Vogtle Electric Generating Plant Units 1 and 2
License Amendment Request to Revise Technical Specification (TS)
Sections 5.5.9, "Steam Generator (SG) Program" and TS 5.6.10,
"Steam Generator Tube Inspection Report" for Interim Alternate Repair Criterion

Enclosure 5

Westinghouse Electric Company LLC, LTR-CDME 08-11-NP, "Interim Alternate Repair Criterion (ARC) for Cracks in the Lower Region of the Tubesheet Expansion Zone," dated January 31, 2008 (Non-Proprietary)

LTR-CDME-08-11 NP-Attachment

Interim Alternate Repair Criterion (ARC) for Cracks in the Lower Region of the Tubesheet Expansion Zone

January 31, 2008

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1.0 INTRODUCTION

An alternate repair criterion (ARC) to limit the inspection depth in the tubesheet expansion zone, known as H*/B*, has been docketed by Wolf Creek Nuclear Operating Corporation since February 2006 and has been undergoing NRC review since that time. The H*/B* ARC seeks to minimize the depth of rotating coil inspection of the SG tubes within the tubesheet. The premise of H*/B* is that the expansion joint provides sufficient structural restraint to prevent the tube from pulling out of the tubesheet under normal operating and accident conditions, and that the accident induced leakage during accident conditions is bounded by a factor of two on the observed normal operating leakage. Because of the technical complexity of H*/B*, review of it cannot be completed in time for the Spring 2008 refueling outages.

This report provides technical justification for an interim alternate repair criterion (IARC) that requires full-length inspection of the tubes within the tubesheet but does not require plugging tubes if any circumferential cracking observed in the region greater than 17 inches from the top of the tubesheet (TTS) is less than a value sufficient to permit the remaining circumferential ligament to transmit the limiting axial loads (the greater of 3x NOP or 1.4x SLB end cap loads). Axial cracks below 17 inches from the TTS are not relevant to the tube pullout arguments because axial cracks do not degrade the axial load carrying capability of the tube. Axial cracks do not require plugging if they are below 17 inches from the top of the tubesheet.

The calculation of the limiting circumferential ligament is provided in Section 3 of this report. The calculation assumes that friction loads between the tube and tubesheet from any source are zero. This assumption avoids potential effects of uncertainties in tube and tubesheet material properties.

Also, based on the same assumption that the contact pressure between the tube and the tubesheet from any source is zero, this report provides a basis for demonstrating that the accident induced leakage will always meet the value assumed in the plant's safety analysis if the observed leakage during normal operating conditions is within its allowable limits. This analysis is provided in Section 4 of this report. The need to calculate leakage from individual cracks is avoided by the calculation of the ratio of accident induced leakage to normal operating leakage.

The tube-end weld is specifically excluded from the tube by TSTF-449, Rev. 4. Because friction between the tube and the tubesheet is ignored, the weld may become an important component in the transfer of the tube pullout loads to the tubesheet. Therefore, the minimum ligament necessary to transfer the pullout loads is also calculated in Section 3. Because the tube-end weld is not considered a part of the tube, discussion of the inspection methodology is beyond the scope of this technical discussion. Discussion of how the weld will be examined is provided as a separate part of the license amendment request.

A bounding analysis approach is utilized for both the minimum ligament calculation and leakage ratio calculation. "Bounding" means that the most challenging conditions from the plants with hydraulically expanded Alloy 600TT tubing are used. Three different tube diameters are represented by the affected plants (11/16" dia., Model F; ¾" dia. Model D5; 7/8" dia., Model 44F). The most limiting conditions for structural evaluation depend on tube geometry and applied normal operating loads. The conditions from the plant that result in the highest stress in the tube below the top of the tubesheet are used to define the minimum required circumferential ligament. The limiting leak rate ratio depends on the leak values assumed in the safety analysis and allowable normal operating leakage that results in the longest length of undegraded tube/crevice for assuring that acceptable leakage during the limiting design basis accident (i.e., steam line break, locked rotor and control rod ejection) above 17 inches below the tubesheet are used. The limiting cases for structural evaluation and leakage evaluation are not necessarily from the same plant. However, the resulting minimum ligament and required undegraded length of tube below the top of the tubesheet can be safely applied for any of the affected domestic plants identified in Table 4-1.

2.0 PERFORMANCE CRITERIA

The performance criteria of NEI 97-06, Rev. 2 (Reference 2-1) are the basis for these analyses. The performance criteria are:

The structural integrity performance criterion is:

All in-service steam generator tubes shall retain structural integrity over the full range of normal operating conditions (including startup, operation in the power range, hot standby, and cool down and all anticipated transients included in the design specification) and design basis accidents. This includes retaining a safety factor of 3.0 against burst under normal steady state full power operation primary-to-secondary pressure differential and a safety factor of 1.4 against burst applied to the design basis accident primary-to-secondary pressure differentials. Apart from the above requirements, additional loading conditions associated with the design basis accidents, or combination of accidents in accordance with the design and licensing basis, shall also be evaluated to determine if the associated loads contribute significantly to burst or collapse. In the assessment of tube integrity, those loads that do significantly affect burst or collapse shall be determined and assessed in combination with the loads due to pressure with a safety factor of 1.2 on the combined primary loads and 1.0 on axial secondary loads.

The structural integrity performance criterion is based on ensuring that there is reasonable assurance that a steam generator tube will not burst during normal operation or postulated accident conditions.

The accident induced leakage performance criterion is:

The primary to secondary accident induced leakage rate for any design basis accident, other than a steam generator tube rupture, shall not exceed the leakage rate assumed in the accident analysis in terms of total leakage rate for all steam generators and leakage rate for an individual steam generator. Leakage is not to exceed 1 gpm per steam generator, except for specific types of degradation at specific locations when implementing alternate repair criteria as documented in the Steam Generator Program technical specifications.

Primary-to-secondary leakage is a factor in the dose releases outside containment resulting from a limiting design basis accident. The potential primary-to-secondary leak rate during postulated design basis accidents shall not exceed the offsite radiological dose consequences required by 10 CFR Part 100 guidelines or the radiological consequences to control room personnel required by GDC-19, or other NRC-approved licensing basis.

The IARC for the tubesheet region is designed to meet these criteria. The structural criterion regarding tube burst is inherently satisfied because the constraint provided by the tubesheet to the tube prohibits burst. However, the structural integrity criterion is interpreted to mean that tube pullout from the tubesheet is equivalent to a tube burst and must, therefore, be prevented.

The accident induced leakage criterion applies directly. The IARC will demonstrate that the accident induced leakage will not exceed the leakage assumed in the accident analysis for the plant which bounds all of the domestic plants which are anticipated to utilize the IARC.

2.1 REFERENCES

2-1 NEI 97-06, Rev.2, "Steam Generator Program Guidelines," Nuclear Energy Institute, Washington D.C., May 2005.

3.0 STRUCTURAL EVALUATION FOR MINIMUM CIRCUMFERENTIAL LIGAMENT

3.1 INTRODUCTION

An assessment to determine the remaining ligament in steam generator tubes (relevant to Model D, Model F, and Model 44F) necessary to support the assumed loading conditions in the presence of postulated, partially circumferential and fully circumferential flaws was performed. Two locations were considered, within the steam generator tube wall at a location deep in the tubesheet and within the tube-to-tubesheet weld. In addition, growth of the crack was simulated by using four default primary water stress corrosion crack (PWSCC) growth rates. Failure was determined to occur when the stress in the remaining ligament of tube or weld metal exceeded the flow stress.

3.2 ANALYSIS

3.2.1 Description of the Steam Generator Models

The tube geometries used in three models of steam generator which may utilize the IARC were analyzed. These were Model D, Model F, and Model 44F. The material properties applied in this analysis are LTL properties provided in References 3-1 through 3-4. The tube dimensions, material, and mechanical properties (at 650°F) are listed in Table 3-1.

3.2.2 Flaw Geometries

1. *Partial circumferential flaw in the steam generator tube wall.* This postulated flaw in the steam generator tube wall is assumed to have an initial depth of 0.010 inch and an initial arc length of 0.060 inch on the tube's inner diameter. The flaw extends from the tube's inner diameter to a depth of 0.010 inch such that the side faces of the flaw run parallel to the radii of the tube. Figure 3-1 shows a section of a steam generator tube, its radial and axial axes, and the crack face. Figure 3-2 shows the partial circumferential crack on the crack face. The initial depth and arc length are chosen to represent a typical surface flaw with a semi-elliptic shape and a 3:1 aspect ratio subject to mode I crack opening (Reference 3-5). Thus, the length of the semi-major axis is initially three times that of the semi-minor axis, and the tensile axis of the load which opens the crack is normal to the direction of crack propagation. The initial depth of 0.010 inch is a commonly accepted initial flaw depth upon initiation. The flaw simultaneously grows by PWSCC both radially and circumferentially, and it maintains its initial shape. Upon breaching the outer diameter of the tube, the flaw continues to grow circumferentially until the remaining area of the tube cannot support the applied loading.

2. *Full circumferential flaw in the steam generator tube wall.* The postulated, full circumferential flaw in the steam generator tube wall is assumed to have an initial depth equal to 0.010 inch, consistent with the partial circumferential flaw. The

depth is also measured from the tube's inner diameter. Figure 3-3 shows the geometry for this type of flaw. This type of flaw grows by PWSCC radially only until the remaining ligament can no longer support the applied loading.

3. *Partial circumferential, through-wall flaw in the steam generator tube wall.* This type of geometry was chosen to correspond to the type of flaw that may exist upon detection. The assumed initial arc length of this flaw is 40 degrees, and the flaw grows by PWSCC circumferentially only until the remaining ligament can no longer support the applied loading. The geometry for this flaw is identical to the geometry shown in Figure 3-2 with the exception that the crack depth is through-wall.

4. *Partial circumferential flaw in the weld metal.* This geometry is similar to that described in number 1 above, except that it is in the weld and grows due to PWSCC in the shape of a conical frustum on an angle determined by the plane of maximum principal stress. The initial depth and arc length are 0.010 inch and 0.060 inch, respectively. Figure 3-4 is a schematic of a conical frustum and the surface on which the crack grows, and Figure 3-5 is a schematic of the flaw on that surface. The growth is simultaneously radial and circumferential until the remaining ligament cannot support the applied loading.

5. *Full 360 degree circumferential flaw in the weld metal.* This flaw, of 0.010 inch initial depth grows radially only due to PWSCC. It also grows in the shape of a conical frustum on an angle determined by the maximum principal stress until the remaining ligament cannot support the applied loading. Figure 3-6 is a schematic of this flaw geometry.

3.2.3 Initiation

Implicit in the preceding section is that the flaws are presumed to exist as the initial condition for the crack growth cycle. A crack growth cycle as defined in this analysis is full power operation for the length of time for the crack to grow from initial conditions until the minimum residual ligament is attained. The time variable is important to establish the ultimate required residual ligaments for different planned plant operating periods between inspections.

3.2.4 Pressure Loading for Flaws in the Tube Wall

The requirement for tube integrity is that the tube be able to support loads due to a pressure difference of $3*\Delta P_{NOP}$ or $1.4*\Delta P_{SLB}$, whichever is more limiting. A review of the data available shows that the most limiting condition is due to ΔP_{NOP} of Surry Units 1 and 2 [ ]^{a,c,e} Therefore, the most limiting pressure differential to determine end cap loads is based on $3*\Delta P_{NOP}$ of the Surry Units 1 and 2 and equals [ ]^{a,c,e} This is conservative relative to the actual loads. Once a PWSCC flaw initiates, the faces of that flaw are subject to internal pressure, which in this case is the primary side pressure (2250 psia).

3.2.5 Pressure Loading Effects in the Weld Metal

The plants being addressed for this study all have flush welds. The weld is assumed to have an elliptic shape with a semi-major axis equal to the tube wall thickness, a semi-minor axis equal to 0.014 inch, and a crown extending 0.008 inch below the tubesheet cladding surface. This is a conservative idealization of the actual weld nugget. In-process measurements of the welds have determined that the weld protrusion from the tubesheet surface is between 0.008 inch and 0.013 inch. Also, visual examination of the welds show that the autogenous weld nugget is elliptical and inclined to horizontal with the interface between the weld and the tube approximately 0.035 inch into the tubesheet bore. Therefore, the idealized representation of the weld is conservative to the actual manufacturing condition.

Three main crack paths are most likely to occur due to the applied loading. One is the horizontal surface between the tube bottom and the weld. In the most idealized fashion, the end cap loads result in a tensile stress along this interface. The second crack path is the vertical line from the tube-tubesheet interface to the bottom of the weld metal. In this case, the end cap loads result in a shear stress along this line of crack propagation. The third crack path is in the weld metal, between the previous two paths, and whose loading is a combination of tensile stress and shear stress. Figure 3-7 is a schematic of the weld geometry and the crack paths just discussed. The simplifying assumption used in this study is that the stress tensor of an infinitesimal volume of material in this region is comprised of the stress components calculated for the first two crack paths. This results in the maximum principal stress acting on a line that is approximately 35 degrees counter-clockwise from the tube bottom, where the center of rotation is 0.020 inch above the bottom surface of the tubesheet cladding and along the tube-tubesheet interface. Figure 3-8 is a representation of an infinitesimal volume of material, the applied stress tensor, and the principal stresses. As the crack grows, a decreasing area of the weld metal is subject to the maximum principal stress, however the flaw area is then subject to internal pressure on its faces.

3.2.6 Constraint

The tube region subject to cracking is deep in the tubesheet (>17 inches below the top of the tubesheet). The tubes are assumed to be flush against the tubesheet due to the hydraulic expansion process; however, there is no interference force due to pressure. No motion is possible in the lateral direction. Furthermore, it is also assumed that there is no friction acting on the joint between the tube and the tubesheet. The result of these assumptions is that only vertical displacement is allowed and the stresses in the tube wall are purely tensile; there is no bending stress component because of the lateral restraint of the tubesheet. Similarly, the weld metal is subject only to the tensile loads transmitted by the tube. Therefore, any crack in the weld metal will also open in a purely tensile mode. This is the reason that a weld crack in a direction radiating away from the tube's centerline is not considered here. In this case, the residual weld nugget on the tube results in mechanical interference with the residual weld nugget on the tubesheet, and the tube cannot pull out of the tubesheet.

3.2.7 Force Balance

1. *Partial circumferential flaw in the steam generator tube wall.* The force balance for this scenario is one in which the end cap load plus the force due to the internal pressure acting on the faces of the flaw is balanced by the force reacted over the tube wall's cross-sectional area minus the flaw area. As the flaw grows, the areas of both the tube wall cross-section and the flaw change. The equation used in this part of the study is

[ ]a,c,e

where

P is the pressure [ ]a,c,e

P_i is the internal pressure (2250 psia),

r_i is the inner radius of the steam generator tube,

d is the crack depth,

$\Delta\theta$ is the arc length of the crack,

σ is the stress reacted by the steam generator tube's cross-section, and

r_o is the outer radius of the steam generator tube.

2. *Fully circumferential flaw in the steam generator tube wall.* The force balance dictated by this case is one in which the end cap load plus the internal pressure acting over the crack faces of a fully circumferential flaw is balanced by the force reacted by the steam generator tube wall's cross-sectional area minus the area of the flaw. Again, the areas of both the flaw and the steam generator tube wall's cross-section change as the flaw grows. The equation used to model this situation is

[ ]a,c,e

where the variables are the same as previously defined.

3. *Partially circumferential, through-wall flaw in the steam generator tube wall.* This situation is identical to scenario 1 with the exception that the initial flaw is through-wall at the beginning of the crack growth cycle, and the initial arc length of the flaw is 40 degrees. This models a reasonable flaw length that would be detected by +Pt inspection which is assumed to be throughwall. The force balance for this case is

[ ]a,c,e

where the variables are the same as previously defined.

4. *Partial circumferential flaw in the weld metal.* The welds applicable to the plants under consideration are flush welds. Thus, the weld was modeled as an ellipse. The starting point of the ellipse region is the steam generator tube wall's inner diameter. This case is one in which normal stress and shear stress components are present. The normal stress results from a potential crack propagation path that runs along the interface between the steam generator tube wall and the weld metal. The shear stress component is from a potential crack propagation path that runs vertically from the interface between the steam generator tube and the tubesheet to the crown of the weld. The infinitesimal element of weld metal is assumed to have the normal and shear stress components that result from each of the two crack propagation paths (assuming that only one is active and the other is fixed). Hence, the normal stress component used is

[ ] a,c,e

and the shear stress component is

[ ] a,c,e

b is the semi-minor axis (0.014 inch). The three principal stresses that result from calculating the invariants of the stress tensor comprised of the above components are:

[ ] a,c,e

and the direction of the principal axes is determined by:

[ ] a,c,e

The crack propagation direction is found to be approximately [ ][a,c,e] extending from the steam generator tube-tubesheet interface toward the centerline of the steam generator tube. This results in a crack propagation surface that is an inverted frustum of a cone. Using the surface of revolution technique (see Reference 3-6), the surface area of this conical frustum is

a,c,e

[ ]

where θ is the approximately [ ][a,c,e] angle defined above, y is the vertical location of the intersection of the crack propagation line and the ellipse, and the rest of the variables are defined for scenario 1 above. The area of a flaw extending a depth d into this surface and over an arc length $\Delta\phi$ extending over this surface is

a,c,e

[ ]

where all of the variables have been previously defined. The resulting force balance for this scenario is

a,c,e

[ ]

where, in this case, σ is the stress reacted by the remaining surface area of the frustum.

5. *Full circumferential flaw in the weld metal.* This number is similar to number 4 with the exception that the flaw is now fully circumferential. The area of the flaw in this case is

a,c,e

[ ]

The resulting force balance is

a,c,e

[ ]

where, again, σ is the stress reacted by the remaining surface of the frustum.

3.3 RESULTS AND DISCUSSION

The required remaining ligaments are shown in Table 3-3. The required remaining circumferential ligaments for initially non-360 degree throughwall circumferential flaws are expressed in terms of degrees of arc. The required remaining radial ligaments for full 360 degree non-throughwall circumferential flaws are expressed in terms of inches.

3.3.1 Steam Generator Tube Wall Cross-Section

The values contained in Table 3-3 indicate that the required remaining ligament for partially circumferential flaws is approximately [ ]^{a,c,e} while the required remaining ligament for fully circumferential flaws is approximately [ ]^{a,c,e} The Model F steam generator tube requires less remaining ligament than do either the Model D or Model 44F steam generator tubes.

3.3.2 Steam Generator Tube Cross-Section with an Initial 40 Degree Arc Length, Through-Wall Flaw

The results contained in Table 3-3 show that a partially circumferential flaw that is initially through-wall requires about the same remaining ligament of material as the case for which the initial flaw was not initially through-wall [ ]^{a,c,e} Since the force balance is based on net tensile force, this result is expected.

3.3.3 Weld Metal

The results for the weld metal calculations are also shown on Table 3-3. The required remaining ligaments for both the partially circumferential and fully circumferential flaws are approximately [ ]^{a,c,e} arc length and approximately [ ]^{a,c,e} for the partially circumferential and fully circumferential flaws, respectively , significantly less than required for the steam generator tube wall.

This situation for the weld is mechanically different than for the steam generator tube wall. In the latter case, the pressure differential that causes the end cap load is based on the internal pressure which acts on the flaw's faces. The end cap loading relieved in the wall during crack growth is replaced by another pressure loading on the crack faces. For the weld, the pressure differential causes an end cap load, which in turn results in a maximum principal stress along an inclined crack propagation path. The maximum principal stress [ ]^{a,c,e} is much greater than the initial stress reacted by the steam generator tube wall [ ]^{a,c,e} However, as the flaw grows in the weld metal, it is the maximum principal stress in the area of the flaw that is relieved and replaced with the primary pressure loading [ ]^{a,c,e} over the crack faces. In addition, the surface area relevant to the weld metal is slightly larger than that contained in the steam generator tube wall due to its incline.

3.4 CONCLUSIONS – STRUCTURAL EVALUATION

- The required arc of ligament for an initial, partially circumferential flaw of 0.010" depth in the steam generator tube is approximately [ ]^{a,c,e} In general, the Model F steam generator tube wall requires the least amount of remaining ligament. However, Model F requires the least amount of time to grow to its critical flaw size. The results of all of the calculations performed are enveloped by an arc length of ligament equal to [ ]^{a,c,e} for this geometry.

- The required arc of ligament for the case when the initial flaw is through-wall over a 40 degree arc is approximately the same as above. This is expected as the critical flaw size is based on net tensile stress. An arc length of ligament equal to [ ]^{a,c,e} is necessary to bound the results for this geometry.

- Initial, fully circumferential flaws in the steam generator tube can grow to approximately]^{a,c,e} through-wall before failure was calculated to occur. The minimum required radial ligament depth is [ ]^{a,c,e} for the bounding case. This is provided for information only since the underlying assumption of the IARC is that circumferential cracks will be considered 100% throughwall.

- Initial, partially circumferential flaws in the weld required a [ ]^{a,c,e} arc of remaining weld material, significantly less than the arc required in the steam generator tube wall. In order to bound the results for this geometry, an arc length of material spanning [ ]^{a,c,e} is required.

- Initial, fully circumferential flaws in the weld metal were able to grow to approximately [ ]^{a,c,e} through-wall before failure was calculated to occur, again significantly less than the ligament required in the steam generator tube wall. A bounding value of [ ]^{a,c,e} of ligament is required for this case. This is provided for information only since the underlying assumption of the IARC is that circumferential cracks will be considered 100% throughwall.

3.5 REFERENCES

3-1 J. A. Begley and J. L. Houtman, WCAP-12522, "Inconel Alloy 600 Tubing-Material Burst and Strength Properties," January 1990.

3-2 G. Whiteman, WCAP-16670-P, "Steam Generator Alternate Repair Criteria for Tube Portion within the Tubesheet at Comanche Peak Unit 2," November 2006.

3-3 WCAP-16124-P, "Justification for the Partial-Length Rotating Pancake Coil (RPC) Inspection of the Tube Joints of the Wolf Creek Model F Steam Generators," September 2003.

3-4 G. Whiteman, WCAP-16506-P, "Steam Generator Alternate Repair Criteria for Tube Portion within the Tubesheet at Turkey Point Units 3 and 4," December 2005.

3-5 T. L. Anderson, Fracture Mechanics Fundamentals and Applications, Second Edition, New York: CRC Press, 1995.

3-6 G. B. Thomas, Jr., Calculus and Analytic Geometry, Alternate Edition, Reading: Addison-Wesley Publishing Company, Inc., 1972.

Table 3-1
Dimensions and Mechanical Properties of the Steam Generator Tubes

Model	D [2]	F [3]	44F [4]
O.D. (in)	0.764	0.703	0.893
Wall Thickness (in)	0.04257	0.0396	0.0495
I.D. (in)	0.664	0.6075	0.775
Material	Alloy 600	Alloy 600	Alloy 600
Heat Treatment	Thermally Treated	Thermally Treated	Thermally Treated
r_o (in)	0.382	0.3515	0.4465
r_i (in)	0.33943	0.3119	0.397

a,c,e

Note [1]: These properties listed are lower tolerance limit (LTL) properties from Reference (3-1).
Note [2]: The expanded tube outer diameter and thinned wall dimensions for the Model D steam generator tubes are from Reference (3-2).
Note [3]: The expanded tube outer diameter and thinned wall dimensions for the Model F steam generator tubes are from Reference (3-3).
Note [4]: The expanded tube outer diameter and thinned wall dimensions for the Model 44F steam generator tubes are from Reference (3-4).

Table 3-2
Interim Alternate Plugging Criterion Pressure Differentials

Plant	Normal Operation ΔP (psi)	Steam Line Break ΔP (psi)	Source Document

a,c,e

Table 3-3
Calculation of Required Minimum Ligament

	Circumferential Extent of Flaw	Minimum Structural Ligament

a,c,e

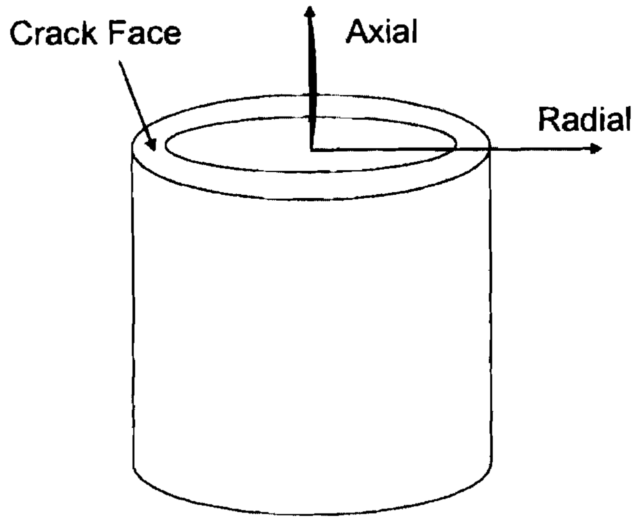

Figure 3-1
A Segment of a Steam Generator Tube Showing the Radial and Axial Axes as Well as the Crack Face

a,c,e

Figure 3-2
The Geometry of a Partially Circumferential Crack on the Crack Surface Shown in Figure 3-1

a,c,e

Figure 3-3
The Geometry of a Fully Circumferential Crack on the Crack Surface Shown in Figure 3-1

a,c,e

Figure 3-4
A Schematic of a Conical Frustum Showing the Surface on Which the Crack Grows

a,c,e

Figure 3-5
Schematic of a Partially Circumferential Flaw in the Weld Metal Along a Conical Frustum

a,c,e

Figure 3-6
Schematic of a Fully Circumferential Flaw in the Weld Metal Along a Conical Frustum

a,c,e

Figure 3-7
The Weld Metal Geometry and the Potential Crack Paths Considered

a,c,e

Figure 3-8
A Schematic Representing an Infinitesimal Volume of Material in the Weld Metal Under the Applied Stress Tensor and Its Transformation to the Principal Stress Tensor.

(This element is in the weld metal to the left of the shear plane vertical line in Figure 3-7.)

4.0 METHOD FOR CALCULATING LEAKAGE

4.1 SUMMARY

The alternate repair criterion (ARC) known as B* (Reference 4-2, 4-3), for "bellwether" approach, specifies the length of sound tubing required for the tube portion within the tubesheet that will assure that a plant's accident induced primary-to-secondary (P/S) leakage limit will not increase greater than a factor of two (2) above the normal operating leakage. The B* criterion relies on the contact pressure between the tube and the tubesheet. Technical issues remain to be resolved in the calculation of contact pressure between the tube and the tubesheet. Therefore, a modified B* approach is presented in this section which demonstrates that a plant with postulated cracks in the tube portion within the lower four inches of the tubesheet will still meet the accident induced leakage limits for safe steam generator operation under the assumption that no contact pressure exists between the tube and the tubesheet.

The modified B* approach shows that for an undegraded 17 inch depth of tube, measured from the secondary side surface of the tubesheet, there is a margin of a factor of 1.7 on the limiting length below the neutral axis of the tubesheet required to meet accident induced leakage limits for the bounding plant among those under consideration. This result means that, for the bounding plant, a 17 inch length of tube in undegraded condition provides more than 1.7 times the length of porous medium (crevice) necessary below the neutral axis of the tubesheet to limit the accident induced leakage to the value assumed in the safety analysis.

Figure 4-1 shows a sketch of the porous medium in the tube-to-tubesheet crevice. The typical machining finish of 125 micro-inches defines the porosity, but is assumed to provide no interlocking or friction.

A summary of the plants that are included in the modified B* analysis is given in Table 4-5. Based on the plant information, the ratio of the allowable accident leak rate to the allowable normal operating leakage limit in the bounding case steam generator is two (2). This value ranges from two (2) to six (6) for the plants under consideration for the IARC. See Table 4-2. This means that the leakage during accident conditions can increase by no more than 2 to 6 times the leak rate during normal operating conditions for the plants under consideration. This section shows that ample margin exists in undegraded crevice length for the bounding plant. The results for the bounding plant envelope all of the plants under consideration.

4.2 MODIFIED B* LEAKAGE ANALYSIS

The approach to the modified B* leakage analysis is similar to that used in the original B* (Reference 4-2). Where B* calculates the length of undegraded tubing, measured from the TTS, required to equilibrate the flow resistance during normal operating and during accident conditions so that the increase in primary to secondary leakage is limited to a function of the ratio of the pressure differential during the limiting design basis accident and normal operating conditions, the Modified B* analysis calculates the ratio of undegraded crevice length determined by eddy current inspection to the length of undegraded crevice required to meet the design basis accident analysis primary to secondary leakage assumption. By definition of the

IARC, 17 inches from the TTS is the available undegraded crevice length because confirmed cracking in this length will require the tube to be plugged. Both the pressure difference ratio and the ratio of the length of crevice during normal operating and the limiting design basis accident are factored into the margin determination as discussed below. By definition, the plant with the smallest allowable accident analysis leakage assumption results in the longest crevice length necessary to assure that accident analysis leakage assumptions are not exceeded. For the plants in question, the Modified B* value ranges from a safety factor of [ ]^{a,c,e} down to [ ]^{a,c,e} at a distance 17 inches below the top of the tubesheet (See the "n" values in Table 4-5). Conservatively using the neutral axis as a reference point, the Modified B* value ranges from [ ]^{a,c,e} down to [ ]^{a,c,e} (See the "n′" values in Table 4-5). Again, these values are the ratio of undegraded tube/crevice length confirmed by eddy current inspection to the length of undegraded crevice calculated using the D'Arcy equation necessary to preclude exceeding the limiting design basis accident analysis leakage assumption.

The D'Arcy formula for axial flow in a porous medium is used to calculate the leakage ratio and to evaluate the potential resistance to leakage in the crevice of the tubesheet. Other available leakage models (Bernoulli, Orifice Flow) are known to be less conservative than the D'Arcy model. Unresolved technical issues regarding the calculation of contact pressure between the tube and the tubesheet in the original B* require that both the bellwether principle and the application of D'Arcy's law do not employ contact pressure equations or relationships in the leakage analysis.

The D'Arcy model for describing axial flow in a porous medium, taken from Reference 4-1 is:

$$Q = \frac{\Delta p}{\mu K l} \tag{1}$$

Where:

Q is the flow rate for the fluid through the medium,

Δp is difference in pressure (or driving head) acting to force the fluid through the medium,

μ is the viscosity of the fluid,

K is the resistance to flow through the medium and

l is the axial length of the medium.

The term $\mu K l$ is the flow resistance, R. In that case, (1) becomes

$$Q = \frac{\Delta p}{R} \tag{2}$$

which produces a relationship between fluid flow, flow resistance and driving potential similar to electrical currents (i.e., $I = V/R$) and allows for similar analogies and assumptions to be made. See Figure 4-1 for a sketch of the system used to describe the porous medium present in the annulus of the tubesheet crevice.

In the following discussion the term R' refers to μK and the axial length of the porous medium is left in the equation as a separate variable as shown in Equation (3).

$$Q = \frac{\Delta p}{\mu K l} = \frac{\Delta p}{R' l} \quad (3)$$

Note that in previous submittals (Reference 4-2, 4-3), the length of the medium was included in the term R (see equation 2), which led to the conclusion that if the resistance of the crack and tubesheet crevice to leakage during normal operating (NOP) conditions was equal to the resistance of the crack and tubesheet crevice during steam line break (SLB), the increase in leakage between NOP and SLB conditions would be governed solely by the pressure differential. The original bellwether ratio of the expected accident leak rate to the required normal operating leak rate of 2 was based on this assumption because the pressure differential at SLB conditions is approximately double that during normal operating conditions. Therefore, the leakage during SLB conditions would be limited to twice that of the leakage during NOP for a length of crevice and a location of the leak that validates the assumption of equal resistance between SLB and NOP conditions.

The purpose of the interim ARC leakage assessment is to calculate the length of porous medium (crevice) required to limit primary-to-secondary (P/S) leakage to an acceptable level during a postulated SLB (or limiting design basis accident) to provide adequate resistance and margin against leakage during accident conditions assuming no contact pressure between the tube and the tubesheet exists. This length is defined as Modified B* and is used to assess the potential for leakage and acceptability of leakage flow rates assuming a full depth inspection of the tube portion with the tubesheet and a 17" length of tube free of all cracking indications. The Modified B* ratio is prescribed as the accident analysis limit divided by the plant Technical Specification limit of 0.1 gpm.

The margin against leakage during an accident event can be defined using equations (1) and (3). An example calculation of the modified B* ratio and the required length of porous medium necessary to accommodate the limiting accident leakage is provided below for the limiting case of zero contact pressure. There is no contact pressure between the tube and the tubesheet ($P_{contact} = 0$ psi) but the tube and the tubesheet are assumed to remain in contact. Assume that a point exists where the viscosity and leakage resistance during normal operating conditions will be equal to that of the viscosity and leakage resistance during accident conditions at some elevation in the tube-to-tubesheet crevice. That is,

$$R'_{NOP} = R'_{DBA} = R' \quad (4)$$

In this case the resistance to flow is calculated assuming that the liquid must flow through a tortuous path that begins at the crack (primary side) and ends at the top of the tubesheet (secondary side). No credit is taken for the increase in contact pressure between the tube and the tubesheet due to tubesheet flexure during accident conditions which would increase the resistance to flow through the crack and crevice.

The following example demonstrates the approach:

If the limiting leakage during NOP is 0.1 gpm and the leakage assumed in the safety analysis for SLB is 0.35 gpm, the ratio between SLB and NOP leakage is:

$$\frac{Q_{SLB}}{Q_{NOP}} = \frac{0.35}{0.10} = 3.5$$

Note that prior knowledge of the shape or orientation of the flaws that contribute to this leakage is not required. The ratio merely reflects the total leakage volume to which the plant is limited during operation. The ratio of the leak rates can be calculated using equations (3) and (4) which gives

$$\frac{Q_{SLB}}{Q_{NOP}} = \frac{\Delta p_{SLB}}{\Delta p_{NOP}} \frac{R'_{NOP}}{R'_{SLB}} \frac{l_{NOP}}{l_{SLB}}$$

$$\frac{Q_{SLB}}{Q_{NOP}} = \frac{\Delta p_{SLB}}{\Delta p_{NOP}} \frac{R'}{R'} \frac{l_{NOP}}{l_{SLB}} = \frac{\Delta p_{SLB}}{\Delta p_{NOP}} \frac{l_{NOP}}{l_{SLB}}$$

$$\frac{Q_{SLB}}{Q_{NOP}} = \frac{\Delta p_{SLB}}{\Delta p_{NOP}} \frac{l_{NOP}}{l_{SLB}} \qquad (5)$$

Substitution of the pressure differentials and the limiting leak rate ratio into equation (5) yields the ratio of the porous medium (crevice) length necessary to maintain the limiting accident analysis leakage assumption. For example, if the limiting primary to secondary pressure differential during normal operations is 1274 psig and the limiting accident pressure differential is 2560 psig the required length ratio for a leak ratio of 3.5 is given by:

$$3.5 = \frac{2560}{1274} \frac{l_{NOP}}{l_{SLB}}$$

$$\frac{l_{NOP}}{l_{SLB}} = 3.5\left(\frac{1274}{2560}\right) = \frac{3.5}{2.009} = 1.74$$

$$\frac{l_{NOP}}{l_{SLB}} = 1.74$$

The length ratio can be used with the data for loss coefficient and viscosity to calculate the required length of tube and crevice necessary to match the limiting leakage flow rate. If the leakage limits for the operating SG are based on "hot" or operational conditions, then the viscosity of the single phase leaked fluid is approximately equal to the viscosity of liquid water at 600°F.[2] The viscosity of liquid phase water at 600°F is approximately 1.76E-6 lbf-s/in^2 (Reference 4-2). The loss coefficient data given in WCAP-16794-P (Reference 4-2) shows that for a contact pressure of approximately 0 psi, the bounding loss coefficient from the 95% confidence interval fit is equal to [ ]a,c,e The value of loss coefficient that approximately bounds all of the test data is [ ]a,c,e (See Figures 4-2 and 4-3).

Note that the primary to secondary leakage at 600°F that corresponds to 0.1 gpm at room temperature conditions is 0.14 gpm. It is necessary to adjust the limiting leak rate for the NOP conditions because the loss coefficient data in WCAP-16794-P (Reference 4-2) is adjusted to represent room temperature conditions. Using the bounding loss coefficient value and the viscosity to calculate the required length of porous medium (crevice) to accommodate the NOP leakage gives

$$Q = \frac{\Delta p}{\mu K l}$$

$$l_{NOP} = \frac{\Delta p_{NOP}}{\mu_{NOP} K Q_{NOP}}$$

a,c,e

[ ]

$$l_{NOP} = \frac{76440.00}{56918.40} = 1.34in$$

Recall that:

$$\frac{l_{NOP}}{l_{SLB}} = 1.74$$

Therefore, the length of tube and crevice necessary to maintain the limiting leakage flow rate at accident conditions is

$$\text{Modified B*} = l_{SLB} = 1.34/1.74 = 0.77\text{in}$$

---

2 : The viscosity and loss coefficient are calculated at normal operating conditions because the normal operating conditions for the set of plants seeking to use the IARC are more closely related. Also, it is conservative to assume that the viscosity of the liquid phase of water during SLB equals the viscosity of the liquid phase of water at NOP condition.

This result shows that the length of porous medium required during the normal operating condition is more limiting compared to the length of porous medium required during an accident condition.

Inspection of the tube to a depth of 17 inches to ensure that the tube is free of cracking indications means that there is at least 17 inches of tube material and crevice to interact and provide leak resistance. Therefore, the available factor of safety against leakage in excess of accident analysis assumptions, *n*, is

$$n = \frac{17}{0.77} \approx 22$$

The result for *n* shows that there is greater than a factor twenty (20) times the length of tube and crevice annulus/porous medium necessary to maintain the maximum allowable leakage limits for plant operation during steam line break conditions in this example.

It is possible for the tubesheet to deflect during operations as the pressure differential from the primary to secondary surface varies so that the tubesheet crevices expand above the tubesheet neutral axis. It is reasonable to expect that the flow resistance of the crevice will decrease as the tubesheet crevice expands. The tubesheet deflection will tend to expand the crevice from the neutral axis of the tubesheet to the secondary side face of the tubesheet in the near and mid-range radii. In the context of this analysis the term near radius refers to the tubesheet radii from the center to a distance of 20 inches, mid range refers to the radius from 20 inches to 40 inches and peripheral refers to tubesheet radii greater than 40 inches from the center. The tubesheet deflection will tend to constrict the tubesheet crevice from the neutral axis to the primary face of the tubesheet in the near and mid-range radii. The effects of the tubesheet deflection are reversed in the peripheral radii so that the crevice tightens above the neutral axis and expands below the neutral axis. In order to accommodate this phenomenon, the available tube-to-tubesheet crevice or available porous medium is only that length within the tubesheet, above or below the neutral axis, which experiences constriction of the tubesheet bore. This will be the reference available crevice length in this analysis. This means that even though there are 17 inches of undegraded crevice available due to the IARC assumptions, only that difference between the neutral axis and 17 inches is assumed to act to provide leakage resistance. In the case of a Model F steam generator the neutral axis is located approximately [ ][a,c,e] below the secondary side face of the tubesheet (Reference 4-2). This means that for a Model F steam generator there is a [ ][a,c,e] long length of porous medium available to resist leakage that can be assured to not dilate due to tubesheet flexure. Following the example above this means that the actual factor of safety against exceeding the accident induced leakage is:

a,c,e

[ ]

This result for *n′* indicate that if the region of the tubesheet crevice affected by tubesheet bow is removed from consideration there is at least a factor of eight (8) on the available porous medium to resist accident and normal operating leakage in this example.

4.3 CALCULATION OF APPLICABLE DENSITIES AND VISCOSITY

Calculation of the leaked fluid density and the applicable viscosity during NOP conditions is required to determine the required length of porous medium. The density of the leaked fluid is important because different operating plants use different leakage assumptions in their safety analyses. For example, a plant may assume that the leaked fluid is "hot" or at operating temperature, which means that the volume of the fluid is increased relative to a "cold" or room temperature condition. Some of the potential plants under consideration have revised the Plant Technical Specifications to use a mass flow rate for the leakage limit which removes the concern of "hot" or "cold" volumes entirely. The modified B* analysis assumes that all leakage volumes are "cold" leakage volumes even though some plant values for accident analysis leakage are at operating conditions. This results in a lower ratio value for allowable leakage rate during design basis accident conditions to normal operating leakage limit and longer required crevice lengths during the design basis accident.

The modified B* analysis also assumes that the fluid viscosity during NOP bounds the viscosity during any accident at lower temperatures. The viscosity term appears in the denominator of equation (3) so it is conservative to keep it at a lower value which reduces the denominator (viscosity of water increases at lower temperatures) and increases the required length of porous medium.

4.4 CALCULATION OF LIMITING LEAK RATES AND PRESSURE DIFFERENTIALS

The Modified B* IARC leakage analysis represents a bounding approach that describes the limiting leak and length ratios for the potential user plants that are noted on Figure 4-1. These plants meet the definition of an H*/B* plant; that is, steam generators with Alloy 600TT tubing that is hydraulically expanded over the full depth of the tubesheet.

The limiting leak rate ratio, accident induced leakage to normal operating leakage, for the plants on this list is the lowest leak rate ratio for any plant, which is two (2). The bounding analysis for the modified B* must justify a leak rate ratio of two (2). The limiting leak rate ratio is taken from Catawba Unit 2 and is assumed to be a cold volume. No leak rate ratio higher than six has been identified (See Table 4-2).

Table 4-2 through Table 4-5 show the accident and normal operating condition leak rates and the associated pressure differentials for each condition. The pressure differentials are calculated assuming hot leg, low TAVG properties for NOP conditions.

The inputs for the calculation of the limiting length of porous medium (crevice) and the limiting leakage ratio are applied consistently. That is, the pressure differential and leak limit for a single plant is used to calculate the porous medium length and the available margin at 17 inches. The longest required length that bounds all of the other plants under consideration is then taken as the bounding, or limiting length, for all of the plants.

4.5 CALCULATION OF BOUNDING MODIFIED B* FOR INTERIM ARC PLANTS

Applying the limiting leak rate and pressure differential data from Table 4-2 in Equation (5) gives a length ratio of [ ][a,c,e]. The calculation of the limiting length ratio is given below

$$\frac{Q_{SLB}}{Q_{NOP}} = \frac{\Delta p_{SLB}}{\Delta p_{NOP}} \frac{l_{NOP}}{l_{SLB}}$$

[ ][a,c,e]

[ ][a,c,e]

[ ][a,c,e]

Calculating the required length of porous medium (crevice) for the limiting plant during NOP conditions yields

$$l_{NOP} = \frac{\Delta p_{NOP}}{\mu_{NOP} k Q_{NOP}}$$

[ ][a,c,e]

[ ][a,c,e]

[ ][a,c,e]

Therefore, the 17 inch length of undegraded crevice within the tubesheet provides more than [ ]^{a,c,e} times the required length required to meet the accident induced leakage limits for the bounding plant. The [ ]^{a,c,e} inch length of undegraded tubing below the neutral axis provides more than [ ]^{a,c,e} times the required length of crevice required to meet the accident induced leakage limits for the bounding plant. The result for the bounding plant envelopes all of the other plants under consideration (see Table 4-5) and the margin for all other plants in Table 4-5 is greater. Therefore, the limiting modified B* result of [ ]^{a,c,e} inches is a bounding result for all of the plants under consideration.

4.6 CONCLUSION

A basis is provided to assure that the accident induced leakage for the limiting accident will not exceed the value assumed in the safety analysis for the plant.

The length of undegraded crevice required to limit the accident induced leakage to less than the value assumed in the safety analysis for the limiting plant is [ ]^{a,c,e} inches. By definition of the IARC, a tube that can remain in service has an undegraded crevice of 17 inches. Therefore, a factor of safety of [ ]^{a,c,e} is available. Expressed in length terms, the length margin in the crevice is [ ]^{a,c,e} inches.

For all IARC candidate plants other than the limiting plant, the margins on length required to limit the accident induced leakage to less than the value assumed in the safety analysis is greater.

In summary, no leakage issue is associated with the IARC unless the normal operating leakage attributable to the tubesheet expansion zone (TEZ) is greater than its limit. Continued operation of the plant with leakage greater than the specified allowable limit is not possible.

4.7 REFERENCES

4-1. NSD-RMW-91-026, M.J. Sredzienski, "An Analytical Model for Flow Through an Axial Crack in Series with a Denting Corrosion Medium." 02/05/1991.

4-2. WCAP-16794-P, G.W. Whiteman, "Steam Generator Tube Alternate Repair Criteria for the Portion of the Tube Within the Tubesheet at the Vogtle 1 & 2 Electric Generating Plants." 10/2007.

4-3. Wolf Creek ET 07-0043; Docket No. 50-482: "Response to Request for Additional Information Related to License amendment Request to Revise Steam Generator Program"; September 27, 2007.

Table 4-1
List of H*/B* Plants

a,c,e

Site	Alpha	SG Model

Table 4-2
Primary to Secondary Leakage Data and Pressure Differentials for the Domestic Fleet.

SLB = Steam Line Break. LR=Locked Rotor. CRE=Control Rod Ejection. NOP=Normal Operating Condition.

a,c,e

Plant Name	Pressure (psi)		P/S Leakage (GPM)			L_{NOP}/L_{SLB}	L_{NOP}	L_{SLB}
	SLB	NOP	SLB	NOP	Ratio		in	in

Table 4-3
Primary to Secondary Leakage Data and Pressure Differentials for the Domestic Fleet.

SLB = Steam Line Break. LR=Locked Rotor. CRE=Control Rod Ejection. NOP=Normal Operating Condition.

a,c,e

Plant Name	Pressure (psi)		P/S Leakage (GPM)			L_{NOP}/L_{LR}	L_{NOP}	L_{LR}
	LR	NOP	LR	NOP	Ratio		in	in

Table 4-4
Primary to Secondary Leakage Data and
Pressure Differentials for the Domestic Fleet.

SLB = Steam Line Break. LR=Locked Rotor. CRE=Control Rod Ejection.
NOP=Normal Operating Condition.

a,c,e

Plant Name	Pressure (psi)		P/S Leakage (GPM)			L_{NOP}/L_{CRE}	L_{NOP}	L_{CRE}
	CRE	NOP	CRE	NOP	Ratio		in	in

Table 4-5
Summary of Required Accident Length and Available Margin for the Domestic Fleet.

a,c,e

Plant Name	L_{SLB}	L_{LR}	L_{CRE}	MAX	Modified B* Safety Margin Ratio	
					n [(1)]	n' [(2)]
	in	in	in	in	$17/L_{ACCIDENT}$	$6.5/L_{ACCIDENT}$

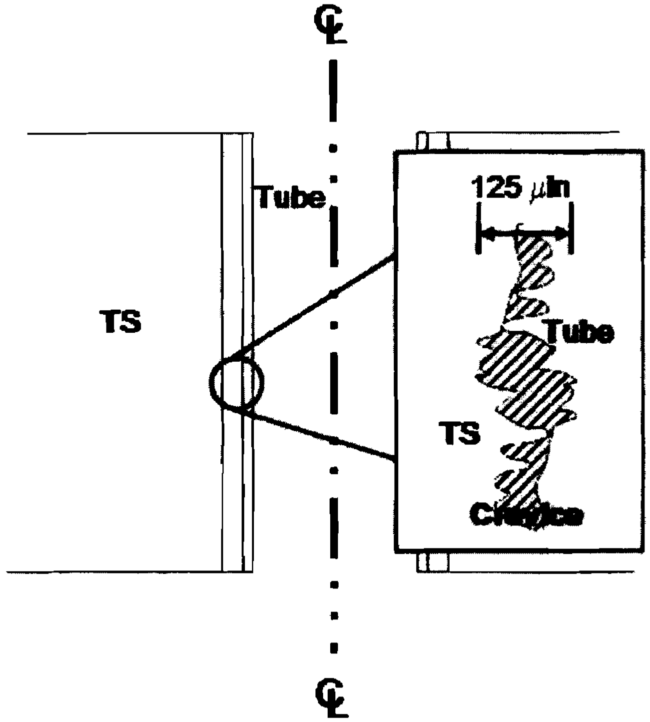

Figure 4-1
Illustration of Tube-to-Tubesheet Crevice and Approximated Porous Medium
Roughness of 125 μin is Typical of Installed Tube and Tubesheet Crevice Surfaces

a,c,e

[ ]

Figure 4-2
Plot of Loss Coefficient Data as a Function of Contact Pressure for Model F and Model D Steam Generators (Reference 4-2)

a,c,e

Figure 4-3
Plot of Loss Coefficient Data as a Function of Contact Pressure for Model 44F and Model 51F Steam Generators (Reference 4-2)

5.0 IARC CONCLUSIONS

5.1 LIMITING STRUCTURAL LIGAMENT

From Section 3 of this report, the bounding structural ligament required for the tube to transmit the operational loads is 115 degree arc. This assumes that the residual ligament is 100% of the tube wall in depth. For the tube-end weld, the bounding circumferential structural ligament is 35 degrees arc. A small circumferential initiating crack is predicted to grow to a throughwall condition before it is predicted to reach a limiting residual ligament. A residual ligament in a part-throughwall condition is not a significant concern, because of the assumption that all circumferential cracks detected are 100% throughwall.

5.1.1 Consideration of NDE Uncertainty

The NDE uncertainty must be addressed to assure that the as-indicated circumferential arc of the reported crack is a reliable estimate of the actual crack. ETSS 20510.1 (Reference 6-1) describes the qualified technique used to detect circumferential PWSCC in the expansion transitions and in the TEZ. This technique is also considered qualified by the industry, and has been routinely used, for the detection of circumferential indications in the tack expansion region just above the tube-end weld. The qualification data is provided in the ETSS.

The fundamental assumption for the IARC is that all circumferential cracks detected are 100% throughwall. Thus, even a shallow crack of small length will be considered to be throughwall. Further, tube burst is not an issue for the IARC because of the constraint provided by the tubesheet; rather, it is axial separation of the tube that is the principal concern. Assuming that all circumferential cracks are throughwall reduces the inspection uncertainty to length of the cracks only. Further, the accuracy of the length determination is an issue only when the indicated crack approaches the allowable crack length (the complement of the required residual ligament) and if the indicated crack length is a reasonable estimate of the structural condition of the tube.

Prior investigations have correlated the axial strength of the tube to the Percent Degraded Area (PDA) of the flaw (Reference 6-2). PDA takes into account the profile of the existing crack, including non-throughwall portions and shallow tails of the crack. Using the data from ETSS 20510.1 for cracks with a 90%, or greater, throughwall condition from both NDE and destructive examination, Figure 6-1 compares the actual crack length and corresponding PDA for the cracks to a theoretical PDA which assumes that all cracks are 100% throughwall. For all flaws greater than 60 degrees circumferential extent, the theoretical PDA line is bounding. As the crack lengths increase, the separation of the actual PDA from the theoretical PDA tends to increase.

It is concluded that if the detected circumferential cracks are assumed to be 100% throughwall, the as-indicated crack lengths will be inherently conservative with respect to the structural adequacy of the remaining ligament. Therefore, no additional uncertainty factor is necessary to be applied to the as-measured circumferential extent of the cracks.

5.1.2 Consideration of Crack Growth

The growth of cracks due to PWSCC in the present study is dictated by four default PWSCC growth rates from Reference 6-3. The distribution of growth rates is assumed to be lognormal. Typical values and conservative values are given, although it is recommended in Reference 6-3 to use the default values only when the historical information is not available and not to use the typical values unless the degradation is mild. (No significant crack growth data exits for circumferential cracking in the tubesheet expansion region.) Both growth sets provided in Reference 6-3 have mean values and 95% upper bound values. See Table 6-1. For this analysis, the typical 95% upper bound growth rate is used.

The residual structural ligament must be adjusted for growth during the anticipated operating period between the current and the next planned inspection. Typically, the operating periods for the affected plants are 18 calendar months; however, some plants have planned outages in which no primary side inspections will be performed. Therefore, the cycle length adjustments are made to the minimum structural ligament required.

The circumferential growth rates are expressed as inches per EFPY in Table 6-2. Referring to Table 6-2, the maximum allowable throughwall circumferential crack size in a steam generator tube is 214° (=360° – 146° [required minimum ligament]) supporting one cycle of operation. The maximum allowable circumferential crack size in a tube-to-tubesheet weld is 294° (360° – 66° [required minimum ligament]) supporting one cycle of operation.

5.2 LEAKAGE

A basis, using the D'Arcy formula for flow through a porous medium, is provided to assure that the accident induced leakage for the limiting accident will not exceed the value assumed in the safety analysis for the plant if the observed leakage during normal operation is within its limits for the bounding plant. The bounding plant envelopes all other plants who are candidates for applying H*/B*. The D'Arcy formulation was previously compared to other potential models such as the Bernoulli equation or orifice flow formulation and was found to provide the most conservative results.

The length of undegraded crevice required to limit the accident induced leakage to less than the value assumed in the safety analysis for the limiting plant is [ ]^{a,c,e} By definition of the IARC, a tube that can remain in service has an undegraded crevice of 17 inches. Therefore, a factor of safety of [ ]^{a,c,e} is available. Expressed in length terms, the length margin in the crevice is [ ]^{a,c,e}

Significant margin on crevice length is available even if only the distance below the neutral axis of the tubesheet is considered. This distance is approximately [ ]^{a,c,e} During normal operating conditions, the tubesheet flexes due to differential pressure loads, causing the tubesheet holes above the neutral axis to dilate, and below the neutral axis, to constrict. No mechanical benefit is assumed in the analysis due to tubesheet bore constriction below the neutral axis of the tubesheet; however, first principles dictate that the tubesheet bore and crevice must decrease. Therefore, the leakage analysis provided is conservative.

For all IARC candidate plants other than the limiting plant, the margin on length required to limit the accident induced leakage to less than the value assumed in the safety analysis is greater than the values noted above for the bounding plant.

It is also concluded that if the normal operating leakage is within its allowable value, the accident induced leakage will also be within the value assumed in the bounding plants' safety analysis. This conclusion applies for all other plants which would benefit from implementation of the IARC.

5.3 REFERENCES

5-1 ETSS #20510.1; Technique for Detection of Circumferential PWSCC at Expansion Transitions.

5-2 EPRI TR-107197; Depth Based Structural Analysis Methods for Steam Generator Circumferential Indications; November 1997.

5-3 EPRI Document 1012987, "Steam Generator Integrity Assessment Guidelines, Revision 2," July 2006.

Table 5-1
PWSCC Growth Rates (Reference 3-6)

Growth Direction		**Radial (%TW/EFPY)**	**Circumferential (in/EFPY)**
Typical Values	Mean	4.5	0.04
	95% Upper Bound	13.1	0.12
Conservative Values	Mean	7.0	0.08
	95% Upper Bound	20.4	0.24

Table 5-2
Calculation of Required Minimum Ligament for
18 and 36 Months Operating Periods

	Bounding Structural Ligament	EFPY (1)	Growth (In./EFPY) (2)	Growth (Deg./EFPY) (3)	Growth for Operating Period (degrees)	Minimum Structural Ligament (degrees)	Required Minimum Ligament (degrees)
Tube	18 CM Operation	1.5	.12	20.65	31	[ ] a,c,e	146
	36 CM Operation	3.0	.12	20.65	62		177
Weld	18 CM Operation	1.5	.12	20.65	31		66
	36 CM Operation	3.0	.12	20.65	62		97

Notes:

4. It is conservatively assumed that 1 EFPY = 1 Calendar Year.
5. 95% upper value of typical growth rates from Reference 6-3.
6. Based on smallest (Model F) mean tubesheet bore dimension.

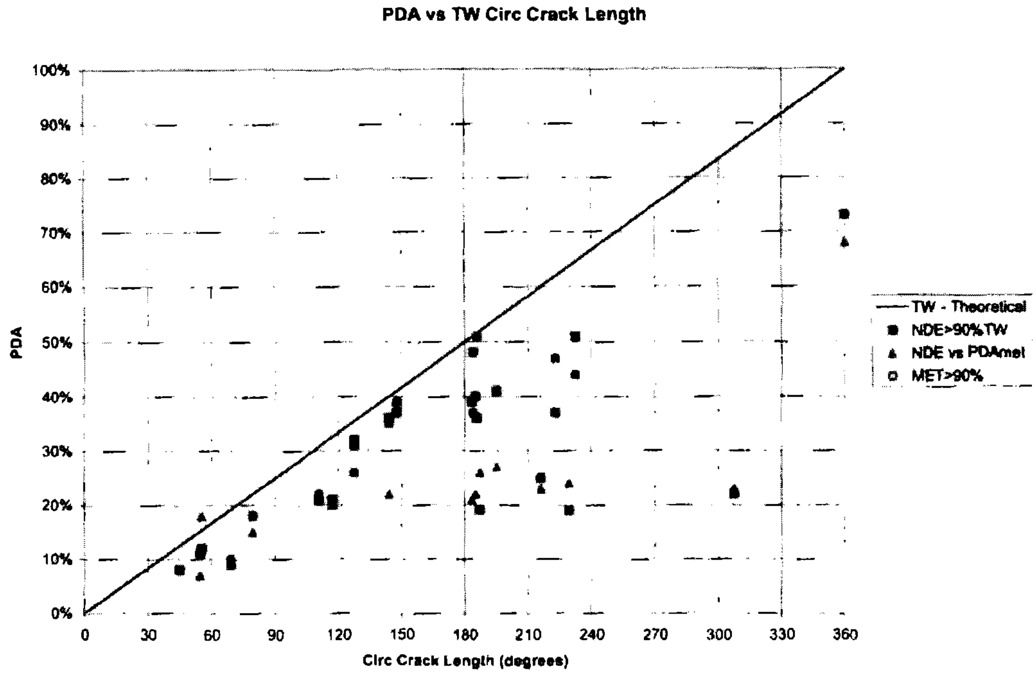

Figure 5-1
Correlation of Circumferential Crack Length and PDA