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F* AND ELEVATED F* TUBE ALTERNATE REPAIR CRITERIA FOR TUBES WITH DEGRADATION WITHIN THE TUBESHEET REGION OF THE KEWAUNEE STEAM GENERATORS

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F* and Elevated F* Tube Alternate Repair Criteria for Tubes with Degradation within the Tubesheet Region of the Kewaunee Steam Generators

Westinghouse Energy Systems

ABSTRACT

An evaluation has been performed to develop acceptance criteria for tubes exhibiting degradation in the tube-to-tubesheet crevice region of the Kewaunee steam generators. These criteria are based on determining the length of additional roll expansion of sound tube to achieve adequate pullout and leakage resistance. Criteria are also developed to address tube degradation in the factory roll expansion; these criteria determine the length of sound, factory rolled tube necessary to achieve adequate pullout and leakage resistance. The length of sound, factory rolled tube and additional tube roll immediately adjacent to (above) the factory roll expansion is referred to as F*. The length of additional roll expansion in the crevice region above the tubesheet mid-thickness is referred to as elevated F*, or EF*.

It is shown that the use of F*/EF* obviates tube plugging or other repair in many cases. Two specific additional roll expansion elevations have been developed. For a tube with "pluggable" degradation, the elevation of the top of the degradation will determine the elevation of the additional roll. It is expected that the elevation of the top of the degradation in the majority of cases will be between the top of the factory roll and slightly above the vertical mid-thickness of the tubesheet, 10.5 inches above the bottom of the tubesheet. For this reason, the top of the EF* length will be placed at approximately the 17 inch elevation and it will extend downward to encompass the EF* length. The other elevation of the additional roll expansion will be adjacent to and immediately above the factory roll. It will address tube degradation in the factory roll. The EF* length, excluding NDE uncertainty in elevation, is 1.44 inches. The F* length, excluding NDE uncertainty in elevation, is 1.12 inches.

Evaluation of the roll expanded joints demonstrates that application of the F* and EF* criteria for indications of tube degradation below the field-applied additional roll expansion or within the factory roll expansion affords a level of plant protection commensurate with that provided by Regulatory Guide 1.121 for degradation located outside of the tubesheet region.

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NOMENCLATURE

ARX	Additional Roll Expansion
BRT	Bottom of Roll Transition
dpm	Drops per minute
EARX	Elevated Additional Roll Expansion
ECI	Eddy current indication
ECT	Eddy current test
EF*	Elevated F* - Axial length of no-detectible-degradation tube additional roll expansion which provides adequate pullout and leakage resistance and applied approximately 15.5 to 17 inches above the bottom of the tubesheet
F*	Axial length of no-detectible-degradation tube factory or retrofit roll expansion which provides adequate pullout and leakage resistance and applied in or adjacent to factory roll
FLB	Feedline break
ID	Inside diameter
KNPP	Kewaunee Nuclear Power Plant
LOCA	Loss of Coolant Accident
LTL	Lower tolerance limit
MA	Mill-annealed
NDD	No Detectible Degradation
NDE	Non destructive examination
N.O.	Normal Operation
OD	Outside diameter
RCS	Reactor coolant system
RE	Roll expansion
RPC	Rotating pancake coil
RT	Roll transition
S/G	Steam generator
SLB	Steamline break
S_r	T/TS interfacial radial contact pressure
SRE	Sound roll expansion
T	Torque
TTS	Top of tubesheet
T/TS	Tube to tubesheet
X	Distance from top of indication to BRT

1.0 INTRODUCTION

This report discusses the technical and licensing basis for an alternate repair criterion applicable to partial depth hardroll expanded steam generator tubes with degradation occurring within the factory hardroll and the tubesheet crevice region. Existing Kewaunee Technical Specification tube repair/plugging criteria apply throughout the tube length, but do not take into account the reinforcing effect of the tubesheet on the external surface of the tube in a roll expansion. Two separate alternate repair and plugging criteria, called F* and elevated F* (or EF*), were developed for tubes with degradation in the expanded region below the bottom of the factory roll transition and for degradation above the roll transition and within the tubesheet crevice region, respectively.

For F*, an evaluation was performed to determine the length of hardroll engagement required to resist tube pullout forces during normal operation, test, upset and faulted conditions; refer to Fig. 1-1. The evaluation is discussed in Section 2.0. The evaluation used the results of previous analyses and tests which quantified the residual radial preload of Westinghouse 51 Series steam generator tubes hardrolled into the tubesheet holes in the factory. The necessary axial length of undegraded tube joint, called F*, required to resist tube pullout forces was determined. It is also shown that the radial preload applied over an axial length of roll expanded tube of length F* is sufficient to resist significant leakage during the aforementioned four types of conditions. On this basis, tubes in the Kewaunee steam generators with no detectible degradation within the F* distance, measured downward from the bottom of the roll transition, are sufficient for continued plant operation, regardless of the extent or nature of tube degradation below the F*distance.

In addition, an alternate repair/plugging criterion has been developed for tubes which exhibit degradation in or immediately above the intended F* distance, i.e., above the bottom of the factory roll transition. This criterion uses a field-applied, additional roll expansion (ARX) adjacent to the factory roll. Refer to Fig. 1-2. The F* axial length of ARX provides the same structural integrity as the F* length of factory roll expansion. Both the factory F* and the ARX of F* length exhibit negligible leakage. The ARX leakage is documented in Reference 1. The evaluation for this use of F* is provided in Section 3.0.

For tubes which exhibit degradation above the factory roll expansion transition up to an elevation of approximately 15 inches above the tubesheet bottom, a criterion referred to as elevated F*, or EF*, has been developed. It also uses a field applied, additional roll expansion. Refer to Fig. 1-3. The EF* axial length of elevated ARX (EARX) provides the same structural integrity and leakage resistance as the other two criteria. The EARX axial length of EF* exhibits negligible leakage when compared to the permissible primary-to-secondary side leakage allocated to this potential source.

The EARX will begin at approximately 17 inches above the bottom of the tubesheet and extend downward approximately 1.44 inches, exclusive of NDE uncertainty in elevation. The EF* distance is larger than the F* distance. This is because F* and EF* are directly related to radial preload, a.k.a. interference fit contact pressure. The EF* criterion is applied above the neutral bending axis of the tubesheet; tubesheet upward bending effects cause a reduction in the radial preload during the bounding conditions, normal operation (N.O.) and feedline break (FLB). In the case of F*, applied within the factory roll or above and adjacent to it, the tubesheet upward bending effects are beneficial or have no effect on the contact pressure. The evaluation of interference fit contact pressure for EF* is also provided in Section 3.0. The development of EARX is documented in Reference 1.

Finally, this evaluation demonstrates that the F* and EF* criteria for tube degradation within the tubesheet afford a level of plant protection commensurate with that provided by Regulatory Guide (RG) 1.121 (Reference 2) for degradation located outside of the tubesheet region.

1.1 Background

The Kewaunee steam generators, particularly "A" steam generator, have very short tube roll expansions (REs). The RE approaches the required F* length, see Fig. 1-1. The roll expanded length of the tube can be considered to consist of two zones, the factory roll transition (RT) and the factory roll region. The roll transition is defined as that portion of the tube where the roll expanded length transitions to the unexpanded length. The RT is approximately [.

]^{a,c,e} inch above the tube end at the bottom of the tubesheet. The roll region is also referred to as the roll expansion or hardroll.

Existing plant Technical Specification tube repair/plugging criteria which have been applied throughout the tube length do not take into account the reinforcing effect of the tubesheet on the external surface of the expanded portion of the tube. The presence of the tubesheet will constrain the tube and will complement tube integrity in that region by essentially precluding tube deformation beyond the expanded outside diameter. The resistance to both tube rupture and tube collapse is significantly increased by the presence of the tubesheet. In addition, the proximity of the tubesheet significantly affects the leak behavior of throughwall tube cracks in this region. Based on the above considerations, the establishment of alternate repair criteria specific to the tubesheet factory and retrofit roll regions is justified.

Taking credit for the reinforcing effect of the tubesheet and the radial contact load between the expanded region of the tube and the tubesheet, the F* and EF* alternate repair criteria are developed. The F* criterion permits operation with any amount of tube degradation below a calculated distance, F*, below the bottom of the roll transition (BRT). Within the F* distance, no detectable degradation is permissible. The F* distance is shown to provide sufficient frictional force between the expanded tube and tubesheet to resist pullout due to the bounding conditions, i.e., normal operation and FLB/SLB postulated accident conditions. The use of the F* criterion does not require any assessment of tube degradation other than elevation, and any type of degradation below the F* distance may be accepted .

Eddy current indications (ECI's) in the top portion of the roll expansion (within the intended F* distance) and immediately above the factory BRT may also be addressed by F*. Adjacent to the factory tube expansion, from below the bottom of the roll transition, F* criteria will apply based on achievement of an ARX of sufficient engagement such that pullout forces that develop during normal or accident operating conditions would be successfully resisted by the elastic preload between the tube and the tubesheet. The ARX will serve as a continuance of the original roll expansion. The necessary engagement length applicable to the Kewaunee steam generators was determined in the ARX program, Reference 1.

Tube degradation not meeting the elevation requirements of F* can be addressed by the alternate repair criteria defined as EF*. The EF* criterion provides for sufficient engagement of the additional, elevated tube-to-tubesheet hardroll, the EARX, such that pullout forces that develop during normal or accident operating conditions would be successfully resisted by the elastic preload between the tube and the tubesheet. The EARX is performed above the mid-plane of the tubesheet. The necessary engagement length applicable to the Kewaunee steam generators was determined based on mechanical interference fit (MIF) analysis.

1.2 Summary and Conclusion

Tube degradation within or immediately above the intended F* distance can be dispositioned with F* if an additional roll expansion of adequate strength and leakage resistance is performed adjacent to and above the factory roll. Both the factory F* and the ARX of F* length exhibit negligible leakage compared to the permissible primary-to-secondary leakage during bounding conditions of normal operation and FLB/SLB. The F* length is 1.12 inch, not including NDE uncertainty in measuring the elevation of the degradation uppermost extent.

Tube degradation in the crevice region above the intended F* distance, up to an elevation approximately 15 inches above the tubesheet bottom can be dispositioned with EF* if an elevated additional roll expansion is performed, beginning at approximately the 15 inch elevation. The additional roll expansion must have adequate strength and leakage resistance. The EF* length at this elevation is 1.44 inches, not including NDE uncertainty in the elevation of the uppermost extent of degradation.

Application of the F* and EF* tube alternate repair/plugging criteria can be shown to afford the same protection commensurate with that provided by Regulatory Guide 1.121 for degradation located outside of the tubesheet region.

a,c,e

Figure 1-1. Configuration for Factory Tubesheet Region F* Alternate Repair/Plugging Criterion for Partial Depth Roll-Expanded Kewaunee Steam Generator Tubes

a,c,e

Figure 1-2. Configuration for Above-Factory Tubesheet Region F* Alternate Repair/Plugging Criterion for Partial Depth Roll-Expanded Kewaunee Steam Generator Tubes

a,c,e

Figure 1-3. Configuration for Tubesheet Region EF* Alternate Repair/Plugging Criterion for Partial Depth Roll-Expanded Kewaunee Steam Generator Tubes

2.0 DEVELOPMENT OF F* CRITERION - FACTORY ROLL

Although the F* criterion will reportedly have little application in the factory rolls of KNPP, the development program for this application will be shown in detail in this section.[1] Essentially the same approach, but augmented by the ARX program, was used for development of the retrofit F* and for the EF* criteria. Development of the latter criteria will be discussed in Section 3.

The F* tube plugging criterion is based on a semi-empirical method of quantifying the axial load bearing capability of the rolled joint, resulting from the radial contact preload pressure and the associated friction between the tube and the tubesheet (TS). The tube-to-tubesheet (T/TS) radial pressure, S_r, which consists of the as-manufactured pressure and as changed by operating loads and temperatures, provides resistance to the leakage of primary-to-secondary and secondary-to-primary water. The use of the F* criterion obviates the necessity of determining the depth, number, inclination, length and circumferential spacing of ECIs. Only the distance from the uppermost part of the ECI to the BRT needs to the determined. In short, the nature and extent of tube degradation need not be determined. Refer to Figure 1-1.

Tube rupture in the conventional sense, as characterized by an axially oriented "fishmouth" opening in the side of the tube, is impossible within the tube/tubesheet roll expansion because the tubesheet prevents the wall of the tube from expanding outward in response to the internal pressure forces. The forces which would normally act to cause tube crack extension are transmitted into the walls of the tubesheet, the same as for a non-degraded tube, instead of acting on the tube material. Thus, axially oriented linear indications, e.g., cracks, cannot lead to tube failure within the RE and may be considered on the basis of leakage effects only.

Likewise, a circumferentially oriented tube rupture is resisted because the tube is not free to deform in bending within the roll expansion. When degradation has occurred such that the remaining tube cross sectional area does not provide a uniform resistance to axial loading, bending stresses are developed which may significantly accelerate failure. When bending forces are resisted by lateral support loads, provided by the tubesheet, the acceleration mechanism is mitigated and the tube separation mode is similar to that which would occur in a simple tensile test. Such a separation mode, however, requires the application of significantly higher loads than for the unsupported case.

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[1] Based on NDE, the factory hardrolls in thc hot leg of Steam Generator A of Kewaunee range from approximately zero to approximately 2.25 inches in axial length. The typical length is 1.25 inches. There is reportedly little or no degradation within this portion of the tube joint. Therefore, there is essentially no need for F* within the factory roll in this S/G. However, because this length approximates F*, the F* criterion wouldn't be applied therc anyway. The factory roll lengths in the hot leg of S/G B are closer to the intended length of 2.25 inches. Therefore, the F* criterion could be used to disposition "pluggable" degradation in the first 1.13 inch of hard roll, below the 1.12 inches (the F* value calculated in this section, including a typical NDE tolerance for elevation uncertainty) of tube below the BRT.

Evaluation of the applicability of any developed criterion for tube indications within the tubesheet, requires that some postulated type of degradation be considered. For this evaluation it was postulated that a circumferential severance of a tube could occur, contrary to existing plant operating experience. However, implicit in assuming a circumferential severance to occur is the consideration that degradation of any extent could be demonstrated to be tolerable below the location determined acceptable for the postulated condition.

When the tubes have been hardrolled into the tubesheet, any axial loads developed by pressure and/or mechanical forces acting on the tubes are resisted by friction forces developed by the elastic preload that exists between the tube and the tubesheet. For some specific length of engagement of the hardroll, no significant axial forces will be transmitted farther along the tube, and that length of tubing, i.e., F*, will be sufficient to anchor the tube in the tubesheet. In order to determine the value of F* for application in 51 Series steam generators, a test program was conducted to measure the elastic preload of the tubes in the tubesheet.

The presence of the elastic preload also presents a significant resistance to flow of primary-to-secondary or secondary-to-primary water for degradation which has progressed fully through the thickness of the tube. In effect, no leakage would be expected if a sufficient length of hardroll is present. The use of F* in numerous plants has demonstrated the effectiveness of the process, both in terms of tube joint strength and a lack of significant leakage. Additionally, resistance to leakage has also been demonstrated in S/G sleeve to tube joints made within the tubesheet by similar Westinghouse mechanical interference joint processes.

2.1 Determination of Elastic Preload Between the Tube and Tubesheet

Tubes were installed in the Kewaunee steam generators using a hardrolling process which expands the tube to bring the outside surface into intimate contact with the tubesheet hole. The roll process and roll torque are specified to result in a metal to metal interference fit between the tube and the tubesheet.

A test program was conducted by Westinghouse to quantify the magnitude of interference fit between the tube and the tubesheet provided by the factory partial depth hardrolling process. The data generated in these tests have been analyzed to determine the length of hardroll required to preclude axial tube forces from being transmitted farther along the tube, i.e., to establish the F* criterion. The amount of interference was determined by installing tube specimens in collars specifically designed to simulate the tubesheet radial stiffness. The roll expansion process used was the same process which was used during steam generator manufacture. This was done to make specimens which would have the same interference fit contact pressures as the tubes in the S/G.

Once the hardrolling of the test specimens was completed, the simulants of the unit cell of the tubesheet (heavy collars) were removed from the tube specimens and the springback of the tubes was measured. The amount of springback was used in an analysis to determine the magnitude of the interference fit contact pressure; this test pressure was designed to duplicate the as-installed, residual tube to tubesheet radial load in Westinghouse 51 Series steam generators.

2.1.1 Radial Preload Test Configuration Description

The test program was designed to simulate the interface of a tube to tubesheet partial depth hardroll for a 51 Series steam generator. The test equipment and configuration consisted of six cylindrical collars, approximately [ ]^{a,c,e} inches in length, [ ]^{a,c,e} inches in outside diameter (OD), and [ ]^{a,c,e} inch in inside diameter (ID). A mill annealed, Alloy 600 (ASME SB-163), tube specimen, approximately [ ]^{a,c,e} inches long with a nominal [ ]^{a,c,e} outside diameter before rolling, was rolled into each collar using a process which simulated actual tube installation conditions in the factory.

The design of the collars was based on the results of a finite element analysis of a section of the S/G tubesheet to determine radial stiffness and flexibility. The inside diameter of the collar was chosen to match the size of holes drilled in the tubesheet. The outside diameter was selected to provide the same radial stiffness as the tubesheet.

The collars were fabricated from AISI 1018 carbon steel; this steel is similar in mechanical properties to the actual tubesheet material. The collar assembly was clamped in a vise during the rolling process and for the post roll measurements of the tube ID. Following the post-roll measurements, the collars were saw cut to within a small distance from the tube wall. The collars were then split for removal from the tube and tube ID and OD measurements were repeated.

Two end boundary, prototypical, conditions were imposed on the tube specimen during rolling. The end was restrained from axial motion in order to perform a tack roll at the bottom end, and the tube was allowed to expand freely in the axial direction during the hardroll.

2.1.2 Preload Test Results: Discussion and Analysis

All measurements taken during the test program are tabulated in Table 2-1. The data recorded were employed to determine the interfacial conditions of the tubes and collars. Measurements were taken of the ID and OD of the tubes before rolling, of the rolled IDs and after removal from the collars, as well as the IDs and ODs of each collar before and after tube rolling. Two orthogonal measurements were taken at six axial locations within the collars and tubes. Additional data of interest were calculated from these specific dimensions.

The calculated dimensions included wall thickness, change in wall thickness for both rolling and removal of the tubes from the collars, and percent of springback.

Using the measured and calculated physical dimensions, an analysis of the tube deflections was performed to determine the amount of preload radial stress present following the hardrolling. The analysis consisted of application of conventional thick-tube equations to account for variation of structural parameters through the wall thickness. However, traditional application of cylinder analysis considers the tube to be in a state of plane stress. For these tests, the results implied that the tubes were in a state of plane strain elastically. This is in agreement with historical findings that theoretical values for radial residual preload are below those actually measured, and that axial frictional stress between the tube and the tubesheet increases the residual pressure. In a plane stress analysis such stress is taken to be zero (References 3 and 4). Based on this information, the classical equations relating tube deformation and stress to applied pressure were modified to reflect plane strain assumptions.

The standard analysis of thick walled cylinders results in an equation for the radial deflection of the tube as:

$$U = C_1 * r + C_2 / r \qquad (1)$$

where, U = radial deflection
r = radial position within the tube wall,

and the constants, C_1 and C_2 are found from the boundary conditions to be functions of the elastic modules of the material, Poisson's ratio for the material, the inside and outside radii, and the applied internal and external pressures. The difference between an analysis assuming plane stress and one assuming plane strain is manifested only in a change in the constant C_2. The first constant is the same for both conditions. For materials having a Poisson's ratio of 0.3, the following relation holds for the second constant:

$$C_2 \text{ (Plane Strain)} = 0.862 * C_2 \text{ (Plane Stress)} \qquad (2)$$

The effect on the calculated residual pressure is that plane strain results are higher than plane stress results by slightly less than 10 percent. Comparing this effect with the results reported in Reference 3 indicated that better agreement with test values is achieved. It is to be noted that the residual radial pressure at the tube to tubesheet interface is the compressive radial stress at the OD of the tube.

By substituting the expressions for the constants into Equation (1), the deflection at any radial location within the tube wall as a function of the internal and external pressure (radial stress at the ID and OD) is found. This expression was differentiated to obtain flexibility values for the tube deflection at the ID and OD respectively, e.g., dU_i/dP_o is the ratio of the radial deflection at the ID due to an OD pressure. Thus, dU_i/dP_o was used to find the interface pressure and radial stress between the tube and the tubesheet as:

$$S_{ro} = -P_o = -\text{(ID Radial Springback)} / (dU_i/dP_o) \qquad (3)$$

The calculated radial residual stress for each specimen at each location is tabulated in Table 2-2. The mean residual radial stress and the standard deviation were found to be [$]^{a,c,e}$ psi and [$]^{a,c,e}$ psi, respectively. In order to determine a value to be used in the analysis, a tolerance factor for [$]^{a,c,e}$ percent confidence to contain [$]^{a,c,e}$ percent of the population was calculated, considering the [$]^{a,c,e}$ useable data points, to be [$]^{a,c,e}$. Thus, a [$]^{a,c,e}$ lower tolerance limit (LTL) for the radial residual preload at room temperature is [$]^{a,c,e}$ psi.

2.1.3 Residual Radial Preload During Plant Operation

During plant operation the amount of preload will change depending on the pressure and temperature conditions experienced by the tube. The room temperature preload stresses, i.e., radial, circumferential and axial, are such that the material is nearly in the yield state if a comparison is made to ASME Code (Reference 5) minimum material properties. Since the coefficient of thermal expansion of the tube is greater than that of the tubesheet, heatup of the plant will result in an increase in the preload and could result in some yielding of the tube. In addition, the yield strength of the tube material decreases with temperature. Both of these effects may result in the preload being reduced upon return to ambient temperature conditions, i.e., the cold condition. However, as documented in Reference 6 for a similar investigation, tube pullout tests which were preceded by a very high thermal relaxation soak showed the analysis to be conservative.

The plant operating pressure influences the preload directly based on the application of the pressure load to the ID of the tube, thus increasing the amount of interface loading. The pressure also acts indirectly to increase the amount of interface loading by causing the tubesheet to bow upward, i.e., placing the roll expansions near the bottom of the tubesheet in compression for normal operating and feedline break (FLB) conditions (FLB results in a higher primary-to-secondary ΔP than steamline break, hence FLB is used to bound the FLB and SLB cases for this analysis). For the loss of coolant accident (LOCA) event, the tubesheet bows in the opposite direction, producing dilation of the tubesheet holes and reducing the amount of tube to tubesheet preload. Each of these effects may be quantitatively treated.

The maximum amount of increase in preload due to tubesheet bow for primary-to-secondary pressure differential will occur at the bottom, central part of the tubesheet. Because F* is measured from the bottom of the hardroll transition (BRT) and leakage is to be restricted by the F* region of the tube, the potential for the tube section within the F* region to experience a net tightening or loosening during operation is evaluated. However, the central location case is not the most stringent case for normal operation and FLB; rather, the most stringent case for normal operation and FLB involves a peripheral tube, obtained for Case 2 on Table 2-3 for normal operation, which is the case with the maximum primary-to-secondary ΔP. The results for this limiting case are presented in the following sections.

2.1.4 Increase in Radial Preload Due to Thermal Expansion Tightening

For conservatism in determining the total residual preload for normal operating conditions, tightening of the tube/tubesheet joint due to differential thermal expansion is minimized by applying the S/G outlet temperature to the tubing. From the limiting case identified in Section 2.1.3 and Table 2-3, this corresponds to a cold leg temperature of about 530°F. The mean coefficient of thermal expansion for the Alloy 600 tubing between ambient conditions and cold leg operating conditions is approximately $7.74 \cdot 10^{-6}$ in/in/°F. That for the steam generator tubesheet is $7.30 \cdot 10^{-6}$ in/in/°F. These values were reconciled as conservative with respect to the 1965, Summer 1966 Addenda of the ASME Boiler and Pressure Vessel Code, which was the code of construction for the Kewaunee steam generators. Thus, there is a net difference of $0.44 \cdot 10^{-6}$ in/in/°F between the expansion properties of the two materials. Considering an actual temperature difference of 459.8°F between ambient and operating conditions, the increase in preload between the tube (t) and the tubesheet (ts) was calculated as:

$$S_{rT} = (0.44E\text{-}6)*(459.8)*(\text{Collar ID}) / 2 / ((dU_i/dP_i)_{ts} - (dU_o/dP_o)_t) \qquad (4)$$

The results indicate that the increase in preload radial stress due to thermal expansion is [ ]^{a,c,e} psi. Note that this value applies for both normal operating and faulted conditions.

2.1.5 Increase in Radial Preload during N.O. and FLB Due to Differential Pressure

The normal operating (N.O.) differential pressure from the primary to secondary side of the steam generator during the most limiting condition evaluated is 1565 psi (see Table 2-3). The internal pressure acting on the wall of the tube will result in an increase of the radial preload on the order of the pressure value. The increase was found as:

$$S_{rP} = - P_o = - P_i \, (dU_o/dP_i) \, / \, ((dU_i/dP_i)_{ts} - (dU_o/dP_o)_t) \qquad (5)$$

In actuality, the increase in preload will be more dependent on the internal pressure of the tube since water at secondary side pressure would not be expected between the tube and the tubesheet in the rolled region. However, the primary to secondary ΔP is used for conservatism.

The increase in radial contact pressure due to differential pressure was evaluated for both normal operating (ΔP = 1565 psi) and faulted (ΔP = 2650 psi) conditions. The results indicate that the increase in preload radial stress is [$]^{a,c,e}$ psi for normal operating conditions and [$]^{a,c,e}$ psi for postulated faulted (FLB) conditions.

2.1.6 Change in Radial Preload due to Tubesheet Bow

An analysis of the 51 Series tubesheet was performed to evaluate the change in preload stress that would occur as a result of tubesheet bow for interior tubes. The analysis was based on performing finite element analysis of the tubesheet and S/G shell using equivalent perforated plate properties for the tubesheet (Reference 7). Boundary conditions from the results were then applied to a smaller, but more detailed model, in order to obtain results for the tubesheet holes. Basically the deflection of the tubesheet was used to find the stresses active on the bottom surface and then the presence of the holes was accounted for. For the location where the increase of preload is a maximum, the radial preload stress would be increased by [$]^{a,c,e}$ psi during normal operation and [$]^{a,c,e}$ psi during faulted (FLB) conditions.

However, the interior tubes are not the limiting case for primary-to-secondary pressure differential. The limiting case involves peripheral tubes where tubesheet bowing has a negligible effect on tube-to-tubesheet preload. Therefore, the N.O. and FLB analyses address only tubes in the peripheral region of the tubesheet. During LOCA, the differential operating pressure is from secondary to primary. Thus, the radial preload will decrease by [$]^{a,c,e}$ psi as the tubesheet bows downward. However, the action of the differential pressure is such that the tube is pushed toward the tube-to-tubesheet well. This case is of no consequence to the determination of F*.

2.1.7 Net Preload in Roll Transition Region for N.O. and FLB Conditions

Combining the room temperature hardroll preload with the thermal and pressure effects results in a net operating preload of [$]^{a,c,e}$ psi during normal operation and [$]^{a,c,e}$ psi for faulted conditions. In addition to restraining the tube in the tubesheet, this preload should effectively retard leakage from indications in the tubesheet region of the tubes, test results are provided in Reference 1.

2.2 Determination of Required Engagement Distance

The value of F* calculated for application to the Kewaunee steam generators is based on determining the length of hardroll necessary to offset the applied loads during the maximum normal operating conditions or faulted conditions, whichever provides the largest value. Thus, the applied loads are balanced by the load carrying ability of the hardrolled tube for both of the above conditions. In performing the analysis, consideration was made of the potential for the ends of the hardroll at the hardroll transition and the assumed severed condition to have a reduced load carrying capability.

2.2.1 Applied Loads

The applied loads to the tubes which could result in pullout from the tubesheet during all normal and postulated accident conditions are predominantly axial and due to the internal to external pressure differences. For a tube which has not been degraded, the axial pressure load is given by the product of the pressure with the internal cross-sectional area. However, for a tube with internal degradation, e.g., cracks oriented at an angle to the axis of the tube, the internal pressure may also act on the flanks of the degradation. Thus, for a tube which is conservatively postulated to be severed at some location within the tubesheet, the total force acting to remove the tube from the tubesheet is given by the product of the pressure and the cross-sectional area of the tubesheet hole. The force resulting from the pressure and internal area acts to pull the tube from the tubesheet and the force acting on the end of the tube tends to push the tube from the tubesheet. For this analysis, the tubesheet hole diameter has been used to determine the magnitude of the pressure forces acting on the tube. Therefore, the forces acting to remove the tube are: Force = $\Delta P * \pi * 0.89^2/4$ where ΔP = [ ]^{a,c,e} for N.O. conditions and [ ]^{a,c,e} for faulted conditions. The forces acting to remove the tube from the tubesheet are [ ]^{a,c,e} pounds and [ ]^{a,c,e} pounds respectively for normal operating and faulted conditions. Any other forces such as fluid drag forces in the U-bends and vertical seismic forces are negligible by comparison.

2.2.2 Coefficient of Friction at Tube-to-Tubesheet Interface

In order to determine the coefficient of friction between hard-rolled tubes and the tubesheet, pull tests and hydraulic proof tests were conducted on 3/4" diameter Alloy 600 tubing, hard rolled into carbon steel collars with an OD to simulate tubesheet rigidity (similar to the tests described in Section 2.1). After rolling, an inside circumferential cut was machined through the wall of the tube at a controlled distance from the bottom of the roll transition. The samples were heat soaked at [ ]^{a,c,e} to simulate the possible effect of reduced preload force due to tube yielding during manufacturing heat treatment. Two sets of pullout tests were conducted, on a tensile testing machine in air at room temperature, and with internal pressure as the acting force on the tube. The pressure tests were performed at room temperature using deionized water. The pull tests performed with the tensile testing machine showed a static coefficient of friction of [ ]^{a,c,e}. For samples which were expelled from the collars during the hydraulic proof tests, the coefficient of friction was determined to range from [ ]^{a,c,e}. For tubes that leaked before tube expulsion, resulting in termination of the tests before expulsion, the lower bound coefficients of friction were determined to range from [ ]^{a,c,e}. On the basis of these results, the use of a coefficient of friction of [ ]^{a,c,e} is considered to be conservative for the 7/8" tubes in the Kewaunee steam generators for application in determining the required engagement distance to resist tube pullout forces.

2.2.3 End Effects

For a tube which is postulated to be severed within the tubesheet there is a material discontinuity at the location where the tube is severed. There is also a discontinuity considered at the upper roll transition. For a small distance from each assumed discontinuity the stiffness, and hence the radial preload, of the tube is reduced relative to that remote from the ends of the roll expansion. For conservatism, the radial preload for a smal distance from the upper roll transition is assumed to experience the same reduction in radial preload as it would if the tube were severed. The analysis of end effects in thin cylinders is based on the analysis of a beam on an elastic foundation. For a tube with a given radial deflection at the end, the deflection of points away from the end relative to the end deflection is given by:

$$u_{rx} / u_{ro} = e^{-\lambda x} * \text{cosine} (\lambda * x) \qquad (6)$$

where, λ = [ ]^{a,c,e} = end effect constant.
x = distance from the end of the tube.

For the radially preloaded tube, the distance for the end effects to become negligible is the location where the cosine term becomes zero. Thus, for the roll expanded 51 Series tubes the distance corresponds to the product of "λ" times "x" being equal to ($\pi/2$) or [ ]^{a,c,e} inch. Figure 2-1 shows a roll expansion which is postulated to be severed at the bottom of the F* region. For a distance of [ ]^{a,c,e} inch above the severed end and below the bottom of the roll transition, the expanded joint has a reduced radial load carrying capability relative to the remainder of the F* length. The effective radial preload carried by these "end-effect" regions is calculated as follows.

The above equation can be integrated to find the average deflection over the affected length to be 0.384 of the end deflection. This means that, on the average, the stiffness of the material over the affected length is 0.616 of the stiffness of the material remote from the ends. Therefore, the effective preload for the affected end lengths is 61.6 percent of the preload at regions more than [ ]^{a,c,e} inch from the ends. For example, for the normal operating net preload of [ ]^{a,c,e} psi or [ ]^{a,c,e} pounds per inch of length, the effective preload for a distance of [ ]^{a,c,e} inch from the end is [ ]^{a,c,e} pounds per inch of axial length or [ ]^{a,c,e} pounds.

2.2.4 Calculation of Engagement Distance Required, F*

The calculation of the required engagement distance is based on determining the length for preload frictional forces to equilibrate the applied operating loads. The axial friction force was found as the product of the radial preload force and the coefficient of friction between the tube and the tubesheet. The value assumed for the coefficient of friction was [ ]^{a,c,e}, from Reference 6. For normal operation the radial preload is [ ]^{a,c,c} psi or [ ]^{a,c,e} pounds per inch of engagement. Thus, the axial friction resistance force is [ ]^{a,c,c} pounds per inch of engagement. It is to be noted that this value applies away from the ends of the tube. For any given engagement length, the total axial resistance is the sum of that provided by the two ends plus that provided by the length minus the two end lengths. From the preceding section the axial resistance of each end is [ ]^{a,c,e} pounds. Considering both ends of the presumed severed tube, i.e., the hardroll transition is considered one end, the axial resistance is [ ]^{a,c,e} pounds plus the resistance of the material between the ends, i.e., the total length of engagement minus [ ]^{a,c,e} inch. For example, a one inch length has an axial resistance of,

[ ]^{a,c,e}

Conversely, for the maximum normal operating pressure applied load of [ ]^{a,c,e} pounds, considered as [ ]^{a,c,e} pounds with a safety factor of 3, the length of hardroll required is given by,

F* = [ ]^{a,c,e} = 1.12 inches.

Similarly, the required engagement length for faulted conditions can be found to be 0.79 inch using a safety factor of 1.43 (corresponding to a ASME Code safety factor of 1.0/0.7 for allowable stress for faulted conditions).

The calculation of the above values is summarized in Table 2-4. The F* value thus determined for the required length of hardroll engagement below the BRT, for normal operation is sufficient to resist tube pullout during both normal and postulated accident condition loadings.

Based on the results of the testing and analysis, it is concluded that following the installation of a tube by the standard hardrolling process or the application of an additional roll expansion, a residual radial preload stress exists due to the plastic deformation of the tube and tubesheet interface. The residual stress restrains the tube in the tubesheet while providing a leak limiting seal condition, provided a sufficient length of undegraded tubing exists below the bottom of the roll transition.

2.3 Limitation of Primary to Secondary Leakage

The allowable amount of primary to secondary leakage in each Kewaunee steam generator during normal plant operation is limited by plant technical specifications to 0.104 gpm (150 gpd). This limit, based on plant radiological release considerations and implicitly enveloping the leak before break consideration for a throughwall crack in the free span of a tube, is also applicable to a leak source within the tubesheet. In evaluating the primary to secondary leakage aspect of the F* criterion, the relationship between the tubesheet region leak rate at postulated FLB conditions (which bound SLB for primary-to-secondary pressure differential considerations) is assessed relative to that at normal plant operating conditions.

The analysis was performed by assuming the existence of a leak path; however, no actual leak path would be expected due to the hardrolling of the tubes into the tubesheet.

2.3.1 Operating Condition Leak Considerations

In actuality, the hardrolled joint would be expected to be leak tight, i.e., the plant would not be expected to experience leak sources emanating below F*. Because of the presence of the tubesheet, tube indications are not expected to increase the likelihood that the plant would experience a significant number of leaks. It could also be expected, that if primary to secondary leakage is detected in a steam generator it will not be in the tube region below F*. Thus, no significant radiation exposure due to the need for personnel to look for tube/tubesheet leaks should be anticipated, i.e., the use of the F* criterion is consistent with ALARA considerations. As an additional benefit relative to ALARA considerations, precluding the need to install plugs below the F* criterion would result in a significant reduction of unnecessary radiation exposure to installing personnel.

The issue of leakage within the F* region up to the top of the roll transition (RT) includes the consideration of postulated accident conditions in which the violation of the tube wall is very extensive, i.e., that no material is required at all below F*. Based on operating plant and laboratory experience the expected configuration of any cracks, should they occur, is axial. The existence of significant circumferential cracking is considered to be of very low probability. Thus, consideration of whether or not a plant will come off-line to search for leaks a significant number of times should be based on the type of degradation that might be expected to occur, i.e., axial cracks. Axial cracks have been found both in plant operation and in laboratory experiments to be short, about 0.5 inch in length, and tight. From field experience, once the cracks have grown so that the crack front is out of the skiproll or transition areas, they arrest.

Axial cracks in the free span portion of the tube, with no superimposed thinning, would leak at rates compatible with the technical specification acceptable leak rate. For a crack within the F* region of the tubesheet, expected leakage would be significantly less. Leakage through cracks in tubes has been investigated experimentally within Westinghouse for a significant number of tube wall thicknesses and thinning lengths (Reference 8). In general, the amount of leakage through a crack for a particular size tube has been found to be approximately proportional to the fourth power of the crack length. Analyses have also been performed which show, on an approximate basis for both elastic and elastic-plastic crack behavior, that the expected dependency of the crack opening area for an unrestrained tube is on the order of the fourth power, e.g., see NUREG CR-3464. The amount of leakage through a crack will be proportional to the area of the opening, thus, the analytic results substantiate the test results.

The presence of the tubesheet will preclude deformation of the tube wall adjacent to the crack, i.e., the crack flanks, and the crack opening area may be considered to be directly proportional to the length. The additional dependency, i.e., fourth power relative to first power, is due to the dilation of the unconstrained tube in the vicinity of the crack and the bending of the side faces or flanks of the crack. For a tube crack located within the tubesheet, the dilation of the tube and bending of the side faces of the crack are suppressed. Thus, a 0.5 inch crack located within the F* region up to the top of the roll transition would be expected to leak, without considering the flow path between the tube and tubesheet, at a rate less than a similar crack in the free span, i.e., less than the Kewaunee technical specification limit of 0.104 gpm. Additional resistance provided by the tube-to-tubesheet interface would reduce this amount even further, and in the hardroll region the residual radial preload would be expected to eliminate it. This conclusion is supported by the results of the preload testing and analysis which demonstrated that a residual preload of nearly [ ]^{a,c,e} psi exists between the tube and the tubesheet at normal operating conditions.

2.3.2 Postulated Accident Condition Leak Considerations

For the postulated leak source within the RE, increasing the tube differential pressure increases the driving head for the leak and increases the tube to tubesheet loading. For an initial location of a leak source below the BRT equal to F*, the FLB pressure differential results in an insignificant leak rate relative to that which could be associated with normal plant operation. This small effect is reduced by the increased tube to tubesheet loading associated with the increased differential pressure as well as the tightening contribution of the tubesheet bending. Thus, for a circumferential indication within the RE which is left in service in accordance with the pullout criterion (F*), the existing technical specification limit is consistent with accident analysis assumptions. For postulated accident conditions, the preload testing and analysis showed that a net radial preload of about [ ]^{a,c,e} psi would exist between the tube and tubesheet.

For axial indications in a partial depth hardrolled tube below the BRT, the tube end remains structurally intact and axial loads would be resisted by the remaining hardrolled region of the tube. For this case, the leak rate due to FLB differential pressure would be bounded by the leak rate for a free span leak source with the same crack length, which is the basis for the accident analysis assumptions.

2.3.3 Operating Plant Leakage Experience for Within-Tubesheet Tube Cracks

A significant number of within-tubesheet tube indications have been reported for some non-domestic steam generator units. The present attitude toward operation with these indications present has been to tolerate them with no remedial action relative to plugging or sleeving. No significant number of shutdowns occurring due to leaks through these indications have been reported.

2.4 Tube Integrity Under Postulated Limiting Conditions

The final aspect of the evaluation is to demonstrate tube integrity under the postulated loss of coolant accident (LOCA) condition of secondary to primary differential pressure. A review of tube collapse strength characteristics indicates that the constraint provided to the tube by the tubesheet gives a significant margin between tube collapse strength and the limiting secondary to primary differential pressure condition, even in the presence of circumferential or axial indications.

The maximum secondary to primary differential pressure during a postulated LOCA is [ ]^{a,c,e} psi. This value is significantly below the residual radial preload between the tubes and the tubesheet. Therefore, no significant secondary to primary leakage would be expected to occur. In addition, loading on the tubes is axially toward the tubesheet and could not contribute to pullout.

2.5 Chemistry Considerations

The concern that boric acid attack of the tubesheet due to the presence of a through wall flaw within the hardroll region of the tubesheet may result in loss of contact pressure assumed in the development of the F* criterion is addressed below. In addition, the potential for the existence of a lubricated interface between the tube and tubesheet as a result of localized primary to secondary leakage and subsequent effects on the friction coefficient assumed in the development of the F* criterion is also discussed.

2.5.1 Tubesheet Corrosion Testing

Corrosion testing performed by Westinghouse specifically addressed the question of corrosion rates of tubesheet material exposed to reactor coolant. The corrosion specimens were assembled by bolting a steel (A336) coupon to an Alloy 600 coupon. The coupon dimensions were 3 inches x 3/4 inch x 1/8 inch and were bolted on both ends. A torque wrench was used to tighten the bolts to a load of 3 foot-pounds. The performance of A508 in testing of this nature is expected to be quite comparable to the performance of A336 (Gr. F-1) steel (a material used for tubesheet construction prior to A508). The arguments used in supporting the F* case relative to corrosion of tubesheet material due to minute quantities of primary coolant contacting the carbon steel were so conservative and had such margin that minor differences in material composition or strength would not change the conclusion.

The specimens were tested under three types of conditions:

1. Wet-layup conditions
2. Wet-layup and operating conditions
3. Operating conditions only

The wet-layup condition was used to simulate shutdown conditions at high boric acid concentrations. The specimens were exposed to a fully aerated 2000 ppm boron (as boric acid) solution at 140 degrees F. Exposure periods were 2, 4, 6, and 8 weeks. Test solutions were refreshed weekly.

While lithium hydroxide is normally added to the reactor coolant as a corrosion inhibitor, it was not added in these tests in order to provide a more severe test environment. Previous testing by Westinghouse has shown that the presence of lithium hydroxide reduces corrosion of Alloy 600 and steel in a borated solution at operating temperatures.

Another set of specimens were used to simulate startup conditions with some operational exposure. The specimens were exposed to a 2000 parts per million boron (as boric acid) solution for one week in the wet-layup condition (140°F), and 4 weeks at operating conditions (600°F, 2000 psi). During wet layup, the test solution was aerated but at operating conditions the solution was deaerated. The high temperature testing was performed in an Alloy 600 autoclave. Removal of oxygen was attained by heating the solution in the autoclave to 250°F and then degassing. This method of removing the oxygen results in oxygen concentrations of less than 100 parts per billion.

Additional specimens were exposed under operating conditions only for 4 weeks in the autoclave as described above.

High temperature exposure to reactor coolant chemistry resulted in steel corrosion rates of about 1 mil per year. This rate was higher than would be anticipated in a steam generator since no attempt was made to completely remove the oxygen from the autoclave during heatup. Even with this amount of corrosion, the rate was still a factor of nine less than the corrosion rate observed during the low temperature exposure. This differential corrosion rate observed between high and low temperature exposure was expected because of the decreasing acidity of the boric acid at high temperatures and the corrosive effect of the high oxygen at low temperatures.

These corrosion tests are considered to be very conservative since they were conducted at maximum boric acid concentrations, in the absence of lithium hydroxide, with no special precaution to deaerate the solutions, and they were of short duration. The latter point is very significant since parabolic corrosion rates are expected in these types of tests, which leads one to overestimate actual corrosion rates when working with data from tests of short duration.

Also note that the ratio of solution to surface area is high in these tests compared to the scenario of concern, i.e., corrosion caused by reactor coolant leakage through a tube wall into the region between the tube and the tubesheet.

2.5.2 Tubesheet Corrosion Discussion

At low temperatures, e.g., less than 140 degrees F, aerated boric acid solutions comparable in strength to primary coolant concentrations can produce corrosion of carbon steels. Deaerated solutions are much less aggressive and deaerated solutions at reactor coolant temperatures produce very low corrosion rates due to the fact that boric acid is a very much weaker acid at high temperature, e.g., 610 degrees F, than at 70 degrees F.

In the event that a crack occurred within the hardroll region of the tubesheet, as the amount of leakage would be expected to be insufficient to be noticed by leak detection techniques and is largely retained in the crevice, then a very small volume of primary fluid would be involved. Any oxygen present in this very small volume would quickly be consumed by surface reactions, i.e., any corrosion that would occur would tend to cause existing crevices to narrow due to oxide expansion and, without a mode for replenishment, would represent a very benign corrosion condition. In any event the high temperature corrosion rate of the carbon steel in this very local region would be extremely low (significantly less than 1 mil per year).

Contrast the proposed concern for corrosion relative to F* with the fact that Westinghouse has qualified boric acid for use on the secondary side of steam generators where it is in contact with the full surface of the tubesheet and other structural components made of steel. The latter usage involves concentrations of 5 - 10 ppm boron, but, crevice flushing procedures have been conducted using concentrations of 1000 to 2000 ppm boron on the secondary side (at approximately 275 degrees F where boric acid is more aggressive than at 610 degrees F).

Relative to the lubricating effects of boron, the presence of boric acid in water may change the wetting characteristics (surface tension) of the water but Westinghouse is not aware of any significant lubricating effect. In fact, any corrosion that would occur would result in oxides that would occupy more space than the parent metals, thus reducing crevice volume or possibly even merging the respective oxides.

2.6 Summary of F* Evaluation

On the basis of this evaluation, it is determined that tubes with eddy current indications in the tubesheet region below the F* pullout criterion of 1.12 inches can be left in service. Tubes with circumferentially oriented eddy current indications of pluggable magnitude and located a distance less than F* below the bottom of the hardroll transition should be removed from service by plugging or repaired in accordance with the plant technical specification plugging limit. The conservatism of the F* criterion was demonstrated by preload testing and analysis commensurate with the requirements of RG 1.121 for indications in the free span of the tubes.

The application of F* in this report addresses existing roll expansions, performed in the factory. The approach may also be applied to roll expansions which are added to the S/G T/TS joints of the partial depth roll expansion design, such as the design of the steam generators at Kewaunee

Table 2-1
Model 51 SG Tube Roll Preload Test - Test Data

a,c,e

Test Location		Collar ID Pre-Roll			Collar OD Pre-Roll			Tube ID Before Roll			Tube OD Before Roll		
No.	No.	0 Deg.	90 Deg.	Avg.	0 Deg.	90 Deg.	Avg.	0 Deg.	90 Deg.	Avg.	0 Deg.	90 Deg.	Avg.
1	1												
	2												
	3												
	4												
	5												
	6												
	Average												
2	1												
	2												
	3												
	4												
	5												
	6												
	Average												
3	1												
	2												
	3												
	4												
	5												
	6												
	Average												
6	1												
	2												
	3												
	4												
	5												
	6												
	Average												
7	1												
	2												
	3												
	4												
	5												
	6												
	Average												
8	1												
	2												
	3												
	4												
	5												
	6												
	Average												
Col. Avgs:													

Table 2-1 (Continued)
Model 51 SG Tube Roll Preload Test - Test Data

a,c,e

Test Location			Collar OD Post-Roll				Tube ID Post-Roll				Tube ID Post-Roll Collar Removed		
No.	No.	Pre-Roll Thickness	0 Deg.	90 Deg.	Avg.	Collar Delta	0 Deg.	90 Deg.	Avg.	Tube ID Growth	0 Deg.	90 Deg.	Avg.
1	1												
	2												
	3												
	4												
	5												
	6												
	Average												
2	1												
	2												
	3												
	4												
	5												
	6												
	Average												
3	1												
	2												
	3												
	4												
	5												
	6												
	Average												
6	1												
	2												
	3												
	4												
	5												
	6												
	Average												
7	1												
	2												
	3												
	4												
	5												
	6												
	Average												
8	1												
	2												
	3												
	4												
	5												
	6												
	Average												
Col. Avgs:													

Table 2-1 (Continued)
Model 51 SG Tube Roll Preload Test - Test Data

a,c,e

Test Location		Tube OD Post-Roll Collar Removed			Post-Roll	Thickness	Collar Flex.	Radii Ratio	Tube ID Spring-
No.	No.	0 Deg.	90 Deg.	Avg.	Thick.	Red.	dU_i/dP_i	(4)	Back
1	1								
	2								
	3								
	4								
	5								
	6								
	Average								
2	1								
	2								
	3								
	4								
	5								
	6								
	Average								
3	1								
	2								
	3								
	4								
	5								
	6								
	Average								
6	1								
	2								
	3								
	4								
	5								
	6								
	Average								
7	1								
	2								
	3								
	4								
	5								
	6								
	Average								
8	1								
	2								
	3								
	4								
	5								
	6								
	Average								
Col. Avgs:									

Notes:
1. All measured dimensions are in inches.
2. The OD stress is calculated using the measured ID springback.
3. The radii ratio is a term that appears frequently in the analysis and is found as $(OD^2+ID^2)/(OD^2-ID^2)$.

Table 2-2
Model 51 SG Tube Roll Preload Test - Stress Analysis Results

a,c,e

Test Location No.	No.	Tube ID Spring-Back	Tube Flex. dU_i/dP_o	Tube Flex. dU_o/dP_o	OD Radial Stress	OD Hoop Stress	OD Axial Stress	Thermal Exp. Radial Stress	Tube Flex. dU_o/dP_i	Oper. Pressure Radial Stress	Total Radial Stress	Total vonMises Stress
1	1											
	2											
	3											
	4											
	5											
	6											
	Average											
2	1											
	2											
	3											
	4											
	5											
	6											
	Average											
3	1											
	2											
	3											
	4											
	5											
	6											
	Average											
6	1											
	2											
	3											
	4											
	5											
	6											
	Average											
7	1											
	2											
	3											
	4											
	5											
	6											
	Average											
8	1											
	2											
	3											
	4											
	5											
	6											
	Average											
Col. Avgs:												

Notes: 1. The OD stress is calculated using the measured ID springback.

Table 2-3
Calculation of F* and EF* Lengths for T/TS Hardroll Interface-Kewaunee Nuclear Powar Plant

Maximum RCS Pressures for all PCWG Cases

a,c

Case	% Tube Plugging	RCS Pressure (psia)	Steam Pressure (psia)	Pri-Sec Delta P (psia)	Thot (deg. F)	Tcold (deg. F)	Limiting (1) Diff Temp (deg. F)	Delta P Ratio (2)	Tcold T ratio (3)	N.O. Srp (4) (psi)	Srt (5) (psi)	Hardroll Preload (psi)	Bending Srb (psi)	Total Sr (6) (psi)	N.O. Pr (7) (lb/in)	N.O. Pend (8) (lb)	Pa (9) (lb)	3Pa (lb)	N.O. F* (10) (in.)
EF*, top of RT 4 inches below top of TS																			
1	25%	2250	685	1565	592.1	532.6													
F*, up to 10.5 inches above TS bottom																			
2	25%	2250	685	1565	592.1	532.6													

a,c

Table 2-4
Preload Analysis Summary for F* Evaluation

Material Properties:		Tube/Tubesheet Dimensions (Tested): a,c
Elastic Modulus	28.7E+06	Init. Avg. Tube OD
Poisson's Ratio	0.30	Init. Avg. Tube Thickness
I600 Coeff. of Therm. Exp.	7.74E-06 in/in/°F	Init. Avg. Tubesheet ID
TS Coeff. of Therm. Exp.	7.30E-06 in/in/°F	Actual Thinning
Operating ΔT	459.8	Apparent Thinning
N.O. ΔP	1565 psi	
Faulted ΔP	2650 psi	

Additional Analysis Input:

Tubesheet Bow Stress Reduction	a,c	Coefficient of Friction
N.O.		
FLB		End Effects:
		Mean Radius (Rolled)
Lower Tolerance Limit Factor		Thickness (Rolled)
95/95 LTL	2.16 (N=36)	λ
		End Effect Length
		Load Factor

EVALUATION OF REQUIRED ENGAGEMENT LENGTH, F*

Elastic Analysis:	N.O.	FLB
RT Preload (LTL)		a,c
Thermal Expansion Prcload		
Pressure Preload		
Tubesheet Bow Loss		
Net Preload		
Net Radial Force		
Net Axial Resistance		
Applied Load		
Analysis Load		
End Effect Resistance		
Net Analysis Load		
End Effect Length		
Add. Length Required		
Total Length Required, F*	1.12 in.	0.79 in.

Table 2-4 (continued)

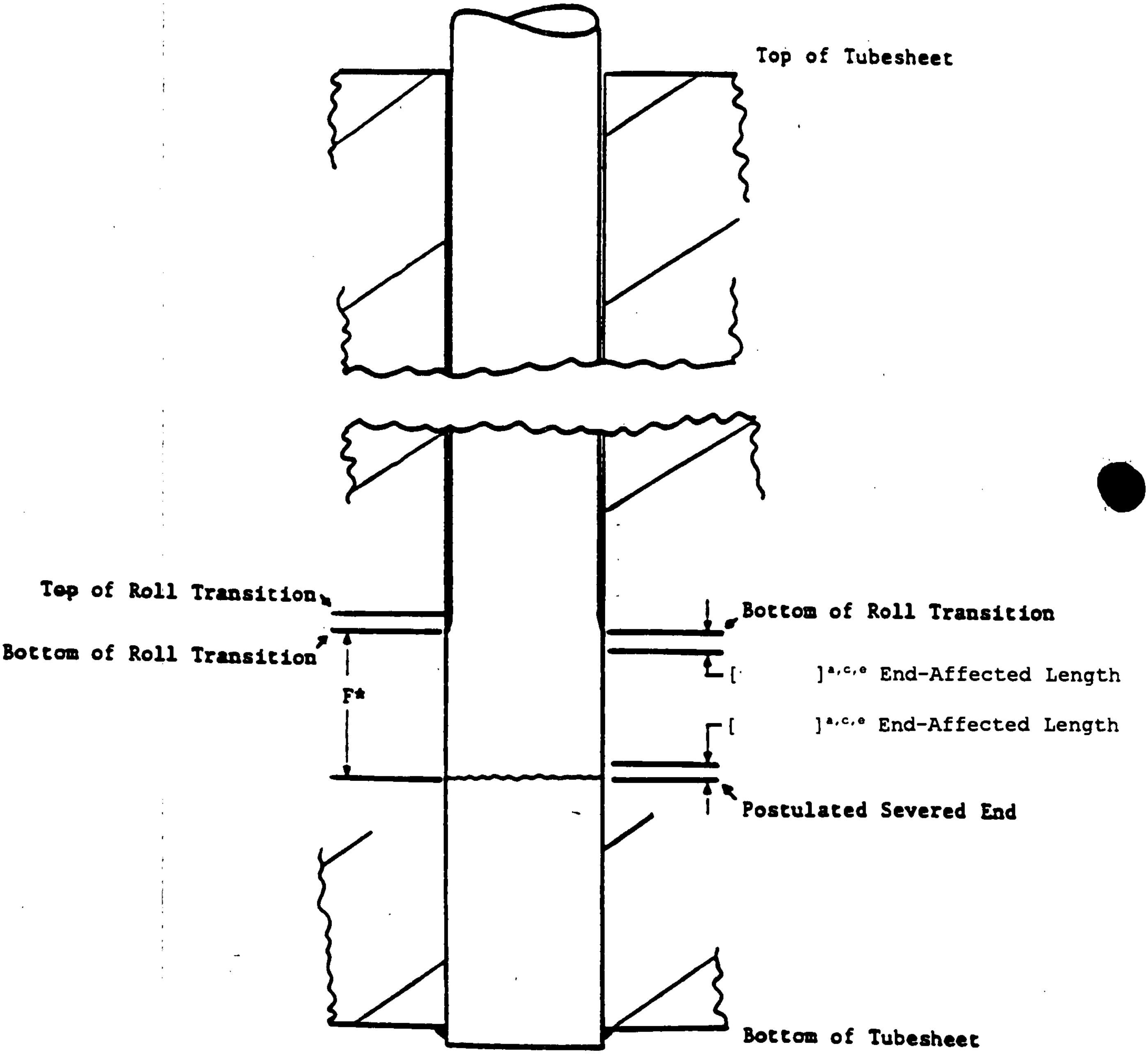
Preload Analysis Summary for F* Evaluation

NOTES:

1) 95/95 Lower Tolerance Limit rolled preload used.
2) For Normal Operation, a safety factor of 3.0 is used.
3) For Faulted Conditions, a safety factor of 1.43 is used (corresponding to ASME Code use of 0.7 on ultimate strength.
4) The required length does not include eddy current inspection uncertainty for the location of the bottom of the hard roll.
5) Preload stresses used were for the most stringent case, i.e., cold leg, peripheral location. The chosen location minimizes the thermal expansion preload and eliminates the preload due to tubesheet bowing.

Figure 2-1

"End-Effect" Regions in a Tube Postulated to be Severed at the Bottom of F* Length



3.0 DEVELOPMENT OF RETROFIT F* AND EF* CRITERIA

As stated earlier, the KNPP steam generators are of the partial-depth roll-expanded tube joint design and degradation within a specified portion of the factory roll expansion is addressed by F*. This specified portion of the factory roll is that portion of the roll below F*. For tubes which exhibit degradation <u>within</u> the intended F* distance in the factory roll or a short distance above it in the factory roll transition (0.25 inch above the bottom of the roll transition) or slightly above the BRT, the roll expansion can be extended upward by a field-applied, modified-after-operation, "retrofit" process. The additional roll expansion length is ideally equal to the F* length. In actuality, the additional roll may be slightly longer than F* to account for uncertainties in the nondestructive examination processes which are used to determine crack tip elevations and the roll expansion elevations. The additional roll expansion of this length will be limited to the lower half of the thickness of the tubesheet and it will be referred to as the additional roll expansion (ARX). It will therefore be beneath the neutral bending axis (NBA) of the tubesheet which is at the approximate vertical mid-thickness of the tubesheet. Application of additional roll expansion and F* above and adjacent to the factory roll and below the NBA is shown Reference 1. Reference 1 shows that the factory and retrofit roll expansions have approximately equal pullout resistance.

Both the factory F* and the ARX F* length exhibit negligible leakage. The ARX leakage table of Reference 1 shows that, averaging all of the N.O. leak test data, the average leakage was approximately 0.6 dpm per repaired tube. If all of the nonsleeved tubes in either KNPP S/G, fewer than 1000 tubes, were retrofit rolled, the total leakage would be approximately 12 gpd. (Note: There are approximately 75,000 drops in one gallon.) This is only 8 percent of the permissible, per-S/G, primary-to-secondary leakage of 150 gpd or only 24 percent of a reasonable fraction of the 150 gpd permissible leakage, such as one-third, or 50 gpd. This leakage is negligible. A similar calculation for the SLB/FLB condition produced an average leakage of approximately 0.74 dpm per repaired tube; for 1000 tubes per S/G, the total leakage would be approximately 14 gpd. This is only 0.03 percent of the 34 gpm permissible flow during this condition and is considered negligible. Even considering allocating only one-third of the 34 gpm to this potential source of primary-to-secondary leakage, the 14 gpd is still a negligible value.

For tubes which exhibit degradation more than slightly above the BRT of the factory roll, an elevated additional roll expansion (EARX) and elevated F* (EF*) criterion can be used. The EF* criterion can be applied to the retrofit roll expanded portions of the tube joint <u>above</u> the NBA. The applicability of EF* is based on the results of the separate qualification of EARX, as projected to the above-NBA elevation. This evaluation involves determination of the tube pullout and leakage resistance of the elevated additional roll expansion. Theoretically, the projected elevation of the EARX and the associated EF* could range from the NBA to the tubesheet top. However, the top of the selected elevation is approximately 17 inches above the tubesheet bottom; the EF* distance is reckoned downward from this point. In the use of ARX below the NBA, the presence of foreign matter such as sludge in the tube-to-tubesheet crevice did not appreciably reduce the effective coefficient of friction from the factory, nonsludge condition. This conclusion was based on the comparable pullout resistance of the two designs. It is assumed that that same coefficient of friction will also apply to the elevated location, above the NBA. Therefore, the axial length of roll expansion required at the approximately 17 inch elevation above the tubesheet bottom will be determined only by the local contact pressure. The local contact pressure at this elevation, above the NBA, is reduced relative to the value below the NBA due to tubesheet upward bending and the attendant, minor, tubesheet hole dilation. Tube-to-tubesheet contact pressure in EARX follows the same consideration as discussed in Section 2.0, except that the effect of tubesheet bow loosening must be considered in the calculation of EARX for the tubesheet-upward-bending conditions. Unlike the condition for F*length requirements below the NBA, the reduction of contact pressure above the NBA must be considered for EF* for N.O. and other tubesheet-upward-bending conditions such as feedline break/steamline break (FLB/SLB). The contact pressure reductions due to upward bending conditions must be subtracted from the beneficial effects of thermal growth mismatch, (TGM), differential pressure tightening (DPT) and the as-installed interference fit contact pressure. Due to the reduced tube radial loading, a greater length of sound tube expansion, i.e., an expanded length of tube which has no detectible degradation, is required above the NBA than below it.

In the calculation of EF* at a given elevation, the tubesheet bow loosening (TBL) effect is a function of radial location from the tubesheet vertical centerline. The most loosening occurs at the location of tubesheet maximum rotation. This occurs at a radius of approximately 7.00 inches from the tubesheet vertical centerline. At the bundle periphery, the loosening effect is a minimum. Therefore, EF* ranges from the F* value at the periphery, at a given elevation, to the maximum value at the seven-inch radius point. Due to the variation in TBL, the EF* value could be calculated as a function of location. However, in the interest of simplicity of application, it is recommended that a constant EF* length, at a given elevation, be used. As with F*, EF* is calculated for the cold leg, where the TGM is minimized. Therefore, EF* is conservatively applied to the hot leg, where it will be essentially exclusively applied.

During LOCA, the secondary side pressure is approximately 1,000 psi; the primary side pressure approximates zero. Thus, the tubesheet bends downward and the tube-to-tubesheet contact pressure will increase for most of the tubes at the tubesheet top and proportionately less for lower elevations, down to the NBA. The action of the differential pressure is such that the tube is pushed toward the tube-to-tubesheet weld and the LOCA case is of no consequence to the determination of EF*.

The intended location of the elevated retrofit joint was also evaluated in terms of the potential effect from denting corrosion. It is expected that if denting corrosion is present, it would occur primarily in the vicinity of the tubesheet top, probably affecting or preventing retrofit roll expansion there. For this reason, the approximate elevation of 17 inches was selected for the top of the EARX joint.

3.1 Details of Determination of EF* Based on Structural Requirements

Calculations for EF* use the same methodology as the F* calculations in Section 2, and are not shown here. The EF* results are shown in Table 3-1. Figure 1-3 depicts the EF* length. The major change to the analysis results from the fact that dilatation of the tubesheet holes results in a loss of preload on the order of 1300 psi during normal operation and 2300 psi during a postulated FLB event. Hence, F* increases from 1.12" to 1.44" during normal operation, and from 0.79" to 1.15" during a postulated FLB event (note that the normal operation values govern setting the criterion).

3.2 Limitation of Primary to Secondary Leakage

The allowable amount of primary-to-secondary leakage in each KNPP steam generator during normal operation is 150 gpd. In evaluating the maximum number of tubes which can be dispositioned by EF*, approximately 1,000 in the bounding S/G, the average leakage per tube was considered because the ARX/EARX process exhibits extremely small, but finite leakage in laboratory tests, Ref. 1. It was concluded that this average per-tube leakage is a negligibly small fraction of the permissible leakage. Leakage was not an issue for F* for the factory roll expansions because factory roll expansions of F* length exhibited essentially zero leakage in the tests. Similarly, no leakage from F* tubes has been reported in the numerous plants which have used it for up to approximately 10 years.

3.3 Summary of Retrofit F* and EF* Evaluations

This evaluation determined that tubes with indications of degradation in the as-fabricated unexpanded portion of the tube joint may be modified by additional roll expansion above the factory roll and kept in service. Lengths of retrofit F* and EF* were determined for roll expansions which produce approximately the same interference fit radial contact pressure between the tube and tubesheet as the factory roll.

The values for retrofit F* and EF*, 1.12 inches and 1.44 inches, respectively, were determined for two elevations in the tubesheet and are depicted in Figure 1-2 for F* adjacent to the factory roll and in Figure 1-3 for the EF* case, i.e., at the approximate 17 inch-elevation-above-tubesheet bottom and downward, elevation.

Table 3-1
Preload Analysis Summary for EF* Evaluation

Material Properties:		Tube/Tubesheet Dimensions (Tested):	a,c
Elastic Modulus	28.7E+06	Init. Avg. Tube OD	
Poisson's Ratio	0.30	Init. Avg. Tube Thickness	
I600 Coeff. of Therm. Exp.	7.74E-06 in/in/°F	Init. Avg. Tubesheet ID	
TS Coeff. of Therm. Exp.	7.30E-06 in/in/°F	Actual Thinning	
Operating ΔT	459.8	Apparent Thinning	
N.O. ΔP	1565 psi		
Faulted ΔP	2650 psi		
Additional Analysis Input:			
Tubesheet Bow Stress Reduction	a,c	Coefficient of Friction	
N.O.			
FLB		End Effects:	
		Mean Radius (Rolled)	
Lower Tolerance Limit Factor		Thickness (Rolled)	
95/95 LTL	2.16 (N=36)	λ	
		End Effect Length	
		Load Factor	

EVALUATION OF REQUIRED ENGAGEMENT LENGTH, EF*

Elastic Analysis:	N.O.	FLB
		a,c
RT Preload (LTL)		
Thermal Expansion Preload		
Pressure Preload		
Tubesheet Bow Loss		
Net Preload		
Net Radial Force		
Net Axial Resistance		
Applied Load		
Analysis Load		
End Effect Resistance		
Net Analysis Load		
End Effect Length		
Add. Length Required		
Total Length Required, F*	1.44 in.	1.15 in.

Table 3-1 (continued)

Preload Analysis Summary for EF* Evaluation

NOTES:

1) 95/95 Lower Tolerance Limit rolled preload used.
2) For Normal Operation, a safety factor of 3.0 is used.
3) For Faulted Conditions, a safety factor of 1.43 is used (corresponding to ASME Code use of 0.7 on ultimate strength.
4) The required length does not include eddy current inspection uncertainty for the location of the bottom of the hard roll.
5) Preload stresses used were for the most stringent case, i.e., cold leg, peripheral location. The chosen location minimizes the thermal expansion preload and eliminates the preload due to tubesheet bowing.

4.0 REFERENCES

1. WCAP-14679, "Qualification of Additional Roll Expansion for the Kewaunee Nuclear Power Plant Steam Generators", June, 1996. (Proprietary)

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5. ASME Boiler and Pressure Vessel Code, Section III, "Rules for Construction of Nuclear Vessels," The American Society of Mechanical Engineers, New York, New York, 1965 Edition.

6. WCAP-11241, "Tubesheet Region Plugging Criterion for the Central Nuclear de ASCO, ASCO Nuclear Station Units 1 and 2 Steam Generators", October, 1986. (Proprietary)

7. Thurman, A. L., "Tube/Tubesheet Contact Pressures for Kewaunee Steam Generators", Letter NSD-JLH-6179, June 3, 1996 (Proprietary)

8. WCAP-10949, "Tubesheet Region Plugging Criterion for Full Depth Hardroll Expanded Tubes," Westinghouse Electric Corporation, September, 1985. (Proprietary)