing)

Conservative elements in the qualification of the repair roll included, but were not limited to the following:

Transient Analyses (General)

1) The worst case geometrical configurations and/or dimensions were used to develop the differential dilations and axial tube loads. The configuration and/or dimensions that resulted in the highest axial loads were used in the transient analyses.

[c] Transient Analyses:

2) Secondary side water level was maintained at [b] during the entire transient, increasing tube-to-shell temperature difference.
3) No credit was taken for direct impingement of main feedwater on the inside shell surface, increasing tube-to-shell temperature difference.
4) Natural convection of water for the entire feedwater downcomer was assumed, increasing tube-to-shell temperature difference.

[c] Transient Analyses:

5) A maximum value for the Initial OTSG secondary inventory was used to bound plant operation.
6) Main feedwater isolation valve actuation and stroke times are maximized to bound actual operation in the plant.
7) Maximum safety injection flow rates were used to bound plant characteristics and maximize RCS cooling.
8) Safety injection actuation delay times were zero.
9) Nominal control rod worth was inserted (no stuck rod penalty)
10) Used maximum AFW flow and minimum AFW temperature to the affected OTSG for 10 minutes (where applicable).
11) ONS-Specific MSLB: Used operator action at two minutes to trip the Reactor Coolant Pumps, which maximizes Reactor Coolant System cooldown.

[c] Transient Analyses:

12) Limiting break selection:
   a) The break is large enough to depressurize the plant to obtain actuation of the low pressure safety injection. This low temperature water eventually flows back to the OTSG tubes.
   b) The break is small enough that a two-phase discharge through the break occurs with liquid from the vessel region and steam provided from the OTSG. Venting steam from the OTSG tubes allows the tubes to be "wetted" over their entire length with relatively cold, two-phase reactor coolant.
   c) The break is at an elevation above the RC pump spill-over elevation such that the hot-leg-to-steam generator manometer effect allows cold LPI fluid to flow backwards from the reactor vessel, through the RC pump, into the cold leg suction piping, and eventually in the OTSG.

[c] Break:

13) One hundred percent decay heat was modeled.
14) Maximum emergency core cooling system (ECCS) flow from all pumps was modeled to maximize the cold water addition to the RCS and minimize and tube temperature.
15) Minimum ECCS flow actuation delays were modeled to maximize the addition of cold ECCS fluid to the RCS.
16) ECCS fluid temperature was set to a minimum value to maximize the cooling of the OTSG tubes when this fluid enters the OTSG tubes.

[c] Break:

17) Ninety percent decay heat was modeled.
18) Maximum emergency core cooling system (ECCS) flow from all pumps, including the makeup pumps, was modeled to maximize the cold water addition to the RCS and minimize and tube temperature.
19) Minimum ECCS flow actuation delays and maximum setpoint pressures were modeled to maximize the addition of cold ECCS fluid to the RCS.
20) The CFT fluid conditions were set to allow CFT injection at the earliest time.
21) ECCS and CFT fluid temperatures were set to a minimum value to maximize the cooling of the OTSG tubes when this fluid enters the OTSG tubes.
22) The steam generator shell was modeled as an adiabatic boundary condition to minimize heat losses from the shell.

Repair Roll Testing:

23) Test conditions were selected to bound the worst case combination of joint structural strength and/or leakage, [b].

24) Leak tests were performed at the maximum possible pressure differential of 2575 psig, derived from the safety relief valve setpoint and assuming no operator intervention.

25) A full circumferential sever was modeled for the testing, which is conservative for structural strength and leakage since the majority of the degradation within the tubesheet is short, axial cracks. The model assesses the joint strength of a repair roll without taking any credit for the original roll expansion or the tube-to-tubesheet weld. The tested configuration results in very conservative leak rates since leakage for short axial cracks under tensile loads would be much less than the tested circumferential sever.

26) Leak rates were developed based on static testing with axial loads and differential dilations constant throughout the 20-minute leak test.

Exclusion Zones:

27) An exclusion zone of [e] from the secondary face is conservative since the maximum possible slippage is approximately [b].

28) An exclusion zone of [e] from the primary face is conservative to ensure that a repair roll is remote from the original [e] roll expansion.

29) Plant-specific exclusion zones were based on maximum differential dilations of [d]. Many of the plant-specific exclusion zones were due to a [c] minor dilation of [d] with a major dilation of less than [d]. Even though these dilations were not tested, the leakage due to these [c] conditions would probably be minimal.

Applied Leak Rates:

30) Bounding no-slip leak rates were developed by calculating a 1-sided 95% UCL limit.

31) The bounding leak rates, [d] are assumed to be constant for the entire transient, even though the maximum pressure differential occurs [c] in the transient for the [c] and for only [c] of the [c].

32) A post-slip leak rate was applied to all repair rolls that have the potential to slip, regardless of whether a circumferential crack is actually present. The repair roll will not actually slip unless a large circumferential flaw is present. As described above, since the majority of the degradation within the tubesheet is short, axial cracks. Application of only a no-slip leak rate may be used if the tube is inspected full length, including the region of tube outside of the new pressure boundary and the tube-to-tubesheet

weld transition region, to verify that there are no limiting circumferential cracks present. The no-slip leak rate is this case would still be conservative as described above in item 18.

All repair rolls installed under previous submittals meet the repair roll qualifications of this topical report.

Appendix A Exclusion Zones and Repair Roll Leak Rates for ANO-1

The limiting condition for ANO-1 repair roll slip is the [c], primarily due to minor dilations greater than [d]. These locations result in an exclusion zone because the condition has not been tested. [e].

For the UTS at ANO-1, a repair roll can be placed with the roll centerline between [e] tubesheet depth at any radial position with a leak rate of [d] applied to each repair roll that serves as a pressure boundary. Additional qualified locations are shown in Figure A-1.

For the LTS at ANO-1, a repair roll can be placed with the roll centerline between [e] at any radial position with a leak rate of [d] applied to each repair roll that serves as a pressure boundary. Additional qualified locations are shown in Figure A-2.

The predicted leakage at steady-state 100% power conditions from each repair roll that serves as a pressure boundary is [d].

All repair rolls installed under previous submittals meet the repair roll qualifications of this topical report.

Figure A-1 ANO-1 Upper Tubesheet Exclusion Zones

[d & e]

Figure A-2 ANO-1 Lower Tubesheet Exclusion Zones

[d & e]

Appendix B Exclusion Zones and Repair Roll Leak Rates for CR-3

The limiting condition for CR-3 repair roll slip is the [c], primarily due to minor dilations greater than [d]. These locations result in an exclusion zone because the condition has not been tested. [e]

For the UTS at CR-3, a repair roll can be placed with the roll centerline between [e] tubesheet depth at any radial position with a leak rate of [d] applied to each repair roll that serves as a pressure boundary. Additional qualified locations are shown in Figure B-1.

For the LTS at CR-3, a repair roll can be placed with the roll centerline between [e] at any radial position with a leak rate of [d] applied to each repair roll that serves as a pressure boundary. Additional qualified locations are shown in Figure B-2.

The predicted leakage at steady-state 100% power conditions from each repair roll that serves as a pressure boundary is [d].

All repair rolls installed under previous submittals meet the repair roll qualifications of this topical report.

Figure B-1 CR-3 Upper Tubesheet Exclusion Zones

[d & e]

Figure B-2 CR-3 Lower Tubesheet Exclusion Zones

[d & e]

Appendix C Exclusion Zones and Repair Roll Leak Rates for DB-1

The limiting conditions for DB-1 repair rolls vary with depth and radial position. The limiting conditions are [c]. For both transients, a minor dilation greater than [d] results in an exclusion zone because the condition has not been tested. [e].

For the UTS at DB-1, a repair roll can be placed with the roll centerline between [e] tubesheet depth at any radial position. A leak rate of [d] shall be applied to each repair roll that serves as a pressure boundary from [e] radial position. A leak rate of [d] shall be applied to each repair roll that serves as a pressure boundary from [e] radial position. A leak rate of [d] shall be applied to each repair roll that serves as a pressure boundary from [e] radial position. Additional qualified locations are shown in Figures C-1

See Figure C-2 for qualified repair roll locations and applicable leak rates for the LTS at DB-1.

The predicted leakage at steady-state 100% power conditions from each repair roll that serves as a pressure boundary is [d].

There are no previously installed repair rolls in service at DB-1. The four repair rolls that were installed under previous submittals have been plugged.

Figure C-1 DB-1 Upper Tubesheet Exclusion Zones

[d &e]

Figure C-2 DB-1 Lower Tubesheet Exclusion Zones

[d & e]

Appendix D Exclusion Zones and Repair Roll Leak Rates for Oconee (ONS-1, ONS-2, and ONS-3)

The limiting conditions for ONS-1 repair roll slip are the [c], primarily due to minor dilations greater than [d]. These locations result in an exclusion zone because the condition has not been tested. [e].

For the UTS at ONS, a repair roll can be placed with the roll centerline between [e] tubesheet depth at any radial position. A leak rate of [d] shall be applied to each repair roll that serves as a pressure boundary from [e] radial position. A leak rate of [d] shall be applied to each repair roll that serves as a pressure boundary from [e] radial position. Additional qualified locations are shown in Figure D-1.

For the LTS at ONS, a repair roll can be placed with the roll centerline between [e] tubesheet depth at any radial position. A leak rate of [d] shall be applied to each repair roll that serves as a pressure boundary from [e] radial position. A leak rate of [d] shall be applied to each repair roll that serves as a pressure boundary from [e] radial position. Additional qualified locations are shown in Figure D-2.

The predicted leakage at steady-state 100% power conditions from each repair roll that serves as a pressure boundary is [d].

All repair rolls installed under previous submittals meet the repair roll qualifications of this topical report.

Figure D-1 ONS Upper Tubesheet Exclusion Zones

[d & e]

Figure D-2 ONS Lower Tubesheet Exclusion Zones

[d & e]