ALTERNATE REPAIR CRITERIA FOR PRIMARY WATER STRESS CORROSION CRACKING IN ONCE-THROUGH STEAM GENERATOR TUBE ENDS

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ABSTRACT

PWSCC was identified in the early 1990's within the roll expanded region near the primary tubesheet face in alloy 600 tubes of Once Through Steam Generators. Axial tube end cracks (TECs) located behind the tube-to-tubesheet roll expansion joint are of no structural concern, but nonetheless require repair per plant Technical Specifications. Therefore, there was a need to develop a method of permitting affected tubes to remain in-service.

Framatome ANP completed an extensive program that was documented in a topical report and was approved by US NRC (1999) to allow these tubes to remain inservice by accounting for primary to secondary leakage under postulated MSLB conditions. Leakage is calculated following each tube inspection, must remain below site specific limits and is based on test results that applied simulated axial loads and tubesheet bow to a tube/tubesheet mockup and measured the resultant leakage though EDM notches. Testing demonstrated that joint tightness is the key parameter which correlates with leakage. Joint tightness is quantified via "delta dilation," which depends upon axial tube load, tubesheet deformation, and primary side pressure. Test results were used with plant specific delta dilations to develop bounding leakage estimates for various regions of the tubesheet. The bounding leak rate was assigned to each identified TEC and all were summed to determine the total leak rate. Due to its deterministic nature, and its use of delta dilation values which do not reflect the difference between actual plant axial loads and those employed in the tests, this approach produces excessively conservative results.

During recent inspections, the number of TECs has continued to increase and continued initiation is expected in both the hot and cold tube end regions. This, coupled with the conservatisms discussed above, led to increases in the number of tube repair rolls required to meet leakage limits. Consequently, the authors undertook an effort to reduce the conservatisms in the leakage determination process by accounting for the differences in tube loading conditions in the testing (Poisson effect) and by eliminating the deterministic leakage calculation approach. A Monte Carlo code (LeakTEC) was developed to perform the calculations in this manner. This new approach was recently approved by the NRC for use at one of the affected plants.

INTRODUCTION

Maintaining SG tube integrity is the element most critical to ensuring long-term safe operation of a nuclear steam generator. SG tube degradation has been experienced in varying degrees of severity since the early 1980s and continues to affect those designs that operate with tubes fabricated from UNS N06600 (alloy 600) material. PWSCC is found in highly stressed regions of the tubes typically associated with a geometrical discontinuity in the tube wall (e.g., expansion transitions, dents or small radius u-bends), and has affected many thousands of tubes in PWR SGs. Specifically, in the Babcock and Wilcox designed OTSGs [Fig. 1], the tube region adjacent to the seal weld area in the hot leg [Fig. 2] has been greatly affected by PWSCC due to the elevated residual stress caused by the tube-to-tubesheet welding process, coupled with high RCS temperature. Indications of cracking do not satisfy the standard Technical Specification plugging criteria of 40%TW because they cannot be reliably sized by the NDE technique used to inspect the area. An alternate repair criteria, or means of justification for continued service of affected tubes, needed to be developed and approved by the US NRC prior to allowing the defective tubes to remain inservice.

The basis for the ARC was developed by AREVA Framatome ANP, under the auspices of the B&W Owners Group. It demonstrated that leakage from this specific tube degradation type during the bounding postulated accident is very small [1]. The test program involved subjecting conservatively designed tubesheet mockup blocks to a range of pressure, axial loading, and dilation conditions to develop the specific leak rates as a function of tube position in the SG. The original application of the leak rate test data to the real degradation was deterministic in nature and resulted in overly conservative estimates of accident leakage. This required that significant numbers of affected tubes be roll repaired to minimize the projected total aggregate SG leakage for future operating cycles. This paper provides a summary of the results of the original mockup testing and of the ARC in its original form, and discusses how the leakage determination process was modified to reduce excessive conservatisms, as well as utilize a probabilistic approach for calculating TEC leakage.

NOMENCLATURE

B = sample estimate of the intercept
DD_i = delta dilation for crack i
E = modulus of elasticity at MSLB tube temperature (psi)
F = critical value from the F-distribution
$Leakage_i$ = leakage rate for crack i
M = sample estimate of the slope
n = the index corresponding to the specified probability and confidence
N = number of data pairs used to calculate the regression coefficients
Num = number of Monte Carlo trials
$NumCracks_n$ = number of TECs identified in the current outage
$NumRepaired_n$ = number of TECs removed from service during the current outage
$NumCracks_{(n+1)}$ = number of TECs expected at the next outage
p = probability (fractional)
P = axial load
q = internal pressure (psi)
Ri = inner radius within roll expansion (inch)
R_o = outer radius within roll expansion (inch)
R_{mid} = mid wall radius within roll expansion (inch)
RnS = probabilistic standard error of regression
$RnVxx$ = probabilistic value of variance/covariance
$Rn\beta 3$ = probabilistic intercept
$Rn\beta 4$ = probabilistic slope
S = sample estimate of the standard error of regression
$SGLeak_k$ = total SG leakage rate for trial k
t = tube wall thickness (inch)
v = Poisson's ratio
V_{11} = sample estimate of the variance of the intercept
V_{12} = sample estimate of the covariance of intercept and slope
V_{22} = sample estimate of the variance of the slope
Z_x = a random normal deviate
$1-\alpha$ = confidence (fractional)

ARC	Alternate Repair Criteria
CM	Condition Monitoring
EDM	Electro Discharge Machine
FEM	Finite Element Model
ID	Inside Diameter
LTE	Lower Tube End
MSLB	Main Steam Line Break
NRC	Nuclear Regulatory Commission
OA	Operational Assessment
OD	Outside Diameter
OTSG	Once-Through Steam Generator
POD	Probability of Detection
PWSCC	Primary Water Stress Corrosion Cracking
SG	Steam Generator
TEC	Tube End Crack
UTE	Upper Tube End

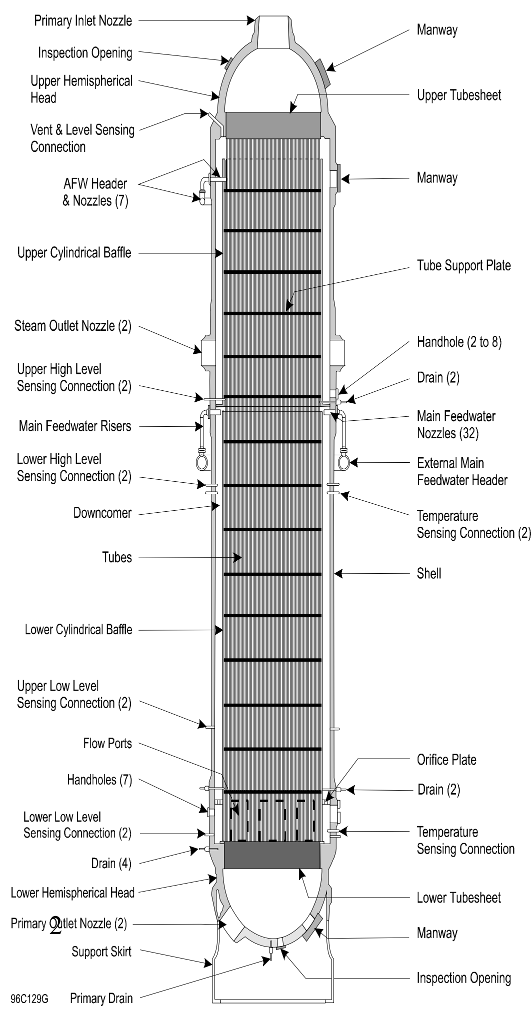
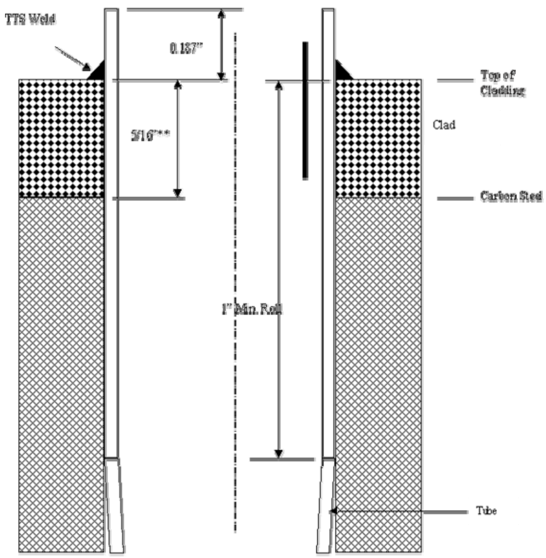


FIGURE 1 OTSG GENERIC SCHEMATIC



** Nominal value. Actual clad thickness varies.

FIGURE 2 TUBE END REGION

ORIGINAL ARC BASIS

The intent of the ARC is to allow TEC remain inservice provided the following crit are met: Indications can be axially oriented o contained entirely in the region above the car steel-cladding interface, the tube-to-tubesl weld must be capable of carrying all design b loading conditions (some OTSGs suffered t end/weld damage due to primary side loose p impinging on the tubes), and the total postul leakage from the SG must remain below s specific licensing requirements. Leakage calculated using upper bound leakage test res for both the actual number of indications dete during an inspection (Condition Monitoring) the number postulated to exist at the end of the next inspection interval (Operational Assessment). The following paragraphs describe the analyses and testing program that provides the basis for assessing TEC leakage.

Tube-to-Tubesheet Joint Modeling

Tubesheet distortion caused by differential thermal and pressure effects during a MSLB alters the tightness of the roll expanded tube-to-tubesheet joint [Fig. 2]. Finite element analyses were performed to conservatively determine key parameters, including axial tube load under MSLB conditions and resulting joint tightness. The analysis determined that both parameters vary with the radial distance from the center of the tubesheet in the OTSG. Figure 3 illustrates this for the axial tube load.

The resulting delta dilation between tube OD and tubesheet bore ID in the expansion region is the critical parameter in determining RCS leakage through the TEC and through the rolled joint during the event. Figure 4 illustrates how the delta dilation changes with radial position in the SG. The Figure depicts the original curve which did not account for actual SG axial load, and the adjusted curve used for the revised approach to the ARC (solid line). As is shown, there is actually a small increase in delta dilation (joint loosening) when accounting for the axial load experienced in the SG during the modeled accident conditions. Due to the role of radial position on the magnitude of this key parameter, the ARC in its original form defined a number of concentric tubesheet zones within which each TEC was assigned the same leakage value.

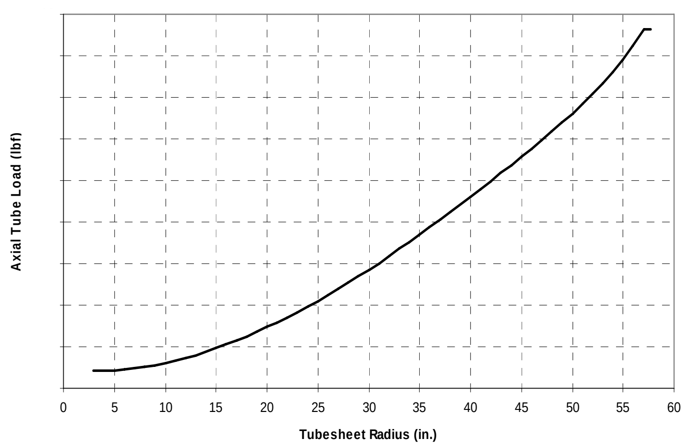


FIGURE 3 TUBE LOAD VERSUS RADIUS

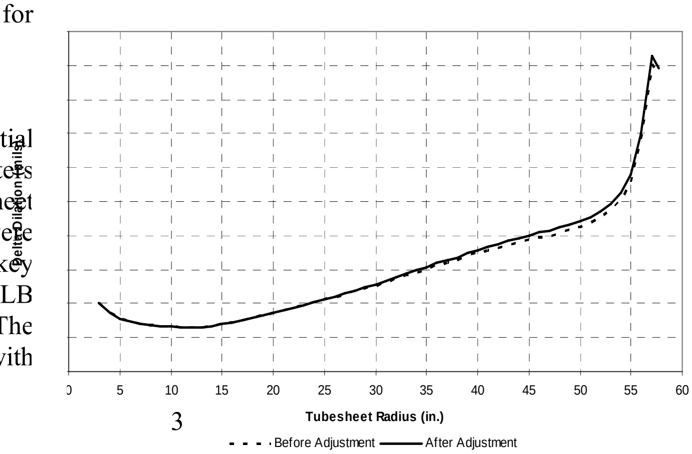


FIGURE 4 DELTA DILATION VERSUS RADIUS

Mockup Testing

This section describes a series of bounding leak tests which confirmed that there is a correlation between leakage and joint tightness, and quantified leak rates for 100%TW EDM notches of various lengths under both normal and MSLB conditions.

Test blocks were designed to maximize the “looseness” of the joint in order to produce conservative results. The tests accounted for the affects of the delta dilations between the tube OD and the tubesheet bore ID resulting from the transient conditions as determined in the FEM analyses. Applied test pressures and axial loads were bounding for the plant event under evaluation. Dilations were applied to the mockup blocks using a biaxial approach to simulate the effect of tubesheet distortion during the transient conditions. Additionally, in order to understand the affect of axial load on leakage, two different axial loading conditions were used during the testing; 1660 lbf and 3060 lbf.

The bore-hole dilation and axial tensile load work to reduce joint tightness (a larger, more positive delta dilation) while the internal tube pressure works to increase joint tightness (a smaller, possibly negative delta dilation). Leakage was monitored as the bore-hole dilation was varied, via the bilateral loading. Extensive results were generated under these conditions using three separate EDM notch lengths (0.25”, 0.50”, and 0.625”) to simulate TECs.

Original ARC Implementation

As implemented in its original form, the ARC leakage was determined by assigning each individual TEC (including multiples within a single tube) a leakage value based on tubesheet zone. The limiting leakage value for each tubesheet zone was based upon the most limiting delta dilation within each zone and used a 50% probability / 95% confidence value of the leakage from the tests performed. The summation of all of these values was taken to be the estimated SG TEC leakage under MSLB conditions. The assumption that each TEC leaks at a bounding value for its zone yielded excessive levels of conservatism in a typical SG evaluation.

The original approach conservatively assumes that every TEC has perforated the tube wall and will leak. In actuality, many TECs have not advanced to that depth. It also conservatively assumes that multiple TECs within a particular tube will each contribute equally to a larger leak rate, when in fact the leakage from a tube is limited not by the number of cracks present but by the tightness of the joint. Finally, it assumes that the axial tube load applied during the tests was representative of the load which would occur during a MSLB, when in fact the typical plant loads are much lower than that of the tests. Taken together, these assumptions yield very conservative leakage estimates.

MODIFIED ARC

As presented above, the parameters most relevant to the evaluation are axial tube load and delta dilation. The delta dilation values developed originally reflect tubesheet distortion, tube/tubesheet thermal deformation, and free (non-end capped) pressure tube dilation effects, but do not reflect the affect of axial load [2]. For the ARC as it was originally implemented, that approach is appropriate because the leakage test results are applied in a similar manner. Specifically, even though a bounding axial load was imposed during the leak testing (3060 lbs), the calculated delta dilations for the leak tests did not reflect that effect; therefore, the tested joint was actually looser (i.e., greater tube-to-tubesheet delta dilation) than indicated by the calculated delta dilation values. Because the actual MSLB tube loads are substantially lower than the tube load employed during the leak tests, exclusion of this effect imposes an excessive level of conservatism on the estimated leak rates. A Poisson Effect adjustment was applied in order to take advantage of lower axial loads (and associated leakage) which would exist in the plant during a MSLB than those loads applied in the original testing program. In the modified ARC, the delta dilation values from the plant specific MSLB FEM analyses, as well as the leakage test results, were adjusted to approximate the Poisson Effect on joint tightness.

Delta Dilation Adjustment

Total tube dilation is a function of both the applied axial load and internal pressure. Using the following equations, the contribution of each was determined in order to adjust the leakage versus dilation data set to more accurately reflect the tightness of the joints during the event at one of the affected plants.

$$\Delta Diameter_{Comb} = \Delta Diameter_{axload} + \Delta Diameter_{pressure}$$

Equation (1)

The contribution to dilation from the internal pressure is calculated using the diametral dilation of a pressurized, non end-capped thick walled cylinder from Table 13.5 of [3].

$$\Delta Diameter_{pressure} = \frac{4qR_oR_i^2}{E(R_o^2 - R_i^2)}$$

Equation (2)

The tube diameter reduction resulting from an axial tensile load is calculated with the following equation derived from the radial dilation of an unpressurized, axially loaded, thin walled cylinder in Table 13.1 of [3].

$$\Delta Diameter_{axload} = -\frac{PR_o\nu}{\pi R_{mid}Et}$$

Equation (3)

The resulting value was then subtracted from the tubesheet mockup bore dilations to arrive at the appropriate delta dilation values.

Plant MSLB delta dilations were similarly adjusted. Figure 4 above depicts the difference between the original delta dilations and the adjusted delta dilations in the UTE (hot leg) of the OTSG.

Leakage Versus Adjusted Delta Dilation

Using the adjusted delta dilations for the test data, a new leakage correlation was developed. Figure 5 illustrates the linear relationship between delta dilation and the logarithm of leakage. Table 1 provides the sample estimates of regression parameters for this relationship.

Regression Line	
Number of Data Points	119
Intercept	-4.7493
Slope	1.0063
Standard Error of Regression	0.79382

Table 1 Leakage Regression Sample Parameters

In order to accurately employ probabilistic techniques for determining total SG leakage, it was necessary to confirm that the variation of log(leakage) about the regression line is normally distributed, and that no systematic variation of residuals exists with respect to delta dilation. Figure 6 illustrates that the regression residuals closely follow a normal distribution. An examination of Figure 7 reveals no significant systematic relationship between the magnitude of regression residual and delta dilation. This validates the underlying assumptions required to implement the probabilistic evaluation described in the next section.

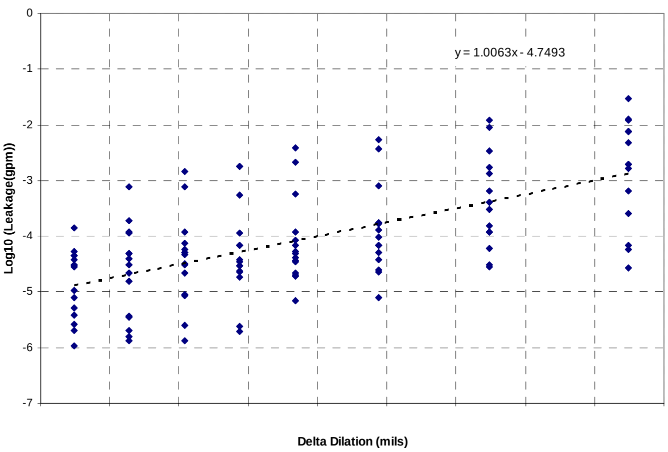


FIGURE 5 DELTA DILATION VERSUS LEAKAGE

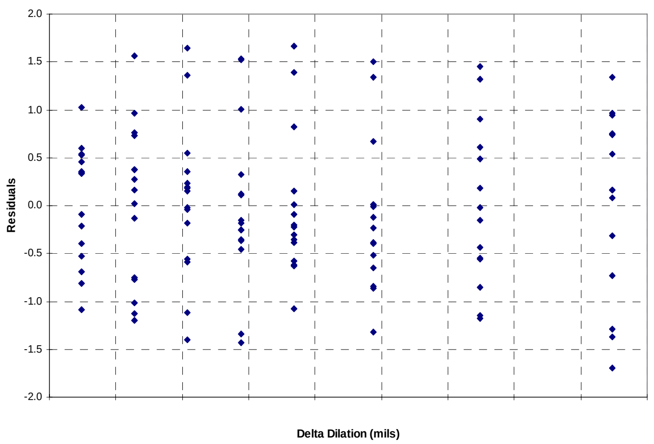


FIGURE 6 REGRESSION RESIDUALS

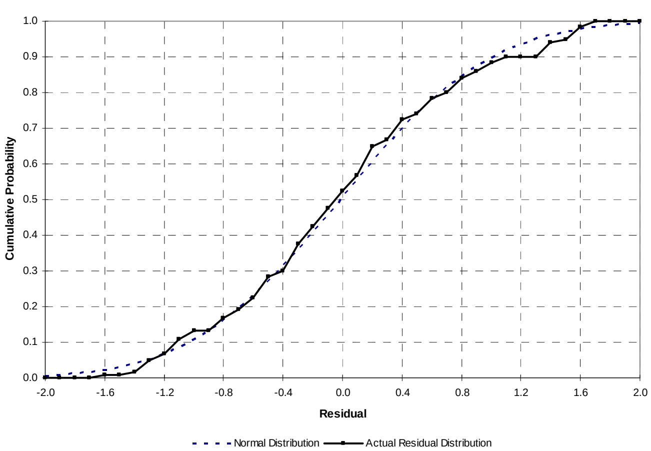


FIGURE 7 CUMULATIVE PROBABILITY OF RESIDUALS

Probabilistic Calculation of Total SG Leakage

For each TEC identified during an inspection, a leakage value corresponding to the tube's delta dilation is obtained by sampling from the leakage regression above. These probabilistic leakage values reflect the uncertainty that is inherent in the regression. The sum of the leakage samples from all identified cracks represents one probabilistic estimate – or one Monte Carlo trial – of total SG leakage. Repeated many times, this process generates a collection of probabilistic estimates of total SG leakage. This collection is the simulated distribution of total SG leakage from which values at a desired probability and confidence level can be directly obtained.

Leakage may be evaluated for either conditioning monitoring (CM) or operational assessment (OA) purposes. The CM evaluation estimates MSLB leakage for all cracks as found, while the OA evaluation accounts for the inspection technique's probability of detection (POD) and any tube repairs performed in the current inspection. The leakage associated with new cracks that develop during the next operating interval must also be accounted for in the OA, but is not performed inside the code.

LeakTEC was developed to accept as an input, a list of tubes which contain TECs, identified by row and column. For each tube the following additional information must also be provided: the affected tube end, the number of cracks, maximum crack voltage, and an indicator as to whether the tube will be repaired. The code determines each tube's radial position within the tubesheet matrix based on the row and column values. Subsequently, the plant specific MSLB delta dilation is determined for each tube based on its radial position within the tubesheet. The capability to further evaluate TECs based on eddy current signal voltage amplitude was also programmed as an added feature, but not utilized in this approach.

The Monte Carlo simulation generates leakage estimates for each crack and determines total SG leakage at desired probability and confidence levels. The approach employed is closely modeled after the process used in the ODSCC ARC used for axial indications detected TSP crevices in Westinghouse designed SGs [4], as well as NRC Generic Letter 95-05 [5]. Probabilistic slope, intercept, and regression error values are generated for each Monte Carlo trial. For each crack, these values are used along with a random normal deviate applied to the regression error, to generate a probabilistic leak rate estimate. These estimates are summed to generate a probabilistic estimate of total SG leakage; a process that is repeated thousands of times. This process as applied to condition monitoring is described in more detail below.

Condition Monitoring Calculation

The χ2 distribution is used to model the uncertainty which is inherent in the sample estimate of standard error of regression provided in Table 1. In the equations below a random χ2 deviate for N-2, or 117 degrees of freedom is used to generate a probabilistic value of the standard error of regression:

$$f_v = \frac{(N-2)}{\chi^2_{(N-2),RANDOM}}$$ **Equation (4)**

$$RnS = S\sqrt{f_v}$$ **Equation (5)**

The same approach is used to generate probabilistic estimates of the variance-covariance values for slope and intercept:

$$RnV_{11} = f_v V_{11}$$ **Equation (6)**

$$RnV_{12} = f_v V_{12}$$ **Equation (7)**

$$RnV_{22} = f_v V_{22}$$ **Equation (8)**

A probabilistic intercept value is then generated by:

$$Rn\beta 3 = B + Z_1\sqrt{RnV_{11}}$$ **Equation (9)**

A probabilistic value for slope must also be generated. While the slope and intercept are individually normally distributed, they are not independent of each other. Taken together they are bivariate normally distributed. The probabilistic value of slope is constrained by the probabilistic value of intercept. This co-dependence is quantified by parameter V_{12}, the covariance of intercept and slope. The probabilistic slope value is calculated as follows:

$$Rn\beta 4 = M + Z_1\frac{RnV_{12}}{\sqrt{RnV_{11}}} + Z_2\sqrt{RnV_{22} - \frac{(RnV_{12})^2}{RnV_{11}}}$$

Equation (10)

Using the probabilistic values of slope, intercept, and regression error, a probabilistic estimate of leakage is obtained for each crack. The sum of the leakage for all cracks represents one probabilistic estimate of total SG leakage:

$$Leakage_i = InvLog_{10}(Rn\beta 3 + DD_i Rn\beta 4 + Z_3 RnS)$$

Equation (11)

$$SGLeak_k = \sum_{i=1}^{NumCracks} Leakage_i$$

Equation (12)

These calculations are repeated many times, generating thousands of $SGLeak_k$ values. Together these values represent the simulated distribution of expected total SG leakage. Once ordered from smallest to largest, leakage values at desired probability and confidence levels can be taken directly from the distribution using an appropriate index value. For example, the one-sided upper 95% probability / 95% confidence value of leakage in an ordered distribution of 10,000 values would be the 9,537th value. This index is the smallest value of n for which the following relationship is true [6].

$$\frac{1}{1 + \frac{Num - n + 1}{n} F_{1-\alpha, 2(N-n+1), 2n}} \geq P$$

Equation (13)

Operational Assessment Leakage

The OA calculation is identical to the process described above, except for one additional step that adjusts the number of cracks in each tube to reflect the inspection POD and to reflect any tube repairs to be performed prior to returning the SG to service. Within LeakTEC this step is performed for all imported tubes prior to each Monte Carlo trial. It is applied probabilistically such that "fractional cracks" are appropriately represented in the results.

As illustrated by the following equation, a POD value of less than one increases the number of inservice cracks expected during the next operating cycle, while tube repairs reduce the number of inservice cracks:

$$NumCracks_{(n+1)} = \frac{NumCracks_n}{POD} - NumRepaired_n$$

Equation (14)

For example if the POD is 0.84, a tube with two cracks identified and repaired during the current outage would yield 0.381 cracks for OA evaluation purposes. To account for the fractional crack, prior to each Monte Carlo trial the fraction is compared with a random number between zero and one. If the random number is greater than the fraction, the number of cracks is rounded down to the nearest integer. Otherwise it is rounded up to the nearest integer. For this example, in a large number of trials the number of cracks evaluated for this tube will equal one in 38.1% of the trials (i.e., 0.381 x 100%) and will equal zero in 61.9% of the trials.

Benchmarking

During the NRC review process, benchmarking calculations were performed to quantify the benefits of utilizing the changes to the original ARC method described in this paper [6]. Actual results from an inspection were used to perform the benchmark. Calculations were performed based on two sets of mockup test results that employed 3060 lbs and 1660 lbs axial load. For the 3060 lbs tests, a separate leak calculation was produced for each of the various levels of Poisson effect adjustment. The input parameters discussed above and the plant specific inspection results were used to benchmark the effect of the change in method.

Figure 8 summarizes the results of the study and illustrates the impact of the improvements in the analysis methods discussed in this paper. The leftmost bar indicates the total MSLB leakage, calculated using the deterministic method and no credit for Poisson's effect on the testing results (0.945 gpm). The second bar from the left (0.566 gpm) is the calculated leakage for the same population of TECs using only the probabilistic methodology. No benefit from a reduction in delta dilations associated with the axial load in the test program was used.

The next three bars from the left reflect varying levels of reduction in the delta dilations due to Poisson's effect, associated with varying levels of axial load assumed to be present within the expansion during the high load leak testing (3060 lbs). The results are arranged in order of increasing axial load reflecting increasing percentage of the total applied axial load used to reduce the delta dilations.

The rightmost bar (0.241 gpm) is the calculated MSLB leakage for the same population of indications using the probabilistic method, but is based on supplemental leak test data collected at an axial load of 1660 lbs. The result does not include any reduction in delta dilation associated with the applied axial load. The calculation for this condition was performed to demonstrate that the methodology, with full application of Poisson Effect, does not produce a non-conservative leak rate. The leak rate using Poisson effect adjustment and probabilistic methodology results in a calculated leakage of 0.298 gpm versus a calculated leakage of 0.241 gpm based on actual test data at a lower axial load (1660 lbs) and without application of Poisson's Effect. The result obtained from the 1660 lbs tests, in which no Poisson effect adjustment was made, is lower than the result obtained from the 3060 lbs tests with full Poisson Effect adjustment. This reinforces and validates the position that the adjustment for the Poisson Effect employed is appropriate.

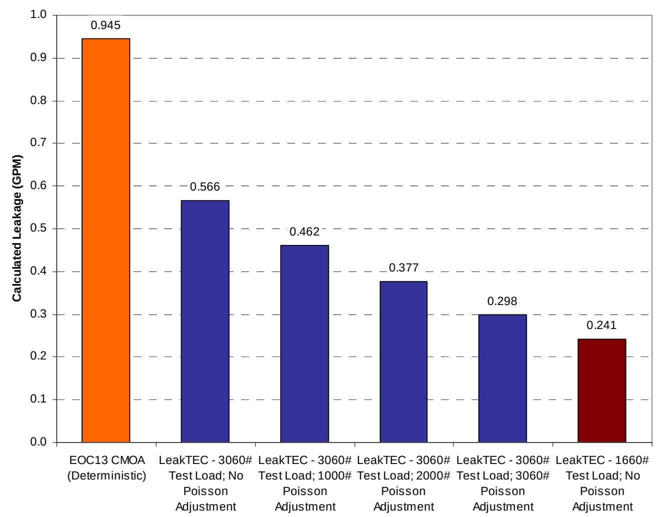


FIGURE 8 COMPARISON OF RESULTS

Results

The modified approach described above was recently licensed and utilized by an OTSG plant in which the deterministic method was no longer effectively managing the increasing TEC population. Significant numbers of preventive repair rolls would have continued to be necessary to maintain leakage below site specific requirements. Using the adjusted delta dilations in combination with the probabilistic calculation resulted in a significant decrease in the operational assessment leakage total for the affected plant and eliminated the need for associated repairs.

SUMMARY

In order to manage increasing PWSCC degradation in the tube ends of OTSGs with alloy 600 SG tubing, reduce outage tube repairs and schedule duration, as well as postulated accident leakage; the authors modified the originally licensed leakage evaluation methodology to remove sources of excessive conservatism. Two strategies were undertaken toward this end: 1) the incorporation of Poisson Effect adjustments to the leakage test data to account for the very conservative axial loading conditions used; and 2) the implementation of a Monte Carlo methodology to probabilistically estimate total SG leakage in lieu of the deterministic process. Recently, the approach was successfully licensed and implemented by one of the affected OTSG plants, significantly reducing the estimated leakage for a mature population of TECs and reducing overall SG outage schedule duration and cost by eliminating the need to preventatively repair affected tubes.

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